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PROTECTION AGAINST BLACKOUTS AND SELF-RESTORATION OF POWER SYSTEMS

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In the power system's control hierarchical structures are used which provide high security of operation. These structures are employed both for operative management and for regulation (primary, secondary, and tertiary) of the processes going in power systems. In turn, to stop a cascade-wise emergency process there exist protections against damage of elements along with systems for liquidation of local disturbances while absent protection superstructures to complete the hierarchical protection pattern. The need for such superstructures is dictated by regularly occurring blackouts in power systems.

In the book it is shown that the main cause of blackouts is the grid overload, which, according to the authors, can effectively be eliminated by short-term sectioning of a power system. Such sectioning arrests the spread of the cascade-wise emergency process and activates the mechanism of a power system's self-restoration. To achieve this, a centralised anti-emergency superstructure should be built, with only minor improvement of local protection systems needed; after that a blackout will be liquidated within about 100 seconds − without staff participation and unnoticed by the majority of consumers.

Reviewer Prof., Dr. habil. sc. ing. Namejs Zeltins

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PREFACE

During the first half of the last century, the electricity supply in most countries was provided by separate power systems whose failures were of a local nature. With the construction of large high voltage transmission lines and the connection of regions, power systems became capable of supporting one another by supplying energy in cases of line failures or large capacity generator failures. The connections made it possible to establish shared reserves of generating sources, to ensure stable voltage and regulate network frequency. When these first lines were connected with power systems, the risk arose that in the event of a minor malfunction a total blackout could occur for all connected systems.

The connection of Latvian power systems to neighboring systems started in 1960, when a 330 kV line was constructed that connected our Republic with Estonia. Estonia, in turn, was connected with Saint Petersburg. During the course of the further development of transmission networks, Latvia was incorporated into the united power system of the Soviet Union, which worked with a common frequency. In order to prevent a total electricity supply blackout for the entire power system in the event of an interruption in supply, automatic emergency control and relay protection systems were gradually improved. Latvian power system specialists, including the author of this book, J. Barkans, made a significant contribution to this work. As a result, the shared power system of the Soviet Union did not experience total electricity supply blackouts for large regions.

With the constant rise in demand for electricity, the power of electrical sources and transmission lines substantially increased. Permitting systems to operate without sufficient power and transmission reserves resulted in several cases of system crashes which caused long electricity supply blackout and major losses. Such large system collapses occurred in the 1960s and 1970s in North America. To avoid such cases, the North American Electric Reliability Council was founded and developed conditions that were compulsory for all electricity supply system participants. In spite of these measures, at the beginning of the 21st century large system crashes in North America continued to occur, and they were joined by European power systems. On January 9, 2005, the Latvian power system also came very near to a nationwide electricity blackout due to the fact that supply from eight transmission lines had been cut during a large storm. However, electricity supply was maintained by the only transmission line still operating.

The authors of the book have analyzed the global electricity supply collapses in detail, and have tried to find answers to the deficiencies in the functioning of the systems that lead to long electricity supply blackouts and substantial losses. The book contains conclusions and proposals for solving the problem. The authors reason that power systems require a fast-acting protective system superstructure that would temporarily separate the system in the event of severe operating malfunctions and would reconnect it after the malfunction has been resolved. The authors’ proposals are based on their experience in working with the Latvenergo AS power system.

The book may be useful for power system operative personnel, creators of energy equipment, as well as the lecturers and students of technical universities.

The monograph Protection against Blackouts and Self-Restoration of Power Systems, which investigates the aforementioned problems, is written by Prof. Jekabs Barkans and Diana Zalostiba, M. sc. ing. The monograph is dedicated to the 85th anniversary of the Latvian Member Committee of World Energy Council (LMC/ WEC).

Through the mediation of the WEC management, this book can reach readers in all the WEC member States. This would provide an introduction to the profound theoretical studies conducted by Latvian scientists in power energy, which may find practical application in the industry.

Karlis Mikelsons

Vice-President of Latvian Member Committee of World Energy Council,
Chairman of the Management Board of Latvian power company, Latvenergo AS

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ABBREVIATIONS

ARC	Automatic re-closing
AUFLS	Under-frequency load shedding automatics
AUFLS1	Fast-acting under-frequency load shedding automatics
AUFLS2	Slow-acting under-frequency load shedding automatics
AUVLS	Under-voltage load shedding automatics
OPC	Over speed Protection Circuit
TPP	Thermal power plant
HPP	Hydro power plant
NPP	Nuclear power plant
SCADA	Supervisory Control And Data Acquisition
UCTE	Union for the Co-ordination of Transmission of Electricity
SBA	Switch failure Backup Automatics
WSCC	Western Systems Coordinating Council
RAS or SPS	remedial action scheme special protection scheme

INTRODUCTION

Abnormal cascading processes developing in power systems, when every disturbance triggers a next one, and so on, result in blackouts, i.e. mass-scale tripping of generating sources and disruption of electricity supply over large areas. Such blackouts imply damaged equipment of power plants, interrupted production cycles, chaos in the conditions of people’s lives, and great economic losses.

For the functioning of a power system definite standards exist. Of importance is to choose its operational parameters, and it is usually done by careful coordination (management) of the decisions to be made. However, despite all this, accidental blackouts persist in major power systems of the world. The 30 events considered in this book are only part of the worldwide blackouts since the second half of the 20-th century.

The existing protections employ diversified local automatic devices. However, incessant blackouts evidence that these protections are sometimes insufficient. When analysing the system blackouts it has been established that their development can include up to 12 various processes. Such diversity might create an impression that these blackouts are individual in character; however, this erroneous impression has been a serious handicap to the elaboration of a new defence strategy. Therefore it was necessary to analyse the issue from the viewpoint of the conceptual choice that would underlie the protection complex against blackouts. The analysis has shown that, if the system security standards are observed, practically all incidents are triggered by overloads in transmission grid. Therefore at the creation of a protection complex most attention should be concentrated on the fast elimination of a grid overload. Taking into account the wide geography of such incidents, a centralised preventive protection scheme is required [1], [2].

The management of a power system is based on the hierarchical principle. This refers both to the operators that keep watch on its condition and to the automatic control (primary, secondary, and tertiary). The same could be said about the protection against blackouts. This means that the new solution should be realised as a “super-structure” that would combine the protections already available in a power system. Its key task is to recognise the overload, to localise it, and to issue the signal to the existing protection to perform the actions necessary for remedying the situation [3].

Using the data of the normal operating condition, the network is split for a short time at the place through which the power close to overload is flowing. This instantaneously eliminates the overload, keeping the lines operating with the allowable load and generating sources, thus overcoming the congestion in the power system. At splitting, one system part remains with a minor power surplus, while the other ─ with the same deficit, which will be removed by automatic fast-acting under-frequency load shedding (AUFLS). When the frequency, with the help of a slow-acting AUFLS with feedback, is recovered to the nominal value, the automatic re-connection of the split system parts and automatic re-closing of consumers will be performed [4].

The work on the creation of a self-restoration complex for elimination of frequency faults was initiated in 1963. The Latvian power system (where J. Barkan was then working) due to weak intersystem links experienced blackouts almost every year. The analysis evidenced that they occurred at a system's splitting into parts with an active power deficit in one of them. Therefore, a solution was sought for restoration of the power system's integrity with deficit liquidation. To this end it was necessary to ensure the automatic frequency recovery to the nominal value. This could be provided using an additional slow-acting AUFLS with a unified high setting for protective actions and automatic change of the return setting in the nominal frequency zone. At equal frequencies it was possible to restore the system's integrity; however, the lines were lacking synchronisators. This function was executed by the synchronism-check devices available on the lines. After that, the automatic re-closing of tripped consumer lines was conceived (implemented in 1964). According to this solution, the restoration process lasted for 100 seconds, so it proceeded unnoticed by most of the consumers. The publication devoted to this solution [5], being reviewed at the central Energy Ministry in Moscow, was incorporated into the anti- emergency guiding instructions and implemented in other power systems. The protection complex had operated for many years, successfully eliminating active power deficit disturbances (which happened then quite often) and transforming them into short-term and practically unnoticed transient processes with the self-restoration ability.

It is self-evident that such a process is not only of direct but also of inverted character, which, if necessary, might advantageously be employed for the solution of an inverse problem. Such a necessity arises when the above mentioned overload is to be eliminated. Thus the blackout problem is solved via a practically unnoticeable 100-second transient process.

Obviously enough, this solution to – as of yet unresolved – problem facing a power system is recommended not on its own but with complementary analytical material supplied and alternative protection means against blackouts discussed. The authors hope that the book, in which these aspects are considered, will be useful for the personnel engaged in maintenance of power systems, the engineers of the equipment producing companies, the energy speciality lecturers, the researchers, as well as the students of higher years in the power engineering speciality.

1. ANALYSIS OF POWER SYSTEM BLACKOUTS

Despite non-stop improvement of the relay protection and anti-emergency means, blackouts in power systems still persist. Therefore, to work out a reliable protection complex against blackouts a thorough analysis of the worldwide blackouts is required. In this section, the history of blackouts, their specific features and protection performance are expounded.

THE HISTORY OF BLACKOUTS IN THE COURSE OF POWER SYSTEM DEVELOPMENT

The power systems are developing as compact load centres connected through an inter-system network. In the early stage these centres were self-balancing, and their integration made it possible to raise power thus ensuring the common reserve [6]. This, however, led to their mutual dependence, and the power balance became more labile. Since then, the blackouts of power systems have happened repeatedly [7], [8].

The history of power system blackouts can conditionally be divided into six stages [1].

The first stage embraces a period of 20-35-ies of the past century. In not very large power systems of those times a large number of generating sources had already been functioning in parallel. The main cause of blackouts was then voltage decrease avalanches due to improper excitation regulators. In the 30-ies these regulators were improved; in the emergency cases they forced excitation of generators, and disturbances of the kind ceased to exist [9].

The second stage of blackout history (1940–1980) is characterised with frequency avalanches. Their main cause was integration of power systems, with weak and insufficiently secure intersystem links formed. This did not allow implementation of organisational measures directed to the observance of the security rules, i.e. the (*n*-1) criterion (reservation of network cross-sections to preserve the carrying capacity of a power system in case one of the links is disconnected). As a result, under emergency conditions a system was split into parts, with a power deficit in one of them. This led to a deep frequency fall; in such a situation, with the boiler pressure decreasing the technological protections tripped the generating units, thus leading to cascading their outages.

As a protective means, fast-acting automatic under-frequency load shedding (AUFLS) was implemented, which tripped the consumers by frequency decline [10]. This made it possible to maintain the frequency at a level though lower but not endangering the operation of generating sources. The low frequency did not allow restoration of a system integrity needed for resuming the power supply. The normal operation had to be resumed by personnel, who performed frequency recovery manually and then synchronised the deficient part with the rest of the power system. Power supply restoration then took 1-3 hours.

The third stage of blackout history is dated back to the 1960-s and refers to the Latvian power system. Owing to the weak intersystem links, power system blackouts occurred practically every year. To improve the situation, J. Barkans (Chief Dispatcher of the Latvian PS) proposed an automatic anti-emergency complex based on the self-restoration principle for frequency disturbance elimination within several tens of seconds. The problem was theoretically solved in 1963. For this purpose, the existing fast-acting AUFLS was complemented with the following three elements:

- slow-acting AUFLS, consisting of several stages with selective time delays and a common frequency setting as well as automatic re-adjustment of the setting for return to the rated frequency level;

- automatic power system re-integration based on the check-of-synchronism relays;
- automatic re-closing of consumers’ lines by the normal frequency indication.

As a result, in the emergency process at a frequency decline the fast AUFLS operates, which stabilizes it on a reduced level. In turn, the slow AUFLS restores the frequency up to the rated value, thus making possible automatic synchronisation and automatic re-closing of consumers’ lines. With the use of the mentioned elements the process of power system self-restoration lasts for 60-100 s. In such a way a frequency emergency turns into a short-term stable transient process. This solution was included into the power system anti-emergency directives of the USSR, which promoted its wide application in other systems (for the details see [5] and §0). After the Latvian power system adopted this scheme in 1964, the problem of frequency disturbances has practically been solved.

It is remarkable that this way of PS self-restoration could be employed not only directly but also in an inverted manner, that is, by transforming an emergency process into a frequency disturbance which would be liquidated fast thus securing accomplishment of the task.

The fourth stage embraces a period around the 70-ies, when power system blackouts caused by stability loss and out-of-step operation were dominant. For liquidation of such blackouts the following means were proposed: fast-acting control of a power system in the cases of stability loss; and its controllable splitting in the cases of out-of-step operation [11], [12], [13], [14].

The fifth stage. In the 80-ies, when the power system schemes acquired a meshed structure, numerous disturbances originated in transmission line cross-sections’ overloadings took place, with voltage avalanche development (§0) [15]. In these cases to a voltage fall the generator excitation regulators respond; as a result, the generators become overloaded with reactive power, which is followed by their large-scale tripping by the protection [9].

The sixth stage of blackout history refers to the beginning of the 21-st century. Currently, in addition to the mentioned above faults, cascading line disconnections caused by voltage avalanches and enhanced wire sagging mainly occur (§0) [7], [16].

THE BLACKOUTS EXPOSED TO ANALYSIS

To assess the possibilities of improving the automatics for protection of power systems against blackouts, the authors have analysed the data on 30 world’s major blackouts of the 2nd half of the past century and further (Table 1.1), with the aim to find some common features to which rather a simple automatic complex of protective means could respond (Appendix 1).

Table 1.1. Blackouts under analysis

Nr.	Date	Power system
1	**09.11.1965**	**USA North-East - Canada**
2	**05.06.1967**	**USA (PJM)**
3	**14.07.1977**	**New-York district**
4	**19.12.1978**	**France**
5	**04.08.1982**	**Belgium**
6	**14.12.1982**	**Canada**
7	**27.12.1983**	**Sweden**
8	**12.01.1987**	**France**

Nr.	Date	Power system
9	**22.08.1987**	**USA (Tenessee)**
10	**21.02.1995**	**USA (PECO)**
11	**26.04.1995**	**USA**
12	**08.06.1995**	**Israel**
13	**02.-03.07.1996**	**West USA – Canada**
14	**10.08.1996**	**West USA – Canada**
15	**20.06.1998**	**Bangladesh**
16	**25.06.1998**	**USA North-West**
17	**11.03.1999**	**Brazil**
19	**06.-07.07.1999**	**USA North-East**
18	**11.1999.**	**Japan**
20	**21.01.2002.**	**Brazil**
21	**12.01.2003**	**Croatia**
22	**14.08.2003**	**USA - Canada**
23	**23.09.2003**	**Sweden-Denmark**
24	**28.09.2003**	**Italy**
25	**12.07.2004**	**Greece**
26	**14.03.2005**	**Australia**
27	**25.05.2005**	**Moscow (Russia)**
28	**04.11.2006**	**European power system**
29	**25.06.2008**	**Belarus**
30	**10.05.1964**	**Latvia**
	01.09.1965	**Latvia**
	18.07.1967	**Latvia (PA operated 4 times a day)**

CONCLUSIONS

At analysing the major blackouts that have occurred in the power systems worldwide, particular attention has been given to the following issues (considered in the ensuing chapters):

- the role of personnel in the liquidation of cascade-wise incidents;
- measures to be taken under normal and pre-emergency operational conditions for blackout development minimisation;
- classification of emergency events and their identification with similar ones;
- the response of generating sources to the deviations in operating parameters and the possibility to keep them running;
- the existing protections and possibilities of applying them for new purposes.

2. CONTROL AND SECURITY OF POWER SYSTEMS

In this section, based on the analysis of power system operation and control, the mechanisms of blackout initiation and causes of cascading emergency development are discussed. A new conception of the protection complex against blackouts is proposed, which is intended for fast liquidation of overload in a power system and its self-restoration to normal condition.

CONTROL OVER A POWER SYSTEM IN VIEW OF ITS SECURITY

From the viewpoint of security, the operational conditions of a power system can be classified as [17]

- normal;
- pre-emergency;
- emergency.

For normal operating conditions the mandatory security standards exist along with power limitations in order to maintain voltage and frequency in the allowable margins [18]. Usually, this concerns observance of the (n-1) criterion, which means that at emergency tripping of one important element of a power system it is kept normally operating thus preventing the development of a cascading emergency. A power system operator performs non-stop monitoring of security criteria ensuring the power reserves needed for frequency and voltage control; a definite reserve is provided to secure the allowable power exchange in transmission lines [19].

A pre-emergency condition is settled when at normal running an element of a power system is tripped, which disturbs its operation. In this case, the emergency condition has not yet begun but the security criteria are not observed any more, and the development of an emergency process can start at any time if there is enhancement of operational condition severity [17]. Still, the situation can be normalised by mobilising the capacities and reserves [20], [21].

Once the emergency condition has taken place, the process is developing in a fast cascade-wise manner. The personnel are unable to control the situation any more, and a blackout can only be prevented by the fast-acting automatic protection means [22], which should be unified and most simple.

To manage the mentioned situation the measures shown in Fig. 2.1 are applied.

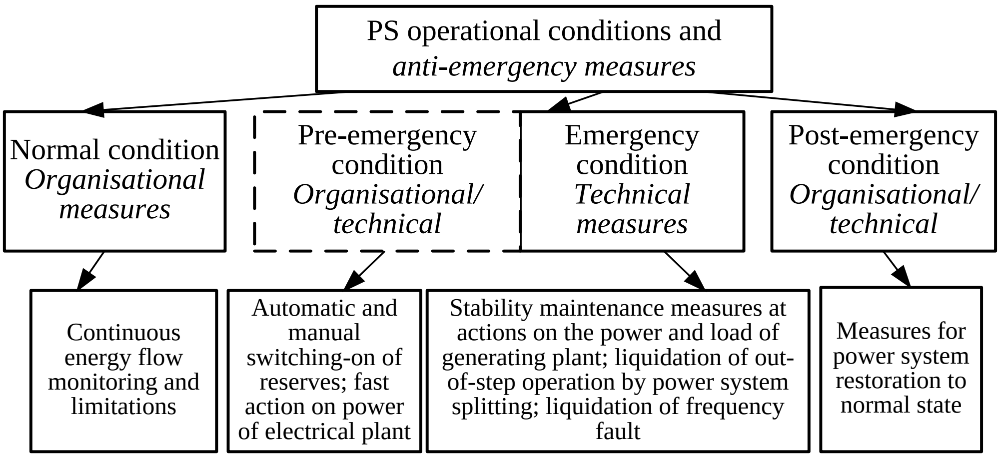


Fig. 2.1. Classification of the anti-emergency measures by operating condition of a power system

Organisational measures are associated with the staff actions that are to be taken in compliance with the written or electronic instructions. These measures should correspond to the human abilities to act and make decisions fast. To provide higher security, the execution of instructions could partially be made automatic. At normal operation these are applied in a usual order; however, in the pre-emergency condition special programs are required that would provide instructions for urgent actions in a changed situation.

Technical measures are unavoidable in the emergency running, when the events are being developed too fast for a human to act, and the blackout can only be prevented with fast-acting technical means. In these cases the staff should be involved in the post-emergency stage.

2.1.1. Personnel in the power system control

Personnel, together with technical instruments, form a unified control complex providing security of a power system. As distinguished from entirely determinate technical instruments, the human is rather an indeterminate being, depending both on his/her innate features and individual abilities [23]. It is of importance to understand what possibilities are concealed in the interaction of people with technical means and what their role is in the control under different operational conditions of a power system.

A person's activities are associated with emotional stress, which arises as response to the unexpected, affecting the successfulness of work. As seen in

Fig. 2.2 [23]), if stress is minor – e.g. at doing monotone and not very interesting work – there will be little success. With stress increasing, an interest arises, the work will be more fruitful, and all the working instruments will be suitable. When the amount of information becomes too large, the rate of situational changes as well as doubts about the outcome will grow; in these cases stress exceeds the critical level, the situation throws into confusion, and the work will be unsuccessful [23]. Under such conditions the involvement of personnel becomes dangerous, so it is better to exclude it from the process.

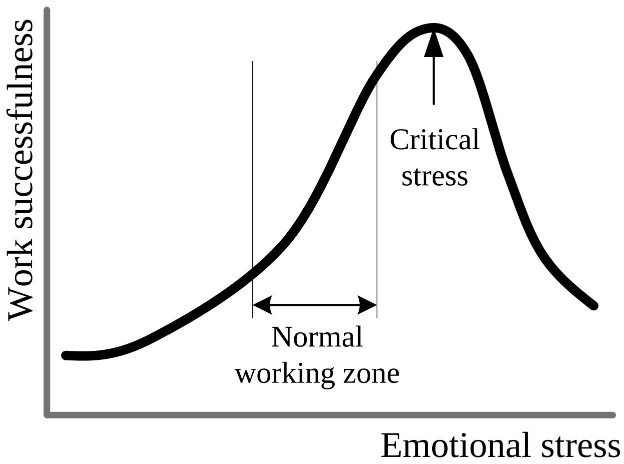


Fig. 2.2. Effect of emotional stress on the successfulness of work

The emotional stress and resultant erroneous actions prevail in the cases when high speed of operation is required. Especially dangerous are errors made by staff in the cases when decisions must be taken in a hurry, under hard-to-identify and fast changing conditions. Therefore, the processes where the people's work might be unsuccessful are to be automated, or there should be corrigible and understandable instructions (forewords) or programs in order to free a person from the necessity to rely upon his/her memory [24].

Having familiarised oneself with the protocols of blackout investigation, one will be able to ascertain that the specific weights of organisational and technical measures are often equal. At the same time, blackout events evidence that the speed of emergency process development exceeds many times the rate of response achievable by people.

As a result, it could be stated that a person can successfully function when there is no hurry, the work is not monotone, and, therefore, not completely determinate. Despite the fact that the improvement of skill and acquisition of working habits receive now much attention, with various special arrangements organised, it should be taken into account that in a hurry a person unavoidably becomes worried and confused. This leads to increased probability of erroneous operation [25], which is one of the causes of severe blackouts in power systems. To improve the situation, it is necessary to reveal such erroneous activities and provide preventive technical measures.

DANGEROUS GRID CROSS-SECTIONS

Under normal conditions the energy flows are held in the permissible limits, by regulating the generating capacities at the power sending and receiving ends of a cross-section, and especially by monitoring the dangerous cross-sections (Fig. 2.3) which contain line complexes connecting the system parts with power flows that could exceed the allowable level [6], [24].

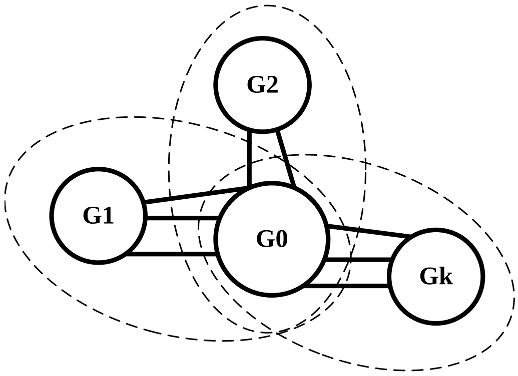


Fig. 2.3. Dangerous cross-sections of a grid

The configuration of such cross-sections depends on the network topology. In Sweden or Canada (Quebec) the transmission lines are directed from the north (radial network), where hydro-power plants are located, to the south (400 and 750 kV, respectively), forming dangerous cross-sections [26], [27]. In the meshed networks a cross-section can be consisting of several differently directed lines; for example [27], in eastern Germany and northern Italy there are cross-sections that carry power flows up to 9 GW.

Sudden cross-section overloads usually arise at disconnection of heavily loaded transmission lines, when the power flow is re-distributed among the lines that keep operating. A notion about the probabilities of faults in different voltage lines can be received from Table 2.1 [24].

Table 2.1. Probabilities of line faults per 100 km/year

Line voltages, kV	1150	750	400-500	330-375	220	110
Stable faults: One-circuit	0.4	0.45	0.5	0.8	1.0	1.4
One circuit from two				0.6	0.8	1.0
Both circuits				0.2	0.2	0.4
Transient one-circuit faults	0.3	0.35	0.4	1.6	2.4	3.2

From the table it follows that the probability of line disconnection is rather high and is to be taken into account while considering potential emergency events. Causes of line faults are various. In the case of a transient fault such a line will be automatically re-closed [28]. On the lines with high carrying capacity one-phase automatic re-closing sets are provided, which in emergency cases limit this capacity to a lesser degree. In the case of stable fault, at a line disconnection the power flows are re-distributed among the remaining (operating) lines, which can cause a dangerous overload and development of a cascade-wise process (for details see §3).

The number of dangerous cross-sections is limited; the places of their location are known and should be under non-stop control. In the emergency cases the cross-sections should be dealt with as complexes which must be simultaneously tripped before the beginning of stability loss, voltage avalanche, and cascading line tripping caused by wire sags.

POWER SYSTEM CONTROL AND RELEVANT MATHEMATICAL MODELS

Nowadays, control over the power system operation is difficult to imagine without appropriate software. Variously-purposed special programs have been worked out and are successfully working in real power systems [6], [12], [22], [29], [30], [31]. Generally, these should fulfil the following tasks [17]:

- to display in real time the state of a power system, removing unavoidable measurement errors;
- to set automatically the maximum allowable power flows through dangerous cross-sections of a transmission line, periodically monitoring the operation security and disconnecting in turn important components of the power system;
- to provide the staff with the list of urgent measures (in the form of instructions) at the initiation of a marginal condition (identified as a pre-emergency) when cascading processes are likely to develop as the situation is becoming worse;
- under normal conditions, by modelling the cyclic disconnections of system elements, to enter the necessary actions in the memory of protection system, which will then be capable of coping fast with a power system blackout.

2.1.2. Topology dependence of power flow limitations

The level of power exchange limitations under normal conditions depends on the topology of a transmission network [6], [11], [32]. If it is radially structured, the power flow P at disconnection of a cross-section's transmission line must not exceed the permissible margin [32]:

$$P = (k/n) P_p \tag{2.1}$$

where P_p is the maximum permissible power flow through a cross-section under normal condition; n is the number of lines in this cross-section; k is the number of lines keeping operation, $k/n < 1$.

For example, if one of three parallel lines is tripped, then the power flow must not exceed 2/3 of the maximum permissible under normal conditions.

In the cases of a meshed network topology, at tripping a line the power flows in the remaining lines can be determined using matrices composed of load distribution coefficients [6], [11], [32]. In such a matrix the columns correspond to the load nodes and the rows – to transmission lines; distribution coefficients α_{ij} (i – nodes, j – lines), which show what proportion of power generated by electric stations is flowing through the corresponding line, occupy the matrix cross-points (see Fig. 2.4a).

For example, α_{35}=0.4 means that through the 5-th line 40% of P_3 node flows (or that at changing generation P_3 by ΔP_3 the power in the 5-th line will change by $0.4\Delta P_3$). To relieve a network cross-section, e.g. by 300 MW, the power in a generating node should be reduced by $1/\alpha_{35} \cdot \Delta P_3 = 2.5\Delta P_3 = 2.5 \cdot 300 = 750 MW$, which is often difficult to fulfill. The same results could be achieved reducing consumption at the power receiving end, for example, by shedding a load.

a)

Lines	Power of nodes: I	II	III	IV	V
1	α_{11}	α_{21}	α_{31}	...	α_{i1}
2	α_{12}	α_{22}	...	...	...
3	α_{13}	...	...	...	...
4	...	...	...	...	...
5	α_{1j}	...	...	...	α_{ij}

b)

Lines	Transmission lines: I	II	III	IV	V
1		γ_{21}	γ_{31}	...	γ_{i1}
2			γ_{32}	...	γ_{52}
3				...	...
4					γ_{ij}
5					

Fig. 2.4. a) Matrix I – coefficients of node power distribution among transmission lines; b) Matrix II - power distribution coefficients after tripping a TL

If to a dangerous cross-section no generating sources are connected, it could be separated and controlled individually using a symmetrical matrix (Fig. 2.4b). The coefficients placed in this matrix, γ_{ij}, show what proportion of the total flow through a cross-section is transmitted over a corresponding line at disconnection of some other line. The total power flow in the lines keeping operation should be compared with the known maximum allowable value for a given cross-section, and, if it is exceeded, the necessary load relief actions should be performed.

SECURITY MEASURES UNDER NORMAL OPERATING CONDITIONS

To define the required security measures the above mentioned real-time programs are employed [18]. It is known [6] that power flows are limited by the following factors: cross-sectional area of line conductors (also from the viewpoint of thermal and mechanical processes), voltage drop in the network, stability securing, etc. A real-time mathematical model of a power system receives information about its state [33]. The algorithm that describes worsening of the situation at variations in the load, generation and power flows identifies such dangerous events as overload or enhanced voltage deviation, as well as defines the maximum permissible power flows.

When analysing the fulfillment of the $(n-1)$ criterion, the model should work cyclically, in the automatic mode, tripping one by one the network elements, defining each time the degree of operation security. If tripping of an element can cause impermissible frequency (voltage) deviations, stability loss or cascade-wise tripping, new limits should be introduced in order to return the power system to the previous security level. When putting limitations on the power flows in a meshed network it is necessary to take into account possible equalising flows and mutual influence of different cross-sections.

When repair is scheduled, at the analysis it is necessary to check whether it is possible, in case of emergency, to trip one more element of those remaining operational [24].

As could be seen, observance of the $(n-1)$ criterion imposes constraints on the carrying capacity of a transmission grid; this raises certain psychological problems, since sometimes it is difficult to put aside economical benefit only because of rare emergencies.

2.1.3. Reserves for power balance maintenance

Security measures should contain the requirements on the reserve maintenance and control [34]. The placement of reserves should be dictated by economical reasons. A reserved unit should not be fully loaded, which, however, is undesirable from the viewpoint of its competitiveness. At the same time, low-economical equipment often has no sufficient power to keep a reserve. In major power systems the requirements on reserve capacities and their placement are standardised, and the task of reservation is in these cases economically justified [20], [35].

The active power balance should be provided in real time, using reserves divided into two parts: rotating and stationary power reserves. To provide reserve for major power systems definite capacity proportions should be territorially distributed, involving power plants that participate in frequency control. The corresponding capacities should have rotating power reserves, which are associated with dependence of consumption on the weather conditions and forecasting accuracy. The reserves can be divided by the speed of their mobilisation into three groups as follows [36], [37].

The primary reserves are mobilised in seconds, with their amounts depending on a system's power. As shown in Fig. 2.5, the reserve mobilisation time for the major European power system (UCTE) under normal conditions is 5-30 s, and under emergency conditions – up to 120 s [38], [39].

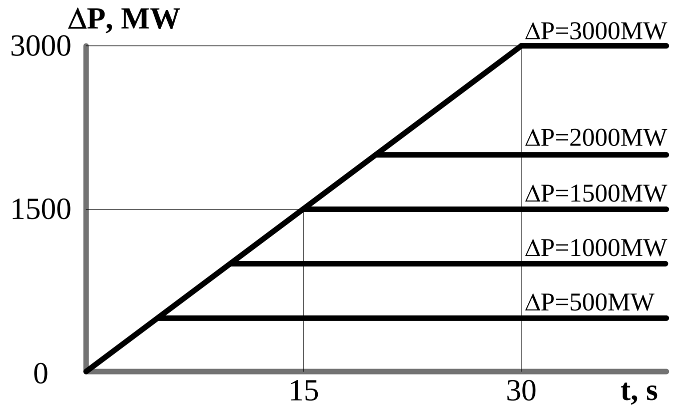


Fig. 2.5. The minimum time for deployment of primary reserves

The secondary reserves are mobilised within the time from several tens of seconds to minutes. The recommended reserve capacities in major power systems depend on their loads; for the mentioned system this dependence is shown in Fig. 2.6.

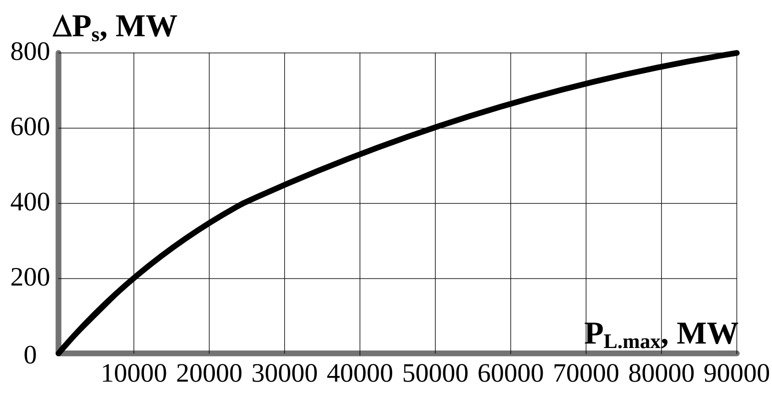


Fig. 2.6. The recommended secondary control reserve as a function of the maximum anticipated load

For primary and secondary reserves not fully loaded capacities are employed, with a power that would be sufficient both for additional load and for load relief during control.

The tertiary reserves are mobilised in the time up to 15 min. To these reserves belong: stand-by hydro- and pumped storage power plants as well as gas turbines, which, being started, can assume load within 15 minutes.

Considering the reaction of generating sources to the frequency variations it should be taken into account that they can be multi-component (see Fig. 2.7). To fast frequency variations corresponding to synchronous oscillations of generators the turbine speed governors do not respond.

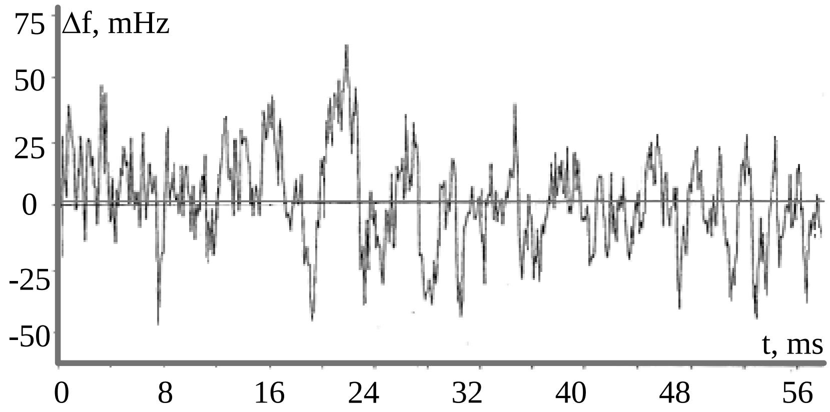


Fig. 2.7. Frequency fluctuations under steady operation

The fast-operating turbines of thermal power plants respond to the load-related frequency variations. The hydro-turbines assume load after the transient negative feedback time has elapsed. To cover slower load changes, the secondary control automatics are used.

PRE-EMERGENCY OPERATING CONDITION

As was mentioned above [32], if the $(n-1)$ criterion is fulfilled then at one element's disconnection no emergency event will begin [17]. The situation is illustrated by Fig. 2.8.

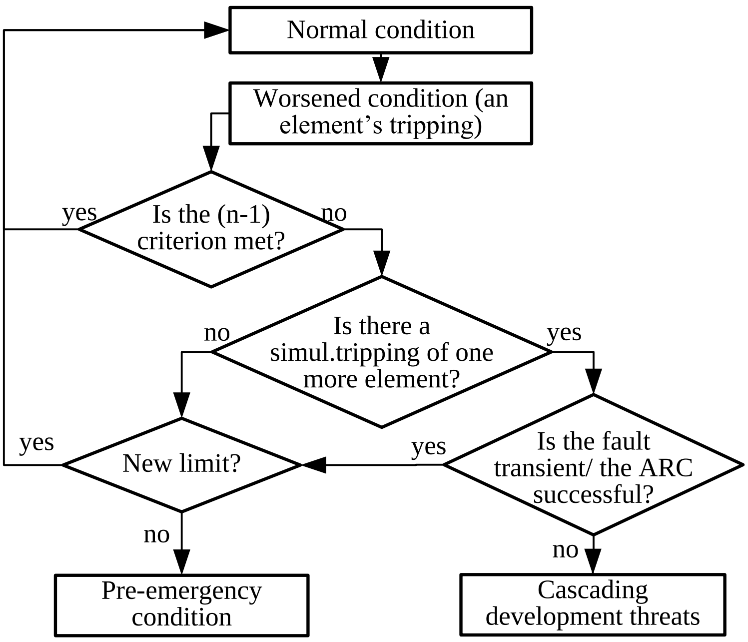


Fig. 2.8. Block scheme of emergency events

In some cases, at a decrease in the network carrying capacity, the $(n-1)$ criterion is not satisfied; then the tripping of one more element poses a real threat of cascade-wise emergency development. Two events can start simultaneously or with a time interval. If this time between disconnections is sufficient, then, by repeating the $(n-1)$ analysis under new conditions and introducing new limitations the emergency can be prevented. In the opposite case there will be high probability of emergency event, with stable or transient fault. As said above, in the case of stable fault on a transmission line the danger of emergency process initiation is real, whereas at transient fault the situation is rescued by automatic re-closing.

At analysing possible disconnections a special attention should be given to revealing and preventing the cases in which additional disconnections could be triggered.

2.1.4. Faults causing additional disconnections

Of particular jeopardy are the faults that cause additional disconnection of one or more elements. Such faults seriously aggravate the power system operation [24]. Below, several characteristic examples are given, which are based on the performed analysis of blackouts.

The fault in a busbar zone gives rise to tripping several connected to it elements. Statistics evidences that such faults are responsible for about 20-25% of the blackouts. Short-circuits in a busbar zone occur in the following cases (Appendix I):

- at faults of disconnectors when operating with them;
- at formation of electric arcs on the disconnectors owing to their poor contacts, especially if the network was overloaded in a pre-emergency situation;
- in the cases of current or voltage transformer faults;
- in the cases of damage in pneumatic pipelines;
- in the cases of circuit-breaker failures at tripping the line short-circuits.

The busbar design should exclude the possibility of a faulty busbar’s arc lapping over non-damaged busbars.

Up to now, power systems still exist where compressed-air operated circuit-breakers are employed. For example, during the blackouts in USA, 1965 [40], Moscow, 2005 [41], Belarus, 2008 [42], and some others, the emergency stock of compressed air could not be replenished due to the absence of power feed to auxiliary services. When a busbar failure occurs, the compressed air-actuated circuit-breakers switch on, which can trigger serious emergency situations. The pneumatic pipes should be protected from mechanical damage and well grounded.

To prevent the development of dangerous emergency processes caused by a circuit-breaker fault in the case of short-circuit on the line, it is necessary to provide a special protection against circuit-breaker failures, which after a short time delay will trip a busbar. If after a circuit-breaker’s disconnection no lines will be in service, then at overloads in the lower voltage networks a voltage avalanche can start (Croatia, 2003 [43]).

At one-side tripping of high-voltage lines a voltage rise occurs, with possible decrease in the excitation of generators up to the falling out of synchronism followed by their disconnection (blackout in New York, 1977 [44], [45]) and/or insulation flashover (Canada, 1982 [16]; Sweden, 1983 [6]).

Simultaneous disconnection of two lines can occur when, for example, the two-circuit towers of these lines are fallen, or under heavy thunderstorm.

The settings of under-frequency load shedding automatics should be insensitive to the voltage variations (blackout in New York, 1977 [44], [45]; Sweden, 1983 [6], [16]).

In the case of a voltage avalanche the autotransformer voltage controller must be blocked, since at its operation the situation is impaired (Sweden, 1983 [6], [16]).

As could be seen, most of the mentioned faults are avoidable, which should be taken into account when designing anti-emergency means.

2.1.5. Anti-emergency means in security norms

To minimise the possibility of system state impairment due to additional disconnections, in the security norms the following anti-emergency means should be built-in:

- of instantaneous action, for tripping short-circuits in the transmission lines;
- special backup automatics against failures of circuit-breakers (SBA);
- double protection for circuit-breakers of important objects;
- providing under frequency fault conditions the automatic frequency recovery up to the rated value;
- the settings of under-frequency load shedding automatics should be insensitive to voltage variations;
- providing under frequency fault conditions the control over generating sources to keep them operating during emergency (§4).

CAUSES AND SEQUENCE OF BLACKOUT DEVELOPMENT

Based on the blackout analysis (Appendix I) the operational conditions of a power system could be classified as follows [1].

- I - normal condition, with fulfillment of the $(n-1)$ criterion and power flow limitation (considered in §0).
- II - pre-emergency condition (§0.), with countermeasures to be taken for restoration of normal condition and prevention of cascading emergency development.
- III - emergency condition, with beginning of cascade-wise processes during which mass-scale tripping of generating sources occurs (§3).
- IV - frequency decline emergency, during which loss of thermal equipment stability is likely to occur (§4).

In the course of blackout analysis it was established that, while in stages I and II (Fig. 2.9) the management is brought to the fore, in stages III and IV the automatics should be used, since the personnel is unable to react to fast changes. The situation is illustrated in Fig. 2.9.

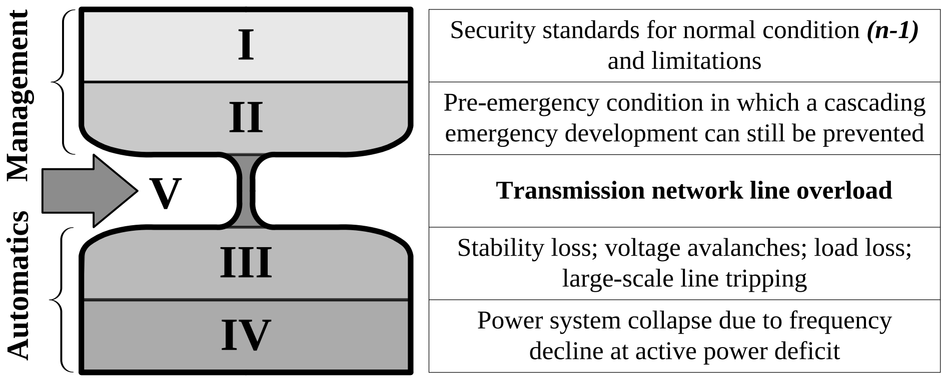


Fig. 2.9. The stages of blackout development

Collapse of a power system can be triggered by the following emergency processes:

- dynamic stability loss at short-circuit occurrence;
- dynamic stability loss at tripping a heavily loaded line;
- static stability loss due to voltage decrease;
- load node voltage drop avalanche;
- out-of-step running;
- accompanying voltage drop avalanche;
- transmission voltage drop avalanche
- large-scale outage of generators due to overload at transmission voltage drop avalanche;

- multiple tripping of lines as a response of protection to the voltage drop;
- multiple tripping of lines due to wire sagging and short-circuits;
- large-scale outages of power plants due to sudden load rejection;
- large-scale outages of power plants due to stability loss of thermal equipment at under-frequency emergency.

As emergency events can be of diversified character, an impression might arise that each of them is unique. This complicates tangibly the creation of an appropriate protection complex against blackouts.

During this analysis it was also found out that the first two stages are connected with others through the V stage with only one process to be considered – that of **dangerous overload of a transmission grid cross-section** (Fig. 2.9) .

The events potentially leading to a blackout are as follows (see Fig. 2.10).

- Primary (cause) - dangerous overload of a transmission grid cross-section.
- Secondary (consequences) as a reaction to the primary events, with cascade-wise development – the main cause of mass-scale tripping of power plants.

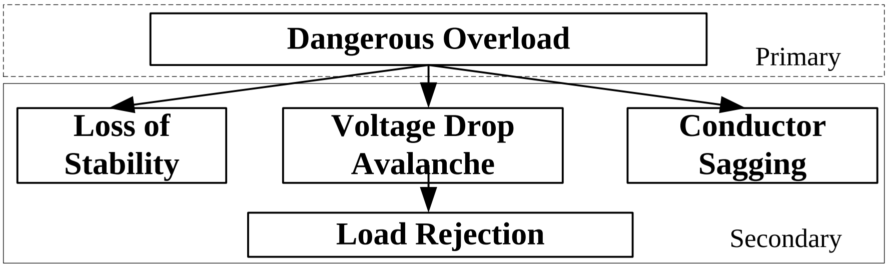


Fig. 2.10. Primary and secondary emergency events

From the above it is clear that by removing the primary cause of emergency and relieving the overloaded cross-section it is possible to avoid the development of secondary emergencies, thus not allowing mass-scale tripping of power plants as the main factor of a blackout.

Usually, the overload of a grid line is created by a regional active power deficit. It is known that for liquidation of such deficit the mandatory protection complexes are provided, which contain feedbacks as well as components for restoration of power system functioning. They can be employed also for new purposes, provided that it will be possible to activate such a protection complex.

CHOICE OF THE CONCEPTION FOR ELIMINATING A TRANSMISSION GRID OVERLOAD

Power systems are large technical formations traditionally controlled by structures based on hierarchical principle. To provide their validity, various protection complexes have been created; most important of them possess negative feedbacks, which ensure the reliability and precision of the control. However, with time it was found that they not always could protect power systems against blackouts; therefore new protection solutions were sought-for. To achieve good results, such a new solution should take into account specific features of a system. For this purpose, the new solutions in the form of a defensive super-structure should include the existing protection complexes as its hierarchical components, with newly created means for their activation.

Transmission grid protection contains components that could be employed to relieve a transmission line by its tripping. However, as concerns a power system's operation, such tripping can give rise to serious complications. Therefore the line should be protected from overload not at all by its tripping but by keeping it operational with maximum allowable power flows, acting for this purpose on other system components.

Power flows of overloaded lines can be changed twofold: acting on the scheme nodes or on its cross-sections. The requirement for the speed of load release is dictated by that for stability maintenance (~ 200ms [29]). This purpose should be served by a preventive fast-acting protection, for which ample information is needed. Besides, such a protection should act simultaneously on a number of objects, which determines its centrally-regional character.

At the choice of defensive conception, it should be taken into account that blackout in major power systems occur rather seldom. Thus, for example, between the greatest collapses in USA (of 1965 and 1977) 12 years elapsed, and only after 26 years (in 2003) a blackout burst out. During this time staff was replaced by new generation(s), with differing skills and approaches; the accumulated experience was lost, and tendencies towards degradation became evident. To cope with it, it is necessary to re-orient the daily used information of normal condition for a two-fold use: to provide the control under normal condition and to prevent emergency situation; that is, such a database, being used permanently, will always be ready to privide information also on emergency condition.

The action on the node power flows refers to the generating sources and loads. For this purpose information is needed about the node flows and their specific weight in the overall flow exchange. Such information is available (since it is required in normal condition), forming a first information database. The notion of its specific weight in the overall power exchange is given by the distribution coefficients [9] forming a second information database (see Fig. 2.11). To relieve the overloaded cross-section, the power at the receiving end should be raised, which cannot be done fast. In turn, the power at the sending end should be reduced. This could be achieved by tripping the generators (as this takes place, for restoration of normal operation several hours are required), or by the turbine fast-valving. As mentioned above §0 the load-relief efficiency is determined by the specific weight of power plants in the line flows, which depends on their topology against the off-loaded lines, and only in rare cases such a plant can affect favourably the power flow.

Similar topology problems arise when loads are shed at the receiving end. Therefore possibilities of action on the power flows of cross-sections should be sought-for [7], [12].

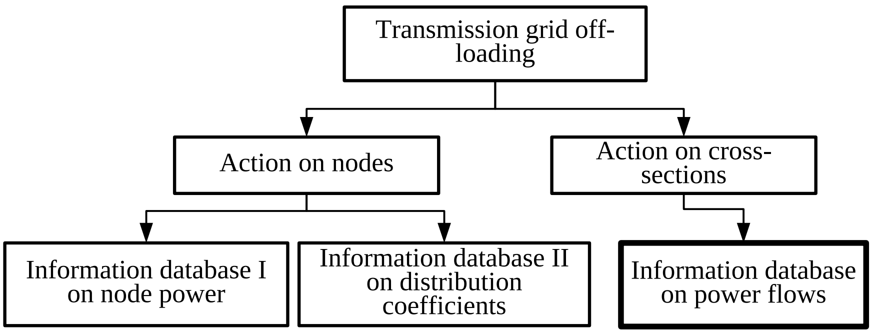


Fig. 2.11. The information databases for cross-section load relief

One of the possibilities to relieve a cross-section is proposed in this work - a short-term splitting (short-term sectioning) of a power system at the place through which the power close to overload is flowing. As a result, the overload is simultaneously eliminated in the overloaded cross-section with the lines kept operating with maximum allowable power flows thus avoiding threat of cascading development. The protection here acts one-fold. When a system is split at the cross-section through which power is flowing, in one its part a power rise will be observed while in the other – a power fall. In major power systems such rises and falls are not large as compared with the total power. In turn, by integrating the mentioned above local means for frequency fault self-liquidation into the new protection complex against blackouts, the self-restoration of this system will proceed without further control, and the normal operation will be recovered automatically within 100 s – that is, unnoticeably for the majority of consumers. Therefore the proposed conception provides fast operation of the control along with its high accuracy & reliability. The solution is simple and easy to introduce – both from the technical and psychological aspects.

As known [14], [29], the power system control over links is widely used for disrupting the out-of-step running. Recently, the principle of protection against blackouts by splitting a power system (i.e. the control of system links) has not only been discussed in the USA and many other countries but also its partial implementation has been initiated [13], [31], [43], [46]-[52]. If such splitting is done at the very beginning of a blackout the generating sources are kept operating so that they can be used to restore the system operation. Currently, the experience is not sufficient to assess in full measure the possibilities of such self-restoration for power systems of the developed states of Europe as well as of USA, Canada, etc..

When choosing the conception of defence actions in power systems, a number of positions are to be assessed (see Table 2.2).

Table 2.2. Choice of protection conception

Position assessment	Choice
For a comparatively rare blackout to use: a) the permanently existing information database for normal condition; b) the information database specially created for rare blackouts	To orient to the information database permanently existing for normal condition;
a) using as much as possible the existing protections and integrating them into a new anti-emergency complex b) creating a new anti-emergency complex parallel to existing protections	To prefer the integration of existing protections into a new anti-emergency complex

As could be seen, preference is given to the anti-emergency complex based on the action upon a cross-section: there is no need to maintain long the special information databases, instead the data on normal condition could be used. In the process of our work it became clear that for fulfilling new tasks it is possible to use tested in practice existing complexes for new purposes, wich would remove doubts as to the efficacy of new solutions and thus alleviate the psychological aspect of implementation. For this purpose the methodology described in this book together with methods specifying the protection elements [53]-[58] could be used.

Therefore the protection complex against blackouts should comply with the new principles provided for preventive (and fast) removal of the root cause of blackouts – the transmission grid overload, and automatic restoration of a power system to normal condition. The hierarchical integration of existing protections suitable for this purpose in the new complex allows avoiding the creation of parallel protection structures. When choosing the protective structure the psychological and technical aspects of implementation should be observed; therefore, to elucidate the causes of secondary emergency initiation and to find out the prospective protection elements, the authors have studied the processes triggering the emergency development and the suitability of existing protections for new purposes.

CONCLUSIONS

In order to reduce the probability of emergency situations under normal and pre-emergency conditions it is necessary to observe security requirements; especial attention should be paid to the situations that can give rise to additional disconnections, which, in turn, can cause blackout development.

One of the causes of emergency situations is the human factor. Taking into account that under the conditions of fast developing cascade emergency process the staff of a power system cannot adequately react to such events, the self-restoration should proceed automatically, without personnel participating.

Based on the results of our blackout analysis, a new conception of the protection complex is proposed, the core of which is fast optimal load relief in a dangerously overloaded transmission grid by short-term power system splitting (sectioning), with further self-restoration to normal condition without staff participation. The centrally-regional character of such a protection complex allows achievement of sufficient speed and accuracy by introducing the elements with feedback.

To make easier the implementation of these complexes the already existing anti-emergency means could be used for new purposes.

3. PECULIARITIES OF CASCADE-WISE FAULTS IN POWER SYSTEMS AND PROTECTION AGAINST THEM

In the previous section, a thorough examination was done on the root causes of blackouts occurring in power systems, and a conception was proposed for protection against them. The conception suggests using to the maximum extent the existing protective means suitable for this purpose; therefore, in this section the issues under investigation are the cascading (secondary) emergency processes triggered by overload as well as the efficiency of currently applied anti-emergency means and their compliance with the newly proposed principles. Towards this end, special mathematical models and algorithms have been created. Since the main pre-condition for fast self-restoration of a power system to the normal operational state is keeping the generating sources running, especial attention is given to the response of electricity generating plants to deviations in the operating variables of a power system as well as to the actions of technological protection during emergency events.

POWER SYSTEM BLACKOUTS AND PROTECTIVE AUTOMATICS

The analysis of wideworld blackouts reveals that in the cases when the countermeasures taken under the pre-emergency state of a power system are inefficient the emergency processes develop, which can be of local or cascade-wise character. The local emergencies are eliminated by protective means that trip the faulty element, with its functions taken over by other system elements. A cascading emergency is followed by other events that aggravate still more its development; as a result, full collapse of the power system could be expected, with cascading outages of electricity generating plants and the necessity to restore their operation. However, the thermal plants need energy for auxiliary services from other sources, which can make up 6-8% of a generating unit's power; the process is therefore involved and time-consuming.

The currently applied protective automatics mainly consist of the following components [6], [22], [29], [31]:

- relay protection that trips a faulty element;
- automatic reclosing to make this element operational;
- automatic connection of reserve;
- automatic emergency control of the active power by the means fulfilling the functions of: stability loss avoidance, out-of-step running liquidation, under- or over- frequency limitation, equipment load relief;
- devices for automatic emergency control of voltage.

The kinds of protective automatics and widely adopted control actions are shown in Fig. 3.1.

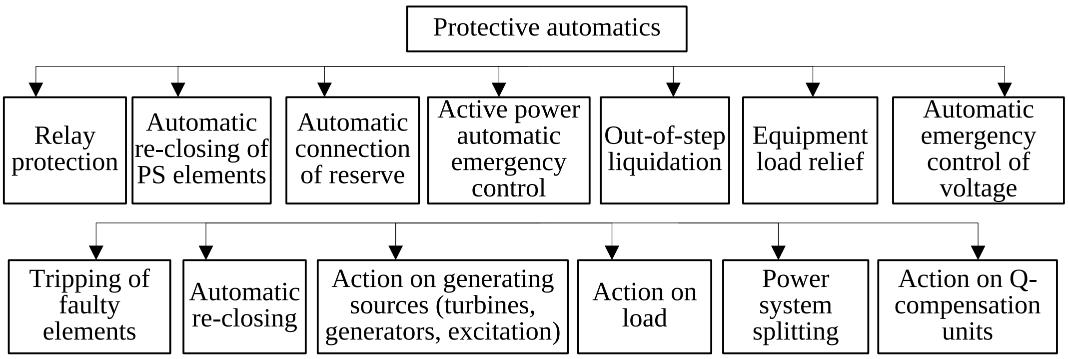


Fig. 3.1.The kinds and control actions of protective automatics

To estimate the possibilities of applying the above mentioned protective means in the framework of the new conception, the emergency processes and their impact on the functioning of system elements have been studied, as well as the effectiveness of existing automatics in liquidation of dangerous disturbances.

STABILITY LOSS DISTURBANCES

Loss of stability is one of the most dangerous disturbances in a power system, which can create pre-conditions for its collapse. The problem is to be considered based on the principles of blackout prevention and protection that are integrated in the proposed protection complex against blackouts.

At classification of stability loss events the following types should be set off [59]-[61]:

Static stability loss, when a grid cross-section is overloaded under stationary condition owing to unpredicted rise in the power flow. Usually, in such a situation the operational condition is estimated as pre-emergency, and for the overload liquidation the reserve mobilisation and load shedding at the power receiving end of cross-section are used; otherwise the voltage drop at this place can happen, followed by stability loss and cascading outages of generating sources. The problems associated with voltage drop and the corresponding reaction of generating sources deserve especial attention and are considered in §0.

Dynamic stability loss at short-circuit occurrence (illustrated by Fig. 3.2a, [59], [61]). Stability is lost in the case when, owing to the difference between the turbine and generator powers, the rotor's acceleration is not compensated at tripping the fault (the acceleration energy *abcd* is greater than the braking energy *dg*).

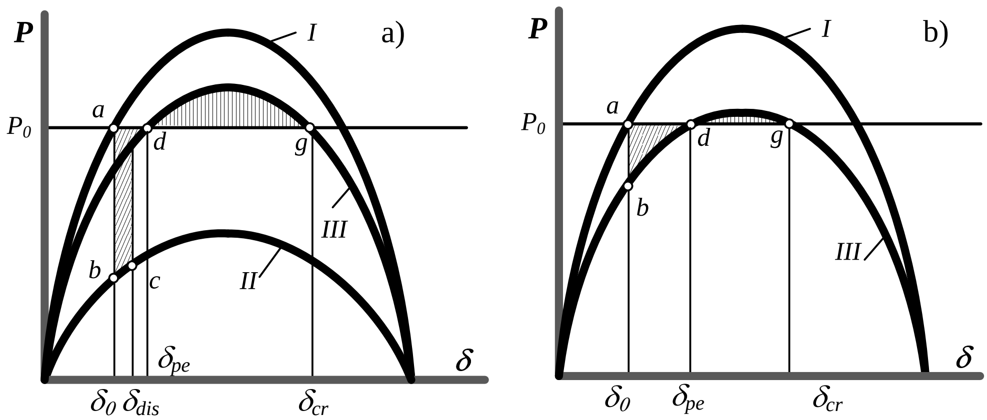


Fig. 3.2. Stability loss process at a) short-circuit, b) overloaded line tripping

I, II and III – respectively, curves of normal, short-circuited and post-emergency operational condition; abcd – the kinetic energy of rotor acceleration; dg – the same for braking; δ_0 *– angle at normal condition;* δ_{dis} *– angle at line tripping;* δ_{pe} *– angle of post-emergency condition;* δ_{cr} *– critical angle*

As is known [22], [30], to eliminate the possibility of such stability loss in the transmission lines the fast protection is provided, including also elements for liquidation of circuit-breaker and protection failures. Usually, these faults are eliminated within the time up to 200 ms [29].

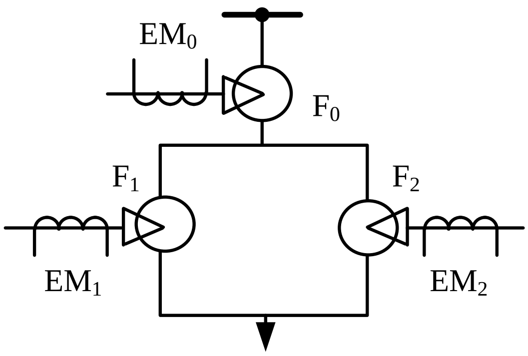
Dynamic stability loss at tripping a heavily loaded line. Also in this case, stability is lost owing to the network overload (Fig. 3.2b). Since this happens within seconds, for the overload liquidation fast actions are needed to maintain stability − for example, action on a generating source's equipment at the power sending end of the overloaded cross-section.

In the cases when the topology of generating plants in the network is favourable with respect to a dangerous cross-section, stability can be saved by its fast off-loading using generator tripping (in this case recovery could be essentially delayed) or turbine fast-valving [59], [60], [61]. In turn, if this topology is unfavourable for the dangerous cross-section, the load relief can exceed the needed amount and stability loss might become unavoidable. With due regard for the topology effect, in the general case the indirect influence of load nodes on the power flow links is not universal, so direct methods for power limitation are preferable.

Turbine fast-valving

In this aim in view, the speed governors of high-power turbines are supplied with a special gate mechanism that under normal condition remains in steady state owing to the equality of oil pressure on both sides [24], [29]. Under emergency condition, at special valves opening on one side and oil pressure decreasing, the gate changes its position and within few seconds the nozzle regulating the speed governor closes, thus causing fast and dosed turbine off-loading. For this purpose in the oil duct three valves for oil pressure release are provided. As shown in Fig. 3.3, F_0 is the blocking valve that in the open position allows for fast relief of the turbine; F_1 is the valve that is opened proportionally to electromagnet EM_1 current according to a given dose of turbine relief; F_2 is the valve that opens completely thus allowing full turbine unloading.

In turn, Fig. 3.4 illustrates the depth of load relief depending on the control pulse length. The movement of servo-drive for valve closing starts with a time delay τ_d from the pulse sending instant T_p. The turbine power considerably lags behind the servo-drive position owing to steam presence. Therefore, to every pulse duration the greatest turbine power decrease $\Delta P_{T\max}$ corresponds. Usually, this is 30-70% of the nominal power. The duration of such a control pulse is 0.1-0.4 s [29].



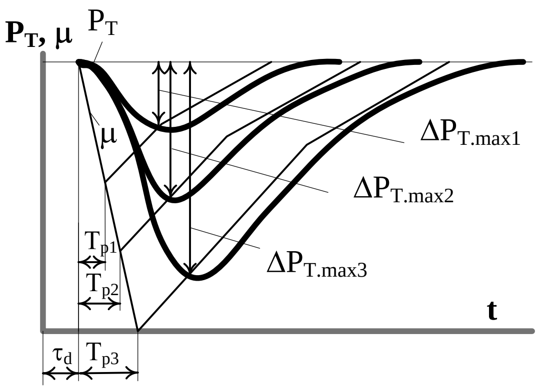


Fig. 3.3. The oil pressure regulation valves in the turbine's rotation governors
Fig. 3.4. The depth of turbine's load relief depending on the control pulse duration

$\Delta P_{T\max}$ *is a turbine power decrease;* T_p *is a pulse sending instant*

Short-term turbine fast-valving is mostly used at TPPs [29]. As concerns hydro turbines, their off-loading is hindered by insufficient operational speed of the control systems. Besides, these units can be switched off if necessary.

3.1.1. Automatics for stability maintenance

To maintain stability in a power system, special protections − local at generating plants and centralised on the system level − are employed.

The local protection is used on a generating unit's scale at the power sending end of the cross-section. For example, the OPC (Over-Speed Protection Circuit) reported in [62] acts on the electro-hydraulic load relief equipment of a turbine, decreasing fast its power if the generator's power exceeds that of turbine's to a dangerous extent. In the case when such a protection is applied, the stability maintenance in other cross-sections beyond the generating unit's busbars must be controlled.

To maintain the system stability on the regional level a centralised preventive protection is applied, which uses fast-acting communication channels for receiving the information on a dangerous situation [12], [22], [29]. The protection has a matrix-wise structure shown in Fig. 3.5.

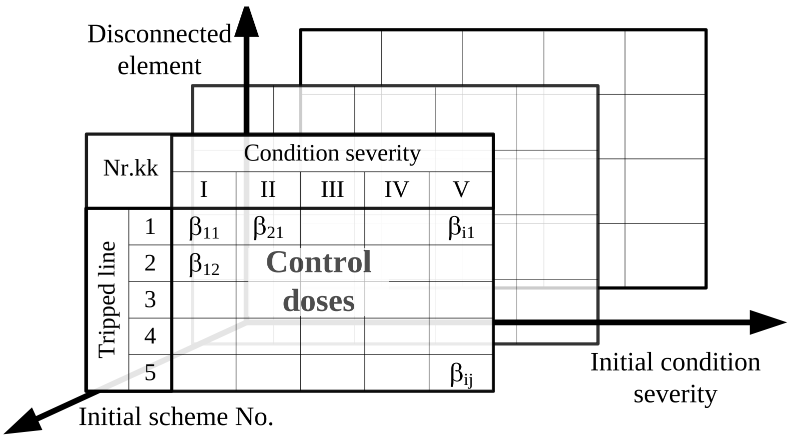


Fig. 3.5. Control dose matrices

Such a matrix contains in its cells the doses in dependence on the initial condition severity (for power flows through the controlled dangerous cross-sections of a network) and the information on the dangerous events. Usually [22], [28], [30], for the control doses the signals on the generator tripping or turbine fast-valving at the power sending end and/or load relief at the power receiving end are used. To every scheme of system operation a definite matrix corresponds.

The matrix-wise structure of control doses can be employed for the purposes stated in the proposed conception. Although also in this case it will be used for another task − namely, for fixing the overload in a transmission network and its removal − the accumulated operating experience would facilitate the implementation.

To summarise, it could be concluded that:

- **dynamic stability loss as the reaction to short-circuit in a transmission grid is avoided using its fast-acting protection (against circuit-breaker and protection failures included);**
- **under emergency, stability maintenance by acting on a power plant as a network node element is effective in the cases when its topological position is favourable with respect to the dangerous cross-section, which limits the protection effectiveness;**
- **as known, to maintain stability the preventive protection means should be used;**
- **our analysis evidences that the protection structures, whose effectiveness has been proved by practice, being applied for the new purposes could form a protective infra-structure in a power system, which would to a great degree would facilitate its implementation and alleviate psychological problems.**

OUT-OF-STEP OPERATION

As is known, stability loss or unsuccessful protective actions can give start to out-of-step operation, which would create the threat of blackout [22], [61]. Despite the well-studied peculiarities of such an operation (when analysing worldwide blackouts), there are situations when new generating sources, due to their specifics, are tripped. In view of importance of the problem, below the potentially dangerous processes are discussed.

The voltage variation processes could be simplifiedly described using the scheme of Fig. 3.6a, where the voltage vectors are shown geometrically by a straight line connecting the ends of U_s and U_g vectors while their beginnings are located at the ends of a straight line whose length is characterised by the summary reactance. Here U_s and U_g are the voltages of generating sources; it is assumed that the voltage vector U_g is rotating with respect to the stationary vector U_s. If $\delta = 180°$, at the intersection with the *x*-axis the oscillation centre is located (Fig. 3.6b) [24], [63]; the minimum voltages at different transmission points are shown by bold vectors (Fig. 3.6c), and the voltages at different values of angle δ − by circles.

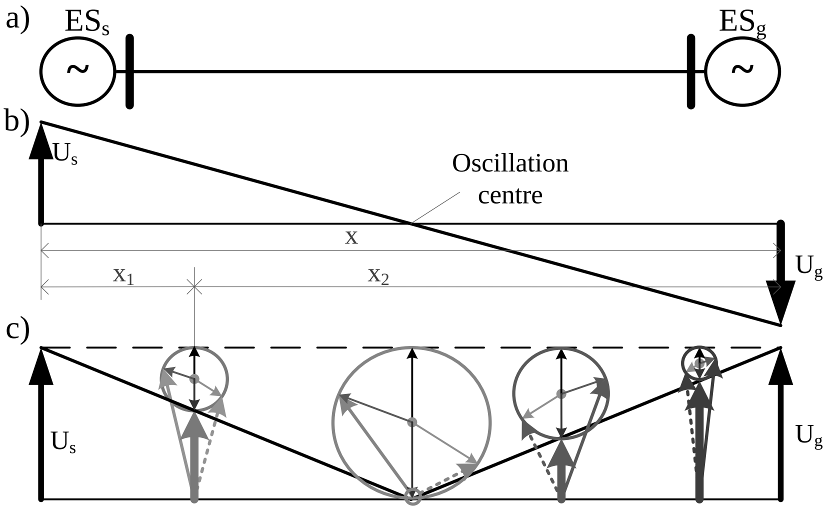


Fig. 3.6. Voltage variations at out-of-step operation

a) a two-machine scheme; b) the geometric point of oscillation centre; c) minimum voltages along a transmission line

The voltage parameter is usually estimated by its module, using (7.34); the voltage at different transmission points in dependence on the angle between voltage vectors is calculated as

$$U(\delta, x) = \sqrt{\left(\frac{U_g x_1}{x_1 + x_2}\right)^2 + \left(\frac{U_s x_2}{x_1 + x_2}\right)^2 + 2\frac{U_g x_1 U_s x_2}{(x_1 + x_2)^2}\cos(\delta)} \quad (3.1)$$

where x_1 and x_2 are the reactances from a transmission point to the generating sources; *x* is the total reactance, $x = x_1 + x_2$; δ is the angle between the voltage vectors.

The voltage drop considerably impairs the carrying capacity of a network cross-section, which can become insufficient for the transmitted power, causing additional stability loss in other network places (multi-frequency out-of-step operation).

Particular attention should be given to the reaction of generating sources to the oscillation process.

3.1.2. Reaction of generating plants to out-of-step operation

It is known [24], [45] that during oscillations in the intensively working speed governors of hydro-turbines the oil pressure falls, and the technological protection trips the equipment. On analysing the previous PS blackouts it has been revealed that similar processes go at nuclear power plants (NPP) [64]. Since in the NPP turbines saturated steam is employed, they have half as large rotational speed, with their sizes being greater. As a result, when the turbines are oscillating under asynchronous condition the oil pressure in their speed governors decreases, and the technological protection switches them off. Thus, for example [65], in 6 nuclear plants from 10 that suffered blackout in USA and Canada in 2003 the turbine speed governors were tripped by technological protections, which was caused by a decrease in the oil pressure. Since under out-of-step operation the generator elements and excitation systems can be heavily damaged, the protection switches them off [45]. Therefore it is especially important to stop quickly the out-of-step running in order to prevent development of cascading tripping.

3.1.3. Protection against out-of-step operation

To stop out-of-step running, a power system's splitting in the endangered cross-section is usually used [13], [66]. To avoid heavy complications, the splitting should be done before the phase angle has reached 180^{o} [67], [68]. Based on the method mentioned in [67], special splitting automatics can model the angle between two (modelled) voltage vectors in the network; if it exceeds the set value, and, at the same time, the frequency on the busbar side relative to its installation place is lower than the frequency at the opposite line end, this automatics trips the line. When both the conditions are present, the transmission line is disconnected at angle between equivalent *EMFs* being in the range $100 \div 130°$ [67], [68]. These requirements are especially topical under new conditions of nowadays.

In the cases when the requirements to secure and fast actions of protection are met and the grid overload is rapidly removed, there would be no threat of collapse at a stability loss followed by development of out-of-step running.

VOLTAGE AVALANCHE

A voltage avalanche is the operational condition at a significant voltage drop [9], [15], [24] which triggers cascading outages of system elements. The following types of avalanches originated in a voltage drop could be distinguished [69]:

- load node voltage drop avalanche;
- accompanying voltage drop avalanche;
- transmission voltage drop avalanche.

In turn, if a reactive power surplus is created that is impossible to consume the voltage rises, which can cause a voltage rise avalanche, and, as a consequence, tripping of generating sources.

3.1.4. Load node voltage drop avalanche

Avalanche of the kind occurs in local load nodes and is associated with the response of reactive power sources to voltage variation [9]. To the voltage decrease the squared decrease in the reactive power of capacitors corresponds. The reaction of synchronous machines is of the opposite character (see Fig. 3.7).

At improper proportion between reactive power sources of the type, in the node a positive feedback is created with respect to the voltage variation, which causes a voltage avalanche. The normal condition in the node is set when the response of reactive power sources to voltage variation is correct, i.e.:

$$d\left(Q_g - Q_{sl}\right)/dU < 0 \tag{3.2}$$

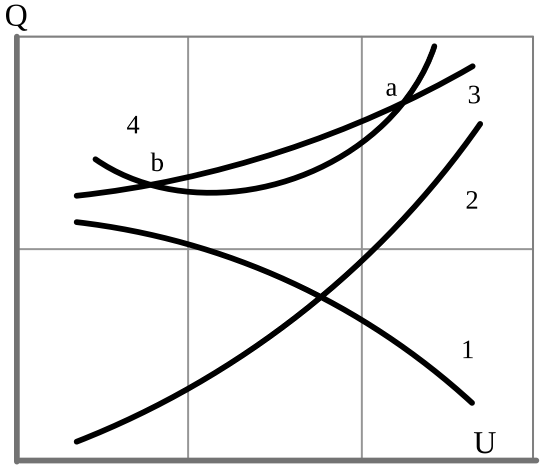


Fig. 3.7. Load node voltage drop avalanche

1−characteristic curve (c/c) of synchronous machines; 2− c/c of capacitors; 3 − full c/c of reactive power sources; 4 − c/c of load changes; a) − stable operation; b) − unstable operation

As the anti-emergency means against a load node voltage avalanche the automatic under-voltage load shedding (AUVLS) is employed.

Load shedding at voltage decrease

For this purpose the load shedding automats are provided with the function of reacting to a voltage decrease [9], [70] - [72]. As seen in Fig. 3.8 [9], selectivity at different load shedding stages is achieved using different voltage U_s settings and time delays t, since, as distinguished from the frequency change processes (with exponential character owing to the inertial rotating mass), the voltage tends to change instantaneously: e.g. up to U_1 after time delay t_1 the first load shedding element operates, and the voltage increases to U_2; then, after the second element has operated – to U_3. Since it is greater than the following settings, the $U_{s3} \div U_{s.n}$ stages will not operate.

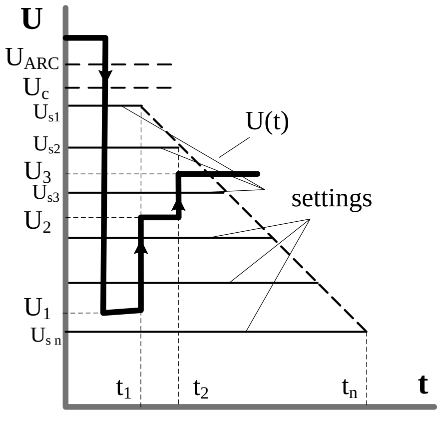


Fig. 3.8. Voltage change character at AUVLS operation

$U_{s.i}$ - voltage settings; t_i - time delays; U_i - voltage changes at load shedding stage operation; U_{ARC} - voltage at which ARC operation begins; U_c – the control voltage

The load shedding stages are supplied with automatic re-closing (ARC). On liquidation of the cause of voltage drop and when the voltage reaches U_{ARC} setting, step-by-step automatic re-closing of consumers takes place with under-voltage control by U_c value. The automatic under-voltage load shedding should be blocked at AUFLS operation.

When the AUVLS is used in the stability maintenance complex, the time delays do not allow sufficient speed of operation; in turn, if selectivity is not observed, the system will operate without feedback.

The automatic under-voltage load shedding is an efficient means of stability maintenance at a load node.

3.1.5. Accompanying voltage drop avalanche

Such an avalanche begins simultaneously with frequency decline in the system part lacking active power [9]. In the process of accompanying voltage drop avalanche the excitation of synchronous machines increases, owing to which the reactive power deficit decreases. If this deficit is too large, the voltage can drop considerably, which causes additional frequency decrease. The relationship between the voltage and frequency deviations is characterised by the coefficient [9]:

$$k_{U,f} = \Delta U / \Delta f \tag{3.3}$$

As known, the active power is voltage-dependent, and at its small variations is characterised by the coefficient [9]:

$$k_{P,U} = \Delta P / \Delta U \tag{3.4}$$

When the variations are large this relationship is non-linear.

The voltage drop proceeds in two stages (Fig. 3.9, [9]). The initial voltage decreases stepwise to the value U_1 determined by the appearance of reactive power deficit. Further, depending on the frequency drop process (characterised by frequency time constant T_f) the voltage additionally decreases according to (3.3).

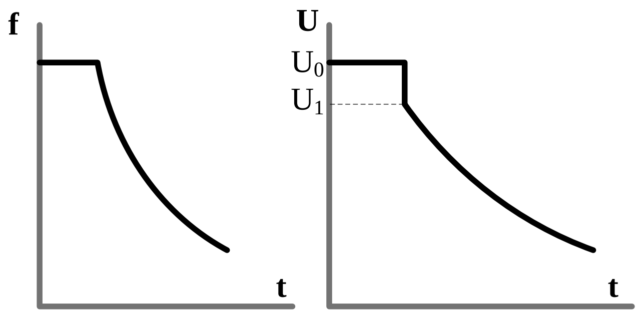


Fig. 3.9. Frequency and voltage decrease during accompanying voltage avalanche

It is known that under the conditions of accompanying voltage drop avalanche severe incidents occur owing to failure of the under-frequency load shedding automatics (AUFLS) if frequency relays are voltage-dependent (as it was, e.g. [6], in France (1978) and in Sweden (1982)). To avoid situations of the kind it is necessary to ensure that AUFLS settings are independent of voltage.

Since the voltage drop in the case of accompanying voltage avalanche is mostly associated with frequency decline, the former is eliminated simultaneously with frequency stabilisation using the AUFLS.

3.1.6. Voltage rise avalanche

A voltage rise avalanche can develop as independent emergency process and as accompanying a frequency avalanche. The process of the kind is triggered by surplus of generated reactive power suddenly arising due to non-compensated capacitive power in the ultra-high (over 330 kV) voltage grids not loaded with active power [30].

The generated capacitive power in transmission lines can increase in two cases:

- one-side trip of an ultra-high voltage line (with large capacitive power);
- automatic tripping of a large number of consumers, e.g. owing to AUFLS operation in a remote region where active power flows over grids with high capacitive power are considerably reduced.

The static curve of reactive power consists of the capacitive power of ultra-high voltage grid and the power of synchronous machines. The generated capacitive power in lines is proportional to the voltage squared, and a voltage rise is accompanied by the power rise (Mvar):

$$Q_c \approx U^2 \omega C \quad (3.5)$$

where U is the line voltage, kV; ω is the angular frequency, rad; C is the line capacity, F.

As seen in Fig. 3.10, in the initial condition the grid voltage is characterised by point A, with 1 being the load characteristic curve and I − the system characteristic curve. When a system is split, an active power deficit arises; at once AUFLS operation follows, the load characteristic shifts right (2-5), and the system characteristic, owing to the power surplus, pass to II. The interruption point B of the system curve characterises the tripping of generators due to the loss of excitation. Equilibrium between the generated and consumed reactive powers is established at point C under elevated voltage, which is described by the inequality $dQ_c/dU > 0$.

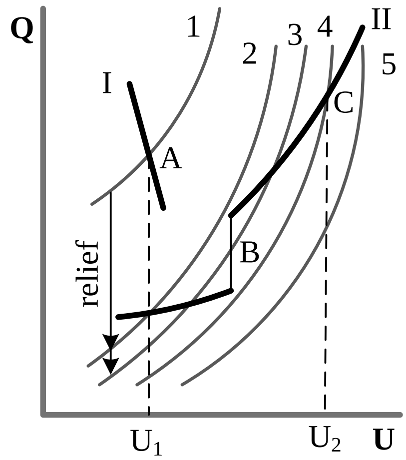


Fig. 3.10. Voltage rise avalanche

1-5 − load characteristics (at PS splitting and AUFLS operation); I-II −the system characteristics; A− the initial operational condition; B − interruption point of characteristic curve II due to generator tripping; C − new operational condition under higher voltage

Voltage rise avalanches can have consequences of dual kind. First, considerable voltage rise poses a threat for the insulation of electrical grid (due to possible short-circuits) and can cause massive damage for consumers' equipments. Second, under elevated voltage the electric machines lose excitation up to full its loss [45]. As a result, the generators can fall out of synchronism and become devoid of protection [45]. In this situation, the active power deficit and the frequency avalanche could repeat − but this will occur already after utilisation of AUFLS resource; as a consequence, a blackout will start.

To avoid such a situation, the transversal compensation reactors must be disconnected, or a high-voltage line must be temporarily tripped, which after normalisation of operating condition will be re-closed [28], [30]. The line tripping proceeds selectively, using the automatics with different settings for voltage $U_{s1} \div U_{s.k}$ and time $t_1 \div t_k$ (Fig. 3.11 [9]).

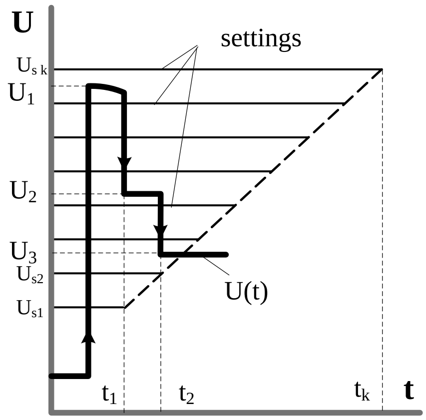


Fig. 3.11. Automatic settings for voltage rise elimination

U_s – voltage settings; ti– time delays; U_i – voltage changes at the protection stage operation

The behaviour of voltage changes is shown in a simplified manner by curve $U(t)$. When voltage rises, at time t_1 the first stage operates for line disconnection, then the second; when voltage decreases to U_3 the next stages do not operate due to $U_3 < U_{s3}$.

For restoration of the operational state of a power system, the line automatic re-closing by normal voltage and frequency is used.

Reducing the capacitive reactive power by switching-on a transversal compensation reactors or disconnecting a high-voltage line for a short term allows prevention of a voltage rise avalanche.

3.1.7. Tranmission voltage avalanche

Avalanche of the kind is especially dangerous when occurring in a region covering large areas with many generating units and creating emergency situation in a system part as a result of generator tripping [15], [60]. Its cause is the unallowable overload with active power of a line in the grid. Overload prevented, such an avalanche would not arise [73].

The voltage at the line power sending end U_1, with a given voltage U_2 and power flows P_2'', Q_2'' at the line receiving end, are described by the expression [74], [75]:

$$\dot{U}_1 = \dot{U}_2 + \frac{P_2''r + Q_2''x}{U_2} + j\frac{P_2''x - Q_2''r}{U_2} = \dot{U}_2 + \Delta U'' + j\delta U'' \tag{3.6}$$

At a given voltage U_1 and power flows P_1'', Q_1'' at the line sending end, U_2 will be [74], [75]:

$$\dot{U}_2 = \dot{U}_1 - \frac{P_1'r + Q_1'x}{U_1} - j\frac{P_1'x - Q_1'r}{U_1} = \dot{U}_1 - \Delta U' - j\delta U' \tag{3.7}$$

where r, x are the line resistance and reactance; $\Delta U', \Delta U''$ are the longitudinal components of voltage drop; $\delta U', \delta U''$ are its transversal components (Fig. 3.12). In the calculations, the active power value is increased by the corona loss ΔP_c, while the reactive one is decreased by the line capacitive power value of $-0.5U^2B$.

Under emergency conditions, at tripping of parallel lines the grid cross-sections become overloaded with active power flows. As a result, with increasing trans-components δU of voltage drop and simultaneously rising reactive power losses:

$$\Delta Q = \sum_{i=1}^{n} 3I_i^2 x_i = \sum_{i=1}^{n} \frac{P_i^2 x_i}{U_i^2} + \sum_{i=1}^{n} \frac{Q_i^2 x_i}{U_i^2} \tag{3.8}$$

in a system additional reactive power flows arise along with increasing longitudinal components ΔU of the voltage drop (Fig. 3.12). This leads to an increase in the total voltage drop U_Δ in the line resulting in a voltage decrease at the line receiving end, i.e. in this case:

$$U_2 = \sqrt{\left(U_1 - \Delta U'\right)^2 + \delta U'^2} \tag{3.9}$$

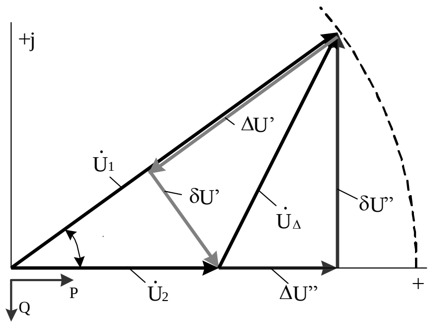


Fig. 3.12. Diagram of voltage drop vectors

$\Delta U, \delta U$ - the transversal and longitudinal voltage drop components; U_Δ - the overall voltage drop

To find the relationships between the given active powers, voltages at the line sending end, and reactive power at the line receiving end, as well as to show schematically the process of a transmission voltage drop avalanche, a circle diagram can be used, which is constructed applying four-pole equations of transmission line with respect to I_1 and I_2 [6], [9]:

$$\begin{cases} \dot{I}_1 = \dot{D}/\dot{B}\,\dot{U}_1 - 1/\dot{B}\,\dot{U}_2; \\ \dot{I}_2 = 1/\dot{B}\,\dot{U}_1 - \dot{A}/\dot{B}\,\dot{U}_2 \end{cases} \tag{3.10}$$

where $\dot{I}, \dot{U}$ are the vectorial meanings of current and voltage; indices 1 and 2 relate to the parameter values at the line sending and receiving ends; $\dot{A}, \dot{B}, \dot{D}$ are the generalised constants of four-pole complex numbers characterising the total admittance Y and impedance Z ratios [76], [77].

On transforming them, we obtain the total power values at the line extreme points:

$$\begin{cases} \dot{S}_1 = \dot{U}_1 \hat{I}_1 = \hat{D}/\hat{B}\,U_1^2 - 1/\hat{B}\,\dot{U}_1\dot{U}_2 = \hat{D}/\hat{B}\,U_1^2 - 1/\hat{B}\,U_1 U_2 e^{j\delta}; \\ \dot{S}_2 = \dot{U}_2 \hat{I}_2 = 1/\hat{B}\,\dot{U}_1\dot{U}_2 - \hat{A}/\hat{B}\,U_2^2 = -\hat{A}/\hat{B}\,U_2^2 + 1/\hat{B}\,U_1 U_2 e^{-j\delta} \end{cases} \tag{3.11}$$

where angle δ varies according to the expression:

$$\delta = \arg\dot{U}_1 - \arg\dot{U}_2 \tag{3.12}$$

The geometrical places of vector ends will be the circular lines:

$$\begin{aligned} \dot{S}_1 &= \dot{C}_1 - \dot{\rho} e^{j\delta} \\ \dot{S}_2 &= \dot{C}_2 + \dot{\rho} e^{-j\delta} \end{aligned} \tag{3.13}$$

with the centres:

$$\begin{aligned} \dot{C}_1 &= \hat{D}/\hat{B}\,U_1^2 \\ \dot{C}_2 &= -\hat{A}/\hat{B}\,U_2^2 \end{aligned} \tag{3.14}$$

and the initial radius vector:

$$\dot{\rho} = 1/\hat{B}\,U_1 U_2 \tag{3.15}$$

From analysis of the circular diagram shown in Fig. 3.13 [78] it follows that, given the active power P_1 at the line sending end, the respective reactive power Q_2 could be found.

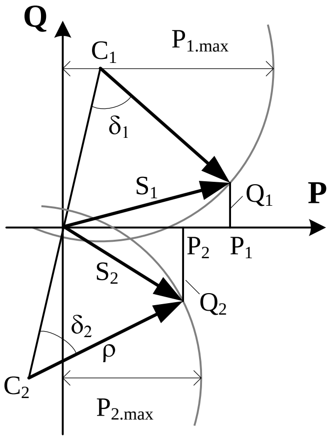


Fig. 3.13. Circular diagram *Q=f(P)*

Taking into account that the constants can be written through the impedance $Z = r + jx$ and the admittance $Y = g + jb$, we obtain:

$$\dot{A} = 1 + \frac{\dot{Z}\dot{Y}}{2} = 1 + \frac{(r + jx)(g + jb)}{2} = \frac{(2 + rg - xb) + j(rb + xg)}{2}$$
$$\dot{B} = \dot{Z} = r + jx \qquad (3.16)$$

where r, x are the resistance and reactance; g, b are the active and capacitive admittance; Then, substituting constants (3.16)into (3.14) and (3.15) we will have:

$$\dot{C}_2 = -\frac{(2 + rg - xb) - j(rb + xg)}{2(r - jx)} U_2^2 = \left(-\frac{r}{r^2 + x^2} - \frac{g}{2} - j\left(\frac{x}{r^2 + x^2} - \frac{b}{2} \right) \right) U_2^2 \qquad (3.17)$$

$$\dot{\rho} = \frac{1}{r - jx} U_1 U_2 = \left(\frac{r}{r^2 + x^2} - j\left(\frac{x}{r^2 + x^2} \right) \right) U_1 U_2 \qquad (3.18)$$

Replacing in equation (3.18) the number in brackets by a complex number in the exponential form, we will add it to the second summand:

$$\dot{\rho} e^{-j\cdot\delta} = U_1 U_2 \frac{1}{\sqrt{r^2 + x^2}} e^{j\cdot arctg(x/r)} e^{-j\cdot\delta} = U_1 U_2 \frac{1}{\sqrt{r^2 + x^2}} e^{j\cdot(arctg(x/r) - \delta)} \qquad (3.19)$$

Transforming the complex number of (3.19) into the trigonometric form gives:

$$\dot{\rho} e^{-j\cdot\delta} = U_1 U_2 \frac{1}{\sqrt{r^2 + x^2}} \left[\cos\left(arctg\left(\frac{x}{r} \right) - \delta \right) + j \sin\left(arctg\left(\frac{x}{r} \right) - \delta \right) \right] \qquad (3.20)$$

Then, combining (3.17) and (3.20) for the ratio of total power at the line extremes we obtain:

$$\dot{S}_2 = \left(-\frac{r}{r^2 + x^2} - \frac{g}{2} - j\left(\frac{x}{r^2 + x^2} - \frac{b}{2} \right) \right) U_2^2 +$$
$$+ U_1 U_2 \frac{1}{\sqrt{r^2 + x^2}} \left[\cos\left(arctg\left(\frac{x}{r} \right) - \delta \right) + j \sin\left(arctg\left(\frac{x}{r} \right) - \delta \right) \right] \qquad (3.21)$$

Transforming the last expression, we will have:

$$\dot{S}_2 = -U_2^2 \left(\frac{r}{r^2 + x^2} + \frac{g}{2} \right) + U_1 U_2 \frac{1}{\sqrt{r^2 + x^2}} \cos\left(arctg\left(\frac{x}{r} \right) - \delta \right) +$$
$$+ jU_1 U_2 \frac{1}{\sqrt{r^2 + x^2}} \sin\left(arctg\left(\frac{x}{r} \right) - \delta \right) - jU_2^2 \left(\frac{x}{r^2 + x^2} - \frac{b}{2} \right) \qquad (3.22)$$

and, by virtue of $\dot{S}_2 = P_2 + jQ_2$, the following will be valid:

$$P_2 = -U_2^2\left(\frac{r}{r^2+x^2}+\frac{g}{2}\right)+U_1U_2\frac{1}{\sqrt{r^2+x^2}}\cos\left(arctg\left(\frac{x}{r}\right)-\delta\right) \quad (3.23)$$

$$Q_2 = -U_2^2\left(\frac{x}{r^2+x^2}-\frac{b}{2}\right)+U_1U_2\frac{1}{\sqrt{r^2+x^2}}\sin\left(arctg\left(\frac{x}{r}\right)-\delta\right) \quad (3.24)$$

Having expressed the angle $\left(arctg(x/r)-\delta\right)$ from the formula for P_2 and substituting it into that for Q_2, we obtain the function of reactive power:

$$Q_2(U_2,P_2) = -U_2^2\left(\frac{x}{r^2+x^2}-\frac{b}{2}\right)+\frac{U_1U_2}{\sqrt{r^2+x^2}}\sin\left(\arccos\left[\frac{\sqrt{r^2+x^2}}{U_1U_2}\left(P_2+U_2^2\left(\frac{r}{r^2+x^2}+\frac{g}{2}\right)\right)\right]\right) \quad (3.25)$$

Using equation (3.25), the dependence of reactive power on the voltage can be constructed for different active power values (in Fig. 3.14 shown with bold lines), with the stability loss boundary under reactive power condition described by the derivative dQ_2/dU_2 (a dashed line), which would give a simplified notion of a transmission voltage avalanche at line overloading with active power [15].

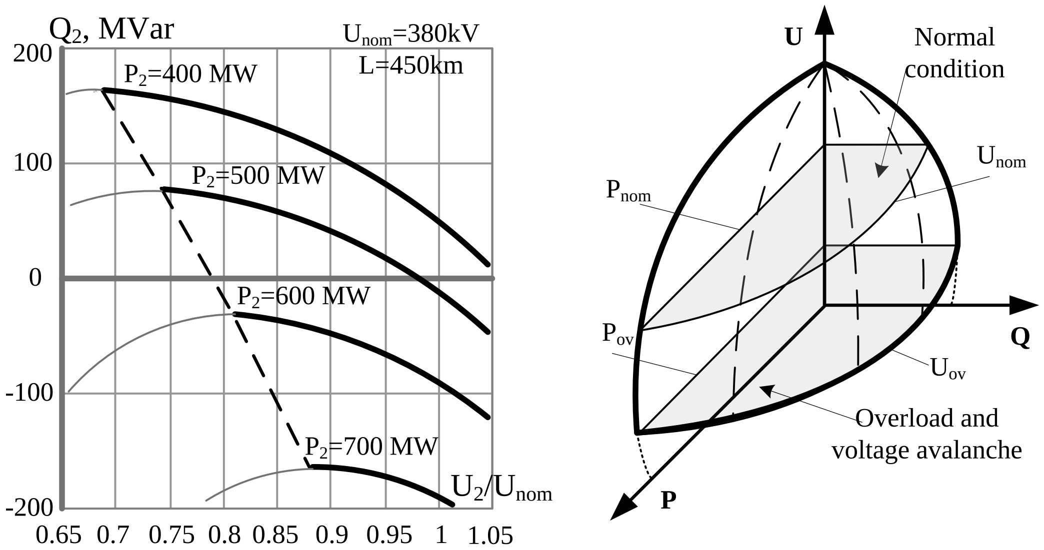


Fig. 3.14. Schematic presentation of a voltage avalanche

As a result of overload, the voltage at the power receiving end can decrease by 15-20%. The different operational conditions in a grid are illustrated by Fig. 3.14b, where P_{nom} and U_{nom} are the nominal values, while P_{ov} corresponds to overload and to U_{ov} decreasing to the emergency level.

The transmission voltage drop avalanche in a network creates an impression of reactive power deficit. In reality, no deficit of the kind initially exists. The transmission voltage drop avalanche will develop at network overloading with active power; as a result, the increase in reactive power losses will be proportional to the current squared. This gives rise to the reactive power flows (absent at normal operation) that could result in a voltage drop. In this case the voltage drop is not the cause but the consequence of a network having been overloaded with active power; therefore the load shedding by under-voltage does not usually give the sought-for result.

3.1.8. Response of generators to voltage drop avalanche

It is known that the generator excitation current has two components [9], [64]:

- no-load excitation current for nominal voltage maintenance during idle running and for voltage drop compensation in the stator inductivity;
- additional excitation current for compensation of the armature reaction at the generator's loading with active and reactive power.

The no-load current can be determined using the open-circuit saturation characteristic (1) (Fig. 3.15) taking into account the magnetic saturation. Since the voltage of a generator can vary in a narrow range, it is possible to approximate its characteristic curve by a straight line (2) passing through the origin of coordinates (a smaller accuracy) or being tangent at the nominal voltage level. In the former case we have:

$$I_0 = aU \tag{3.26}$$

where a is a proportionality coefficient (depending on the generator design), and U is the stator voltage:

$$E = \sqrt{(U + I_r x_r)^2 + (I_a x_r)^2}\,. \tag{3.27}$$

Here x_r is the generator's equivalent reactance, I_a, I_r is the active and reactive stator current, respectively.

A more precise result is obtained in the latter case:

$$I_0 = b(U - U_0) \tag{3.28}$$

where b is a proportionality coefficient.

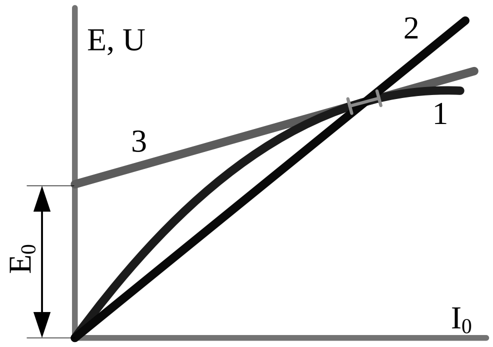


Fig. 3.15. Open-circuit saturation characteristic

1 − no-load curve; 2 − approximation with straight line; 3 − approximation with tangent

Using Potier's diagram, the relationship between the excitation current and the stator operation parameters can be presented by the vector diagram shown in Fig. 3.16 [9], [45].

During the idle running, magnetic flux in the generator is formed by the no-load excitation current. To the stator current compensating the armature reaction an excitation current component corresponds. The resultant magnetic flux matches the following excitation current:

$$\dot{I}_{ie} = \dot{I}_0 + k\dot{I}_{st} \tag{3.29}$$

After transformation we obtain:

$$I_{ex} = \sqrt{[b(U - U_0) + I_R(x + x_a)]^2 + (I_A(x + x_a))^2} \tag{3.30}$$

where $x; x_a$ are the equivalent reactances of stator winding and armature reactions (including the external reactance to the point of voltage determination); I_R, I_A are the reactive and active stator currents; U, U_0 are, respectively, the output stator voltage and a constant for approximating the characteristic saturation curve of the generator excitation system.

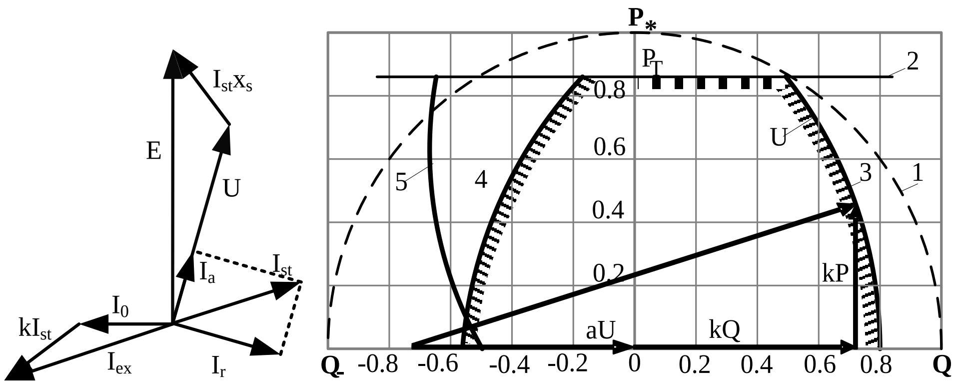


Fig. 3.16. Generator vector diagram; Potier's diagram

1 − limitation by stator current; 2 − turbine power; 3 − limitation by heating of rotor winding depending on voltage; 4 − limitation on reactive power consumption by heating of stator core; 5 − limitation on reactive power consumption from the viewpoint of stability maintenance

Having simplified this equation, we obtain:

$$I_{ex} = \sqrt{[b(U - U_0) + kI_R]^2 + (kI_A)^2} \tag{3.31}$$

where $k = x + x_a$.

Having increased up to the limiting value $I_{ex.\max}$, the excitation current remains further invariable. The generator's operational condition is analysed at a given active power as an independent variable. At the invariable active power the generators take up the following amount of reactive power:

$$Q = \frac{\sqrt{(EU)^2 - (Pk)^2} - U^2}{k} \tag{3.32}$$

where P is the active power of the generator; E is the electromotive force (EMF) and U − the voltage on generator terminals. In our particular case the independent variable is voltage. The excitation regulator raises the current thus responding to its decrease.

The electromotive force E and voltage U change in this case in the opposite directions, and the reactive power of the generator reaches maximum. On reaching the "threshold" level, the excitation current further does not rise. If voltage continues to decrease, the armature reaction is not compensated any more, and the generator reactive power starts decreasing (Fig. 3.17).

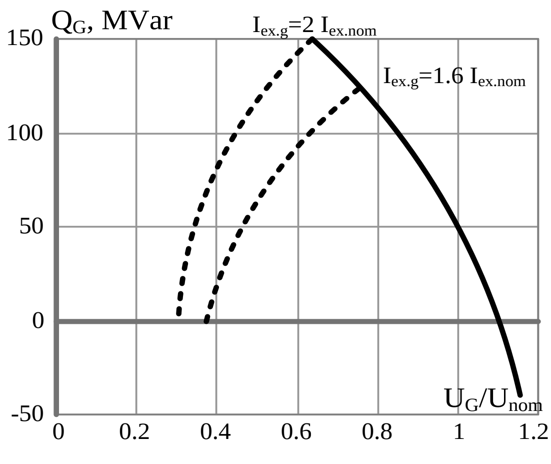


Fig. 3.17. Reactive power of the generators at voltage drop

The condition at which $I_{ex} > I_{nom}$ is allowable only for a short term taking into account the temperature of excitation winding. In this case the excess over the allowable value is long-lasting. Therefore the stator current will also exceed the permissible limit. As a result, the protection against overload (i.e. against external damage) of generators will act, and they will be tripped [45]. This is followed by formation of active power deficit, and in the low-voltage zone cascading outages of generating plants will occur.

The generators respond to a voltage drop by enhanced excitation. This leads to increase in the reactive power. The excitation and stator currents exceed the nominal values, and, on operation of the protection against external damage the generators are tripped in a cascade-wise manner, which triggers a power system blackout.

The radical protection against such blackouts is fast removal of the grid overload.

MASS-SCALE LOAD REJECTION AT UNDERVOLTAGE

It is known [24] that power plants need a definite load for their operation, since the minimum for power boilers should be $\approx 0.4P_{nom}$.

Conventionally, the load can be classified into two groups. The load of the first group is fed through magnetic starter, whereas of the second − through fuses or automatic switches. At the voltage decrease to $\approx(0.7 \div 0.8)U_{nom}$ the magnetic starters are switched off, and the corresponding load is lost. In the second case, the load is decreasing in compliance with its static characteristic curves. As a result, if the load is smaller than the least needed, the technological protections trip such a plant [45].

By removal the overload the blackout caused by voltage avalanche as well as by load rejection would be prevented.

EMERGENCIES OF CASCADE-WISE LINE TRIPPING

The emergencies of cascading line tripping can result in blackouts of power systems. This occurs for two reasons.

In the first case − owing to the line overloading under the conditions of voltage avalanche. When the voltage drops deeply, the line protections of a definite type respond to it as to a fault, tripping the overloaded lines, e.g., due to settings of the 2nd and 3rd zones of some distance protections (at considerably decreasing $Z = U/I$ ratio.) Thus, for example [65], during the USA-Canada blackout of 2003 (see Appendix) within 10 seconds the distance protections tripped 14 lines.

In the second case, at line overload and increased conductor sag, cascade-wise tripping of the lines occurs owing to short-circuits to ground. For example [27], [41], during the blackout in the Croatia (2003) 10 lines were tripped; in the Moscow blackout (2005) the number of tripped lines was 17.

3.1.9. Cascading line tripping caused by increased conductor sagging

When transmission lines are overloaded, the temperature of metal conductors increases; this effect is enhanced under hot and sunny weather conditions. In turn, the temperature rise causes additional conductor sagging. If the distance to ground becomes small or under the line there are trees (bushes), conductors can be sagging into them, which may result in faults-to-ground. Such a fault cannot disappear in itself, so no automatic re-closing is possible. The transmission lines working in parallel take on the power thus becoming overloaded, and the processes repeat in a cascade-like manner [19].

The method described below (proposed by the authors) allows estimating the probability of a ground short-circuit at increased conductor sag caused by overload.

Thermal processes in conductors

In the case of line overloading the temperature of conductors, changing proportionally to the overload square, can exceed many times the permissible level [79]. While this temperature under normal operating conditions is up to 70°C, at overloading it can approach 300°C or even a higher value. When the conductor temperature reaches 500 °C, the steel conductor-carrying elements are tempered, with their hardness lost. Such being the case, conductors must be replaced.

To calculate the conductor temperature the heat balance equation is used [79], [80], [81]. Its right side characterises the energy absorbed by a conductor (Joule's losses, solar radiation heat) whereas the left equation side – the released energy (heat radiation and heat convection):

$$P_t + P_s = P_r + P_c \tag{3.33}$$

where P_t is the value of Joule's losses, W/cm^2, calculated *vs.* the current value with the temperature dependence of conductor resistance taken into account:

$$P_t = \frac{I^2 r_t}{\pi d} \tag{3.34}$$

where I is the current flowing in conductors, A; d is the conductor diameter, cm; r_t is the conductor resistance depending on the temperature: $r_t = r_{norm}\left(1+\alpha_\Omega\left(t_c - t_{norm}\right) + \beta_\Omega\left(t_c - t_{norm}\right)^2\right)$, with r_{norm} being determined by the standard (i.e., t_{norm} usually assumed to be 20 °C); $\alpha_\Omega, \beta_\Omega$ are the thermal resistance coefficients regarding the increase in resistance of conductors caused by their heating (β_Ω is employed if the temperature exceeds 100°C); since these coefficients for steel are small, those of aluminium could be used: $\alpha_\Omega = 0.00387\ 1/C^\circ$ and $\beta_\Omega = 1.1\cdot 10^{-6}\ 1/C^{\circ 2}$; t_c is the conductor temperature, °C.

In (3.35) P_s is the energy of solar radiation absorbed by a conductor taking into account the radiation reflected from other bodies, W/cm^2; this energy for high-voltage lines makes up a significant portion in the heat balance:

$$P_s = \frac{0.12c0.9^{\sec\phi} + 0.01}{\pi}, \tag{3.35}$$

where c is the absorptivity (for conductors 0.5-0.6 is accepted); ϕ is the zenith distance to the Sun (latitude degree); in calculations it is taken to be 60°;

P_r is the heat transfer by radiation obeying Stephan-Boltzmann's law, W/cm^2:

$$P_r = \sigma c\left[T_1^4 - T_0^4\right] \tag{3.36}$$

where σ is Stephan-Boltzmann's constant, $\sigma = 5.67\cdot 10^{-12}$ W/cm^2/K^4; T_1 is the conductor temperature, K; T_0 is the air temperature, K. To pass from Kelvin degrees to Celsius ones, the following expressions are used: $T_K = t_{gr} + 273.15$ and $t_{gr} = T_K - 273.15$ (could be rounded off to 273).

P_c is the value of convective heat losses, W/cm^2, which are more expressed under windy weather. These losses are minimal under no-wind conditions. However, such conditions occur but seldom and are short-term, therefore when the maximum conductor heating is calculated for the worst case, minor winds should be taken into account, i. e. ($v = 0.5m/s = 50cm/s$). In compliance with the boundary layer theory, the heat conduction by convection for a cylindrical horizontal body is calculated in the following way [79]:

$$P_c = \frac{2k\lambda\left(t_c - t_a\right)}{d\ln\left(1+\frac{2\delta}{d}\right)} \tag{3.37}$$

where t_a is the ambient temperature, ºC; λ is the heat conductivity of surroundings (for the air $\lambda = 3.4 \cdot 10^{-6} T^{0.754}$ W/cm, 1°); T is the geometrical mean of the temperature, $T = \sqrt{T_1 T_0}$, K; δ is the thickness of an equivalent heat conducting layer, cm. It is assumed that the temperature fall from the value equalling the conductor temperature to that equalling the ambient temperature occurs within layer δ. In the case of forced convection (wind) it is calculated as $\delta = Md\left(\mu/(\gamma d v)\right)^m$, where v is the wind velocity, cm/s; μ is the air viscosity, $\mu = 1.705 \cdot 10^{-4} (T/273)^{0.754}$; γ is the specific weight of air, $\gamma = 1.29 \cdot 10^{-3} (T/273)^{0.754}$ g/cm^3; M, m are empirically found constants: for overhead transmission lines $M = 2.15$ and $m = 0.5$. Multiwire conductors have uneven surface which significantly enhances heat transfer by convection. Therefore, a correction coefficient should be used, which depends on the conductor diameter d and the wire diameter d_0 as $k = 1 + 2.3d/d_0$.

Having expressed the terms in (3.33) via the mentioned above formulas, we obtain a complex transcendent function from which the conductor temperature cannot be derived explicitly:

$$\frac{I^2 r_{norm}\left(1 + \alpha_\Omega (t_c - t_{norm}) + \beta_\Omega (t_c - t_{norm})^2\right)}{\pi d} + \frac{0.72 \cdot 0.9^{\sec\phi} + 0.01}{\pi} =$$

$$= 3.54\left[\left(\frac{t_c + 273}{1000}\right)^4 - \left(\frac{t_a + 273}{1000}\right)^4\right] + \frac{k \cdot 6.8 \cdot 10^{-6} T^{0.754} (t_c - t_a)}{d \ln\left(1 + 2M\left(0.132\left(\frac{T}{273}\right)^{1.754} \Big/ dv\right)^m\right)} \qquad (3.38)$$

If we analyse (3.38) in a limited interval from the temperature of air to the maximum one (e.g. 500$^{\text{o}}$C), we can see that to every cross-point of released and absorbed energy curves at different current values one definite conductor temperature corresponds (see Fig. 3.18).

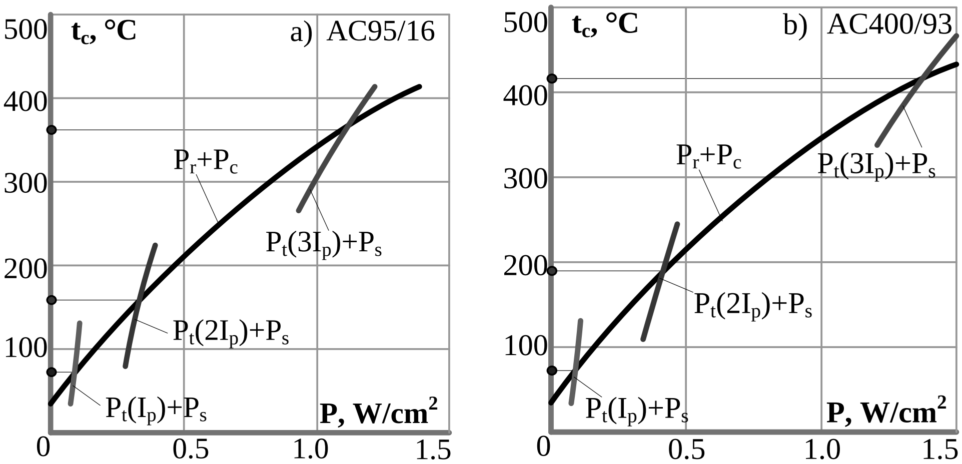


Fig. 3.18. Temperature *vs.* released and absorbed energy at different conductor temperatures: a) for C95/16 conductor; b) for AC400/93 conductor.

The current dependence of conductor temperature can be defined by the iteration method [82].

Using the algorithm displayed in Fig. 3.19, expression (3.38) assumes the form: $f(t) = 0$. After that the temperature limits $[t_{\min}; t_{\max}]$ and the desired precision of the ε value are introduced. The iteration process consists of the following steps:

1) argument t (as the mean from interval $[t_{\min}; t_{\max}]$) of the function and its value $f(t)$

are calculated;

2) if the signs of $f(t)$ and $f(t_{\min})$ values coincide, then the left boundary of the root location interval shifts to point t, i.e. $t_{\min} = t$, but $f(t_{\min}) = f(t)$, and the calculation returns to point 1;

3) otherwise, if these signs do not coincide, then to point t the right boundary of root location interval shifts, i.e. $t_{\max} = t$, and the calculation returns to point 1.

The iteration is continued until the desired precision $|f(t)| \le \varepsilon$ is achieved.

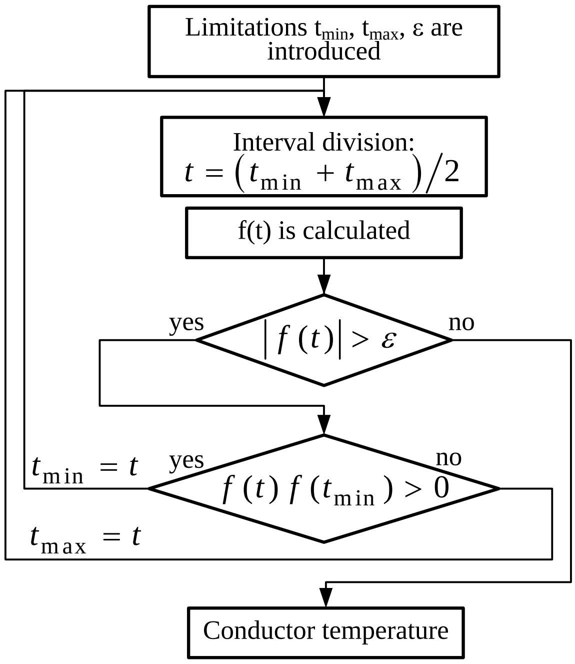


Fig. 3.19. The algorithm for calculation of conductor temperature

To obtain curves for different operating conditions and lines parameters, the calculations are repeated varying the values of current, air temperature and others.

Mechanical processes in conductors

It is known [74], [79], [83], [84] that the sag of conductor and the stress in its material vary depending on the temperature and mechanical load. When the temperature is rising a conductor stretches, whereas the stress in this conductor decreases.

The variation of conductor length is characterised by that of temperature from t_s to t_1:

$$\Delta L_1 = L_s \cdot \alpha (t_1 - t_s), \qquad (3.39)$$

where α is the coefficient of linear thermal expansion, 1/ºC. At a temperature rise a conductor's length increases; since, due to friction, no shift is practically possible in aluminium conductors and steel elements, these are under stress – the former due to pressure and the latter due to expansion. Therefore the mentioned coefficient depends on the ratio of aluminium and steel cross-sections (for details see [74], [84]). In the calculations of AC standard conductors over 120 mm^2 we can assume $\alpha = 18.3 \cdot 10^{-6}$, 1/ºC; L_s is the conductor length in a span, m.

At the conductor length changing, the tensile stress of conductor material also changes from σ_s to σ_1, which, in turn, causes a next change in the conductor length:

$$\Delta L_2 = L_s \cdot \beta (\sigma_1 - \sigma_s) \qquad (3.40)$$

where β is the coefficient of elastic tension of the material, $\beta = 1/E$, which characterises the change per unit of conductor length at the material stress changing per 1 daN/mm^2; E is the elasticity module, daN/mm^2 (for AC conductors the elasticity module is greater than that for aluminium but smaller than for steel. Its value depends on the mentioned above ratio of aluminium and steel cross-sections (for the details see [74], [84]); for AC standard conductors over 120 mm^2 we can assume $E = 8.9 \cdot 10^3$ daN/mm^2); σ_1 is the minimum tensile stress of the conductor, daN/mm^2; σ_s is the initial stress of the conductor.

The new length of the conductor is therefore

$$L = L_s + \Delta L_1 + \Delta L_2 \tag{3.41}$$

Since the ratio of line span l to conductor sag f_{sg} is relatively large, in practical calculations we will assume that the conductor sagging curve is close to a parabola whose length is:

$$L_s = l + \frac{\gamma_s^2 l^3}{24\sigma_s^2} \quad or \quad L = l + \frac{\gamma_1^2 l^3}{24\sigma_1^2} \tag{3.42}$$

where γ_1 is the load created in a conductor by the gravity force, daN/m*mm^2, calculated as $\gamma_1 = g\,G_o / F$, with F being the calculated conductor cross-section, mm^2; G_0 is the conductor mass per 1km, kg/km; $g = 9.81 m/s^2$ is the free fall acceleration of a body; l is the line span (a reduced span in which after the mounting a mechanical stress equalisation in a conductor occurs owing to its “pulling” through suspenders between the anchor towers, m; σ_1 is the minimum tensile stress of conductor, daN/mm^2.

Having substituted all separately calculated expressions into (3.41) we obtain:

$$l + \frac{\gamma_1^2 l^3}{24\sigma_1^2} = l + \frac{\gamma_s^2 l^3}{24\sigma_s^2} + L_s \cdot \alpha\left(t_1 - t_s\right) + L_s \cdot \frac{1}{E}\left(\sigma_1 - \sigma_s\right) \tag{3.43}$$

Assuming that $L_s \approx l$ and multiplying both sides by E, after elementary transformations we arrive at the basic equation for the conductor state:

$$\sigma_1 - \frac{\gamma_1^2 l^2 E}{24\sigma_1^2} = \sigma_s - \frac{\gamma_s^2 l^2 E}{24\sigma_s^2} - \alpha E\left(t_1 - t_s\right) \tag{3.44}$$

where σ_s, γ_s, t_s are the conductor initial conditions for mechanical stress, specific mechanical load and temperature, which depend on the critical span – calculated or given by mounting specifications; σ_1, γ_1 are the conductor state conditions for mechanical stress and specific mechanical load at a temperature rise to t_1.

In order to calculate the sag of a conductor or its distance to ground in dependence on the temperature, as an initial condition we assume the conductor state with the greatest allowable sag $f_{sg.no}$ (according to the design or mounting specifications). Since the conductors are suspended on an invariable height (see Fig. 3.20), the distance to the ground h_g is calculated as the difference between the line parameters at the greatest calculated conductor sag and at its increased sag:

$$h_g = h_0 + f_{sg.no} - f_{sg.t} \tag{3.45}$$

where h_0 is the least distance of a conductor to the ground at its greatest calculated sag, m; $f_{sg.no}$ is the allowable greatest calculated conductor sag, m; $f_{sg.t}$ is the sag, m, at temperature variations (3.46).

The conductor sag, at temperature variations $f_{sg.t}$ with the minimum tensile stress σ_1 in a conductor and its specific mechanical load γ_1, will be:

$$f_{sg.t} = \frac{\gamma_1 l^2}{8\sigma_1} \tag{3.46}$$

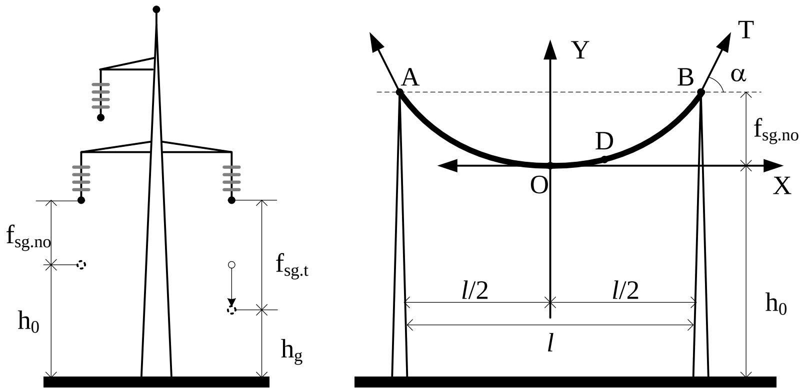


Fig. 3.20. Scheme for sag calculation: a) line parameters, b) sagging curve

l – reduced span; $f_{sg.no}$ – the greatest allowable sag; h_0 – line- to-ground dimensions; $f_{n.t}$, h_g – sag and distance to the ground at a temperature rise

Having expressed σ_1 from (3.46) and substituted it into (3.44) we obtain:

$$\frac{\gamma_1 l^2}{8 f_{sg.t}} - \frac{8 f_{sg.t}^2 E}{3 l^2} = \sigma_s - \frac{\gamma_s^2 l^2 E}{24\sigma_s^2} - \alpha E\left(t_1 - t_s\right) \tag{3.47}$$

With respect to sag $f_{sg.t}$, (3.47) is a cubic equation, which is solved using, e.g., Cardano's method [85] (Fig. 3.21). For its solution the mentioned above iteration method (Fig. 3.19) could be used, since in the interval under consideration the equation has one root at intersection with the sagging axis.

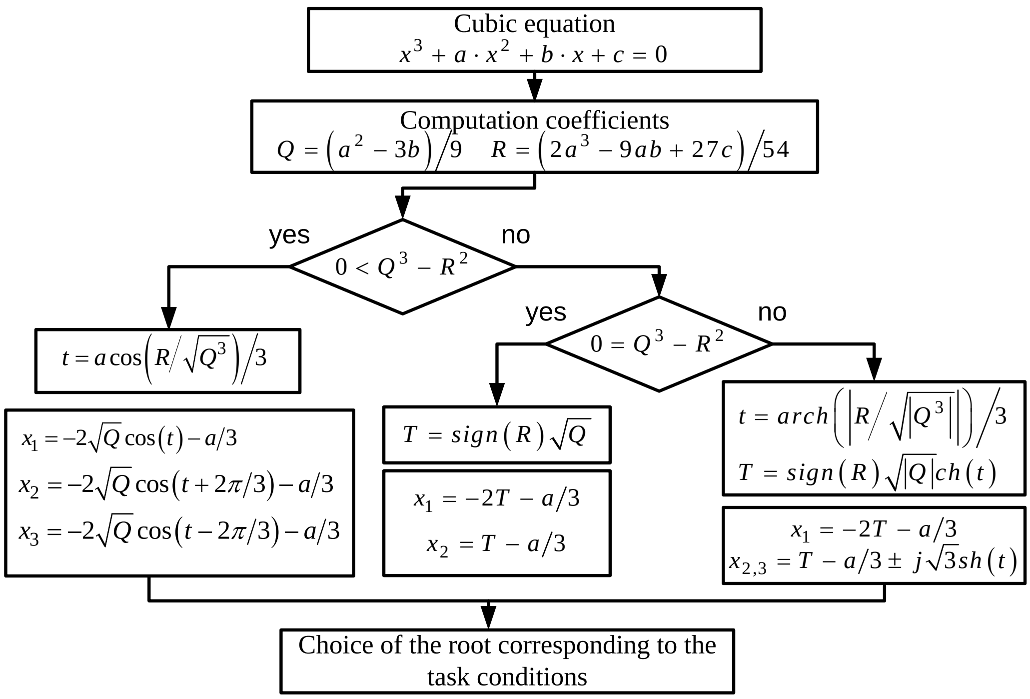


Fig. 3.21. Algorithm for solving the cubic equation in sag calculations

3.1.10. Calculation of the overload, conductor temperature, and distance-to-ground nomogram

Fig. 3.22a displays the algorithm for nomogram calculation of thermal and mechanical processes using the formulas and algorithms given above.

Taking into account that in a limited temperature interval to each current only one temperature value corresponds and trying to avoid iterations, we can calculate an inverse problem with the current expressed as the following function of conductor and air temperatures:

$$I(t_c,t_a)=\sqrt{\frac{\pi d}{r_t}\left(P_r+P_c-P_s\right)}=$$

$$\sqrt{\pi d\,\frac{3.54\left[\left(\frac{t_c+273}{1000}\right)^4-\left(\frac{t_a+273}{1000}\right)^4\right]+\frac{k\cdot 6.8\cdot 10^{-6}T^{0.754}\left(t_c-t_a\right)}{d\ln\left(1+2M\left(0.132\left(\frac{T}{273}\right)^{1.754}\Big/dv\right)^m\right)}-\frac{0.72\cdot 0.9^{\sec\phi}+0.01}{\pi}}{r_{norm}\left(1+\alpha_\Omega\left(t_c-t_{norm}\right)+\beta_\Omega\left(t_c-t_{norm}\right)^2\right)}} \quad (3.48)$$

From similar considerations, the temperature in mechanical processes can be calculated as the function of sagging:

$$t_c(f_{sg.t})=\frac{\sigma_s}{\alpha E}-\frac{\gamma_1 l^2}{8f_{sg.t}\alpha E}-\frac{\gamma_s^2 l^2}{24\sigma_s^2\alpha}+\frac{8f_{sg.t}^2}{3l^2\alpha}+t_s \quad (3.49)$$

Fig. 3.22.b illustrates a simplified nomogram calculation using algebraic functions (3.48) and (3.49).

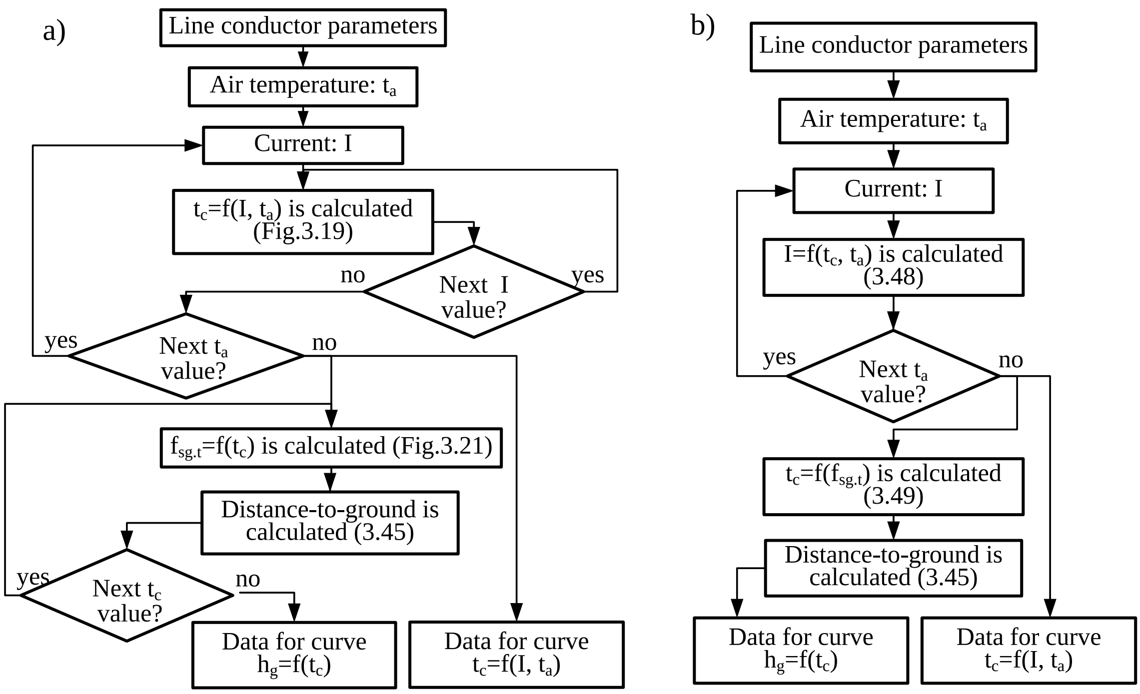


Fig. 3.22. Algorithms for nomogram calculation: a) by iterations; b) algebraically

In the nomogram of Fig. 3.23 the thermal processes are shown in the right quadrant, whereas the mechanical ones – in the left. In the conductor temperature the ambient value t_a (curves I and II) is accounted for; the current values are related to the allowable magnitudes. The distance-to-ground is given in metres. Here the line sagging close to ground (trees, bushes) is assumed, which can be followed by flashover.

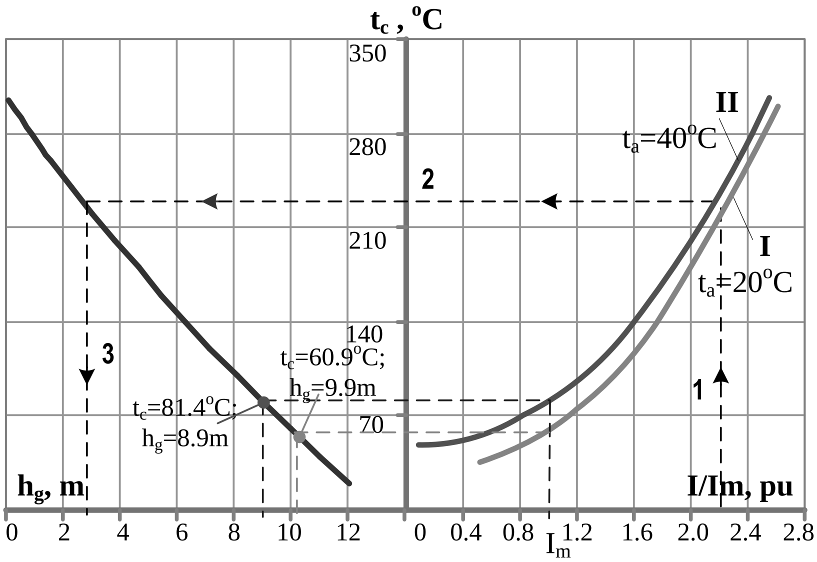


Fig. 3.23. The overload, conductor temperature, and distance-to-ground nomogram:

I/I_m – overload against the maximum allowable from the thermal point of view (1); $U_{nom} = 750kV$; $I_m = 860A$ at $t_m = 70°$; aluminium-steel conductors AC-4x400/93; t_c – conductor temperature (2); h_g – distance-to-ground, m (3).

The conductor heating is noticeably affected by the heat released at solar radiation; in a serene and sunny weather it raises the conductor temperature more than by 10°C (in southern regions even greater [65]); in turn, the conductor sag at a 10°C temperature change increases by 70-80cm on the average.

The proposed calculational procedure allows the probability of short-circuit to ground at overload to be estimated taking into account specifics of mechanical and thermal processes.

Response of line protections to overload

It is possible to use special kind protections against thermal overloads to disconnect overloaded lines. If in a cross-section there is only one line, then a PS splitting will occur at the place through which the maximum power is flowing; in the case of several lines those still operating would take over this flow, and at overload such lines will be tripped, which would lead to splitting the power system into parts at the worst place, thus causing the maximum consumers' tripping in its deficient part. As was mentioned above, the main task is not to trip the overloaded lines but to keep them operating with maximum allowable power flows.

Using short-term system sectioning, it is possible to remove fast a grid overload thus avoiding cascading line tripping caused by voltage avalanche and increased conductor sag.

THE INFLUENCE OF FREQUENCY DECLINE ON THE GENERATING SOURCES

During disturbances, power systems split into parts; this usually occurs in the places of grid cross-section overload. In such cases in one system part there will be load decrease (with frequency slightly increasing in compliance with the speed droop), whereas in its second part a load increase will occur, and, owing to the governor limitations, quite a deep frequency drop will be observed.

Since the reaction of generating sources to a deep frequency decrease can lead to their tripping, it is important to understand the dynamics of its changes. The frequency maintenance in a safe zone of generating sources is secured by fast-acting under-frequency load shedding automatics (AUFLS). The analysis is performed for simple devices usually employed in power systems. The total number of such devices in power systems is ~ 35-40 ths.

The situation created at system's splitting into parts with power deficit in one of them is shown in Fig. 3.24 [22], [86]. In the initial position the deficient part is functioning together with the power surplus region, receiving from there a proportion of energy. The operational condition is described by two characteristic curves: load curve (1), and curve (2) relating to the turbine speed governors. The normal running is characterised by the intersection point of the curves with parameters f_0 and P_0.

After splitting, the power of deficient part will be limited by the generation curve $P_{g.nom}$ (3), and the operational condition stabilises at the f_∞ value essentially differing from the initial one. Since the capacities of generating sources are exhausted, the only opportunity to maintain frequency in the allowable limits is load relief, i.e. at point f_c of transient curve (4) − otherwise, in order to protect equipment against damage it will be tripped by protection.

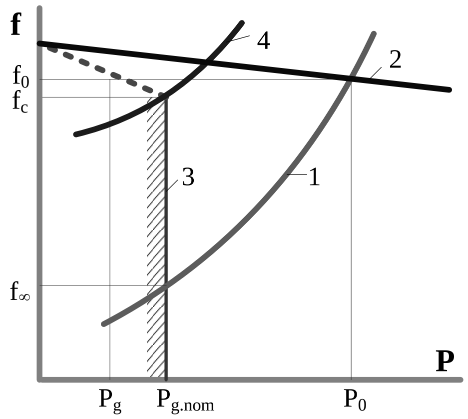


Fig. 3.24. Characteristic curves of frequency decline emergency

1−static load curve; 2− generation curve; 3−deficient region's generation curve;4− load curve after off-loading

The power system operation under the conditions of reduced frequency affects negatively the functioning of thermal units and electric machines. This is explained by the following [64]:

- for thermal power plants: at a reduced productivity of feed pumps in a TPP an imbalance arises between the boiler and turbine capacities; to protect the equipment against stability loss the technological protections switch it off;
- for gas turbines: owing to decrease in the compressor productivity, the temperature of combustion products rises to unallowable extent, and the technological protections switch the gas turbines off;
- for nuclear plants: when at an NPP the cooling agent circulation is slowing down, its active zone is cooled insufficiently. This leads to temperature and, therefore, to power rise, to which the technological protections respond by tripping the reactor;
- Besides, decrease in the turbine turns can cause vibration of its blades; also, when the f/U ratio decreases, the cores of electric machines become oversaturated.

The frequency decline effect on the static stability of thermal equipment at generating sources deserves particular attention and will be considered in §4.

Frequency decline effect on the electric machines

The influence of frequency decline on such electric machines as generators, transformers, and electric motors is expressed in the changes of core induction according to the equation [87]:

$$B = U / \left(\pi \sqrt{2} f \cdot k_w \cdot w \cdot s \right) \tag{3.50}$$

where w is the number of winding turns; k_w is a core coefficient characterising the winding design; s is the core cross-section, cm^2.

Therefore the induction in the cores is directly proportional to the voltage and inversely proportional to the frequency. At frequency decrease (or voltage increase) the core of an electric machine becomes over-saturated, and its magnetic permeability decreases $\left(\mu = B/H\right)$. Taking into account that the reluctance of cores is inversely proportional to its magnetic permeability $\left(R_{magn} = c/\mu\right)$, the magnetic leakage field expands, which causes over-heating of massive constructive elements [45]. Account of this circumstance is taken through the time limitations on the existence of reduced frequency (Fig. 3.25), which allows the situation to be normalised by protective means.

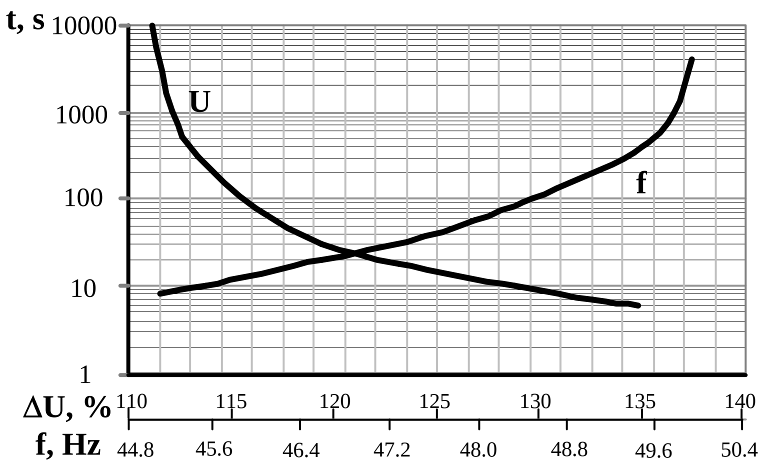


Fig. 3.25. Time limitations *vs*. frequency and voltage changes

3.1.11. Frequency deviation standards

Since under emergency conditions it is impossible to prevent short-term frequency deviations, special standards for their permissible duration have been established (Fig. 3.26 [31]).

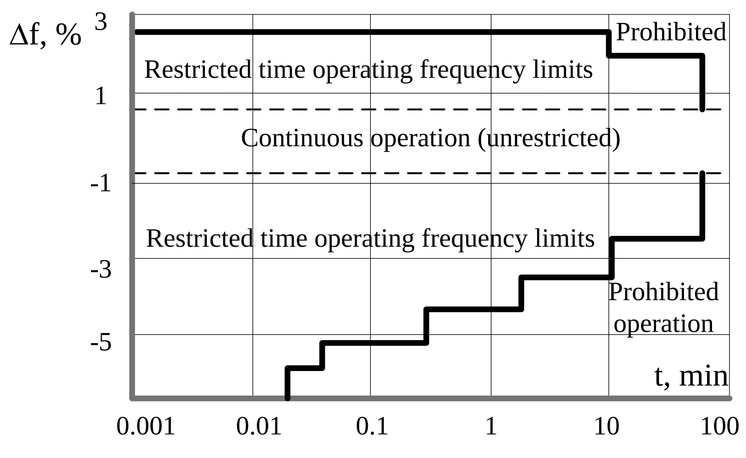


Fig. 3.26. Steam turbine partial or full-load operating limitations during abnormal frequency

For example, in European countries, the frequency decrease to 47÷47.5 Hz and its increase to 52÷52.5 Hz [27], [88] are allowed for a short term.

FREQUENCY VARIATIONS IN THE PROCESS OF POWER DEFICIT ELIMINATION

As was shown above, a dangerous frequency drop creates the threat of equipment damage in the generating sources; as a result, the technological protections trip them, thus leading to system blackouts. To avoid such a situation, the generating sources should be kept operating, for which the control adequate to the emergency situation level is required. This suggests having a clear notion about the character of frequency variations at the actions of the fast-acting under-frequency load shedding automatics (AUFLS1). For the appropriate analysis an algorithm has been worked out that takes into account the discretivity of AUFLS1 stages and their time delays determined by protection against the noises caused by damage.

3.1.12. Frequency variations at load shedding

The behaviour of a transient process of frequency variation is dictated by the fact that in a deficient region the speed governors of turbines fully open their nozzles and do not participate in the process. Therefore this process is only determined by the frequency dependence of load in compliance with characteristic curves. In the general case such curves are non-linear and can be approximated with a polynomial [86]. In the practical calculations the load changes in dependence on frequency are described with the simplified equation using load-damping constant D [88]:

$$\Delta P_l = D\Delta f \tag{3.51}$$

The deficient region can be considered schematically, with one generator feeding an individual load. This condition is characterised by the basic equation of a unit's rotor motion:

$$J\frac{d\omega}{dt} = M_m - M_e = \omega\left(P_g - P_l\right) \tag{3.52}$$

where J is the combined moment of inertia of generator and turbine, M_m, M_e is, respectively, the mechanical and electro-magnetic torque; P_g, P_l is, respectively, generator and load power; ω is the angular velocity of the rotor; *t* is the time.

Having linearised and simplified equation (3.52), we obtain the expression for frequency variation under emergency conditions:

$$T_j\frac{d\omega_*}{dt} = -\omega_*\left(D\frac{P_{l.0}}{P_{g.\infty}} - m\right) \tag{3.53}$$

where ω_* is the system's angular velocity, pu, $\Delta\omega/\omega_0$; $\Delta\omega$ is the angular velocity variation; D is a load-damping constant (if not determined experimentally then usually taken in the 1-3 range depending on the load character [22]); P_{l0} is the total power in the initial condition; $P_{g\infty}$ is the post-transient generating power; m describes the generator power dependence on frequency: $m = \dfrac{\Delta P_g}{P_{g.\infty}}\dfrac{\omega_0}{\Delta\omega}$; ΔP_g is the power change; T_j is the time constant of mechanical inertia (usually 10-14s [22]), which consists of nominal time constants of turbines and generators related to the initial load as well as of such constants for motors and mechanisms:

$$T_j = \Sigma T_{j_{un}}\frac{P_{nom}}{P_{nom.0}} = \frac{\Sigma(T_{gen} + T_{turb})P_{gen} + \Sigma(T_m + T_{mech})P_m}{P_{l0}} \tag{3.54}$$

where T_{turb} is the turbine time constant, s; T_{gen} is the generator time constant, s; T_m is the motor time constant, s; T_{mech} is the time constant of mechanisms, s; P_{gen} is the generator power and P_m is the motor power related to the basic power.

In turn, for one unit this can be calculated (in seconds) as

$$T_{j_{un}} = \frac{0.279 GD^2 n^2 \cdot 10^{-9}}{P_{nom}} \tag{3.55}$$

where GD^2 is the inertia moment of the unit, Nm^2; n is the rotational speed, RPM; P_{nom} is the nominal power of the unit, MW.

Having solved equation (3.53), we obtain:

$$\omega_* = \omega_\infty \left(1 - e^{-\frac{t}{T_f}}\right) \tag{3.56}$$

where T_f is the time constant of frequency variation (in practice changes in the limits 2.5-6s [22]); at a big specific weight of pumps and fans the frequency variation constant is greater [89]. Its dependence on the time constant of mechanical inertia T_j is [22], [90]:

$$T_f = \frac{T_j}{D\frac{P_{l.0}}{P_{g.\infty}} - m} \approx \frac{T_j}{D\frac{P_{l.0}}{P_{g.\infty}}} \tag{3.57}$$

It is often easier to relate the T_f constant to the total power of initial condition [90]:

$$T_f \approx T_j \frac{P_{l.0} - \Delta P_g}{D \cdot P_{l.0}} \tag{3.58}$$

In these cases, the frequency in a transient process can be calculated as

$$f(t) = f_0 - \Delta f_\infty \left(1 - e^{-\frac{t}{T_f}}\right) \tag{3.59}$$

where the resultant frequency decline is

$$\Delta f_\infty = \frac{\Delta P_{\%0}}{100 \cdot D} f_{nom}. \tag{3.60}$$

Here $\Delta P_{\%0}$ is the initial deficit.

In turn, the time from the emergency beginning to the time when the frequency reaches the f_1 value can be calculated as

$$t_1 = -T_f \ln\left(1 - \frac{f_0 - f_1}{\Delta f_\infty}\right) = T_f \ln\left(\frac{\Delta f_\infty}{\Delta f_\infty - f_0 + f_1}\right). \tag{3.61}$$

As was mentioned, to avoid a blackout caused by under-frequency, power systems are provided with fast-acting under-frequency load shedding automats, which at a frequency fall trip the load. Different AUFLS automats have differing operation settings for frequency. Usually, the range of frequency settings is 49.2÷48 Hz, with a step of 0.1÷0.4 Hz; the time delays should be minimal [88], [89]. At the power systems' sub-stations in service are many tens of thousands of such automats, whose mutual indepedence secures their high reliability [6], [10], [29].

The total shed load is distributed among stages in different manners, the simplest of which is the uniform distribution. If the number of stages is large enough, the load relief density coefficient in dependence on the total load connected to AUFLS1 and frequency settings $f_{s.1}$ and $f_{s.k}$ is calculated (in pu) as

$$k_{AUFLS*} = \frac{P_{AUFLS1}}{P_{l.0}} \frac{f_0}{f_{s.1} - f_{s.k}} \tag{3.62}$$

where P_{AUFLS1} is the load connected to AUFLS1; $P_{l.0}$ is the load in the pre-emergency operational condition; f_0 is the frequency in the pre-emergency operational condition (50Hz).

In the ideal case, assuming that the automatics operates without time delay and using (3.62), the minimum value for frequency can approximately be determined as [89]

$$f_{\min} \approx \frac{P_g f_0 - P_{l.0}\left(f_0 - D\cdot f_0 - k_{AUFLS} f_{s.1}\right)}{P_{l.0}\left(D + k_{AUFLS}\right)} \tag{3.63}$$

where P_g is the generation power in a transient process, pu.

The large number of stages and the minimum time delay ensures, to some extent, the selectivity of consumer tripping. However, in the cases of large deficit the time delay in AUFLS stage operation significantly affects the behaviour of frequency changes (Fig. 3.27).

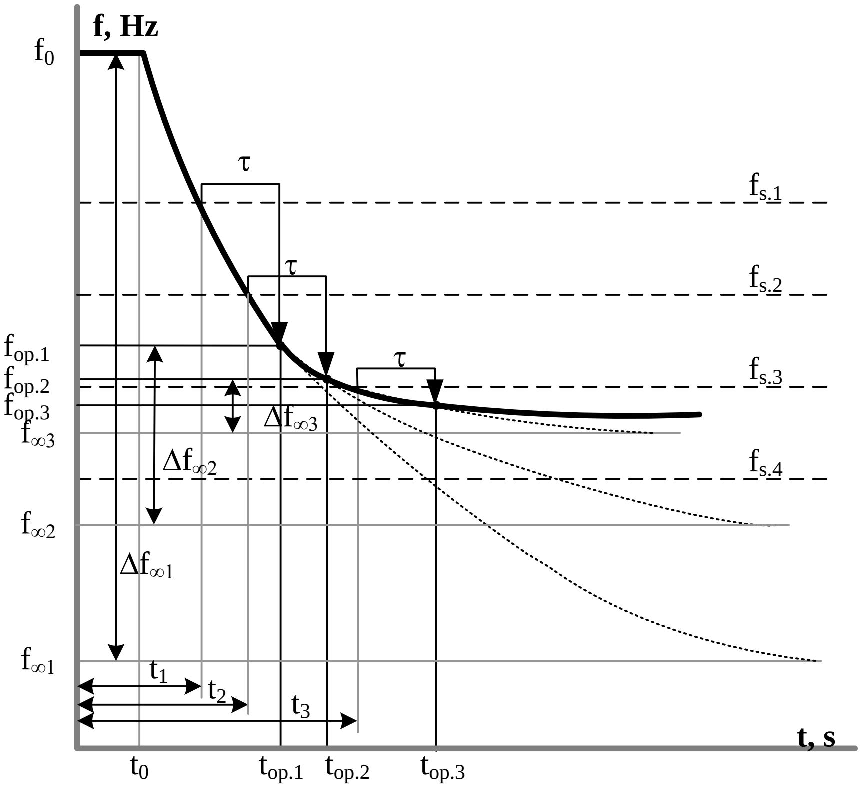


Fig. 3.27. Frequency change process at AUFLS1 operation

f_s – frequency settings; f_{op} –frequency after AUFLS stage operation; f_∞ – stationary frequency; t – the time of starting a load shedding stage; t_{op} – the time of load shedding stage operation

Based on the above mentioned formulas, an algorithm for studying the frequency variation processes at fast-acting AUFLS1 operation (Fig. 3.28) has been worked out.

The steps of this algorithm are as follows.

1) Introduce the initial data containing the information on: a) the number of AUFLS1 stages, the amount of connected load and its distribution among the stages, as well as the frequency setting values and the time delays of stage operation; b) the value of initial deficit; c) the values of frequency variation time constant and load-damping constant.

2) Estimate, using (3.60) and (3.59), whether the frequency decline caused by deficit activates the next AUFLS stage. If 'no', go to point 5. If 'yes', calculate the stage starting time by (3.61).

3) Calculate the stage operation time for time delay τ, which depends on the time of a frequency relay, its delay time, and the own time of circuit-breaker's opening; using (3.59),

calculate the stage operation frequency. Find the value of active power deficit after load shedding stage operation taking into account the change of load owing to its regulating effect by the following equation:

$$\Delta P_{\%.1} = \Delta P_{\%.0} - D\Delta f_{\%1} - \Delta P_{s.\%} \tag{3.64}$$

where $\Delta P_{s.\%}$ is the load connected to the stage, $\Delta f_{\%1}$ is the frequency difference of stage operations with respect to the nominal frequency, % :

$$\Delta f_{\%1} = \frac{f_0 - f_1}{f_{nom}} 100 \tag{3.65}$$;

4) Establish, by comparing the stage operation frequency with settings, whether within the time $t_1 < t \le (t_1 + \tau)$ other stages are started. If 'no', go to point 2. If 'yes', determine the starting time for activated stages and go to point 3.

5) End the calculation if the frequency fall is stopped, or all the stages have operated, or the slow-acting automatics (AUFLS2) time setting has been reached. The calculation results contain information on the operation time for each stage, as well as on the frequency and deficit remaining after operation of each stage.

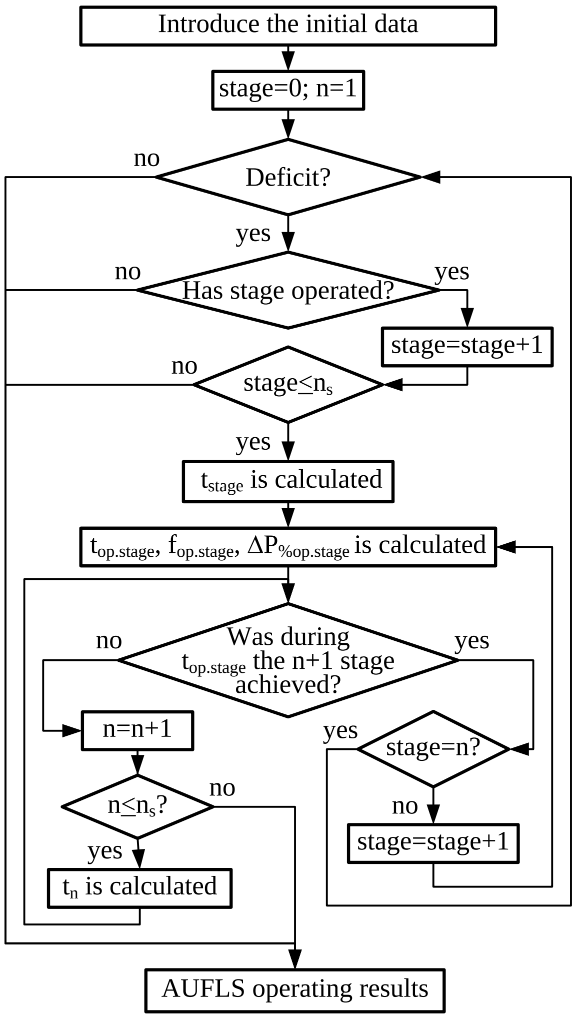


Fig. 3.28. Calculation algorithm for AUFLS1 operation

The results could be complemented with the frequency values calculated for the time needed to stabilise this parameter, e.g. in the range $2 \div 3T_f$, in order to estimate the influence of non-selectively operated stages on the frequency variation process.

3.1.13. The AUFLS1 operation under moderate and large power deficits

The process of frequency changes at operation of fast-acting under-frequency load shedding automatics was defined using a model based on the algorithm presented in Fig. 3.28. In the scope of this model, the following assumptions are made: the frequency variation time constant is $T_f = 3 \div 5s$; the load-damping constant is $D = 1.5 \div 3$; the load is distributed among stages uniformly in the 49.3÷48 Hz range; to each stage 5.5% load is connected; the stage operation delay is $t_d = 0.15 \div 0.3s$;the initial deficit is varying with a 0.1% step.

This process is dependent on the power deficit. As seen in Fig. 3.29, at moderate deficits (e.g. 20-40%) the frequency decline proceeds in the allowable limits, whereas at large deficits (above 40%) the frequency, owing to time delay, decreases almost to the level when the technological protections can trip the unit. The situation can be improved using special stages reacting to the frequency variation rate [22].

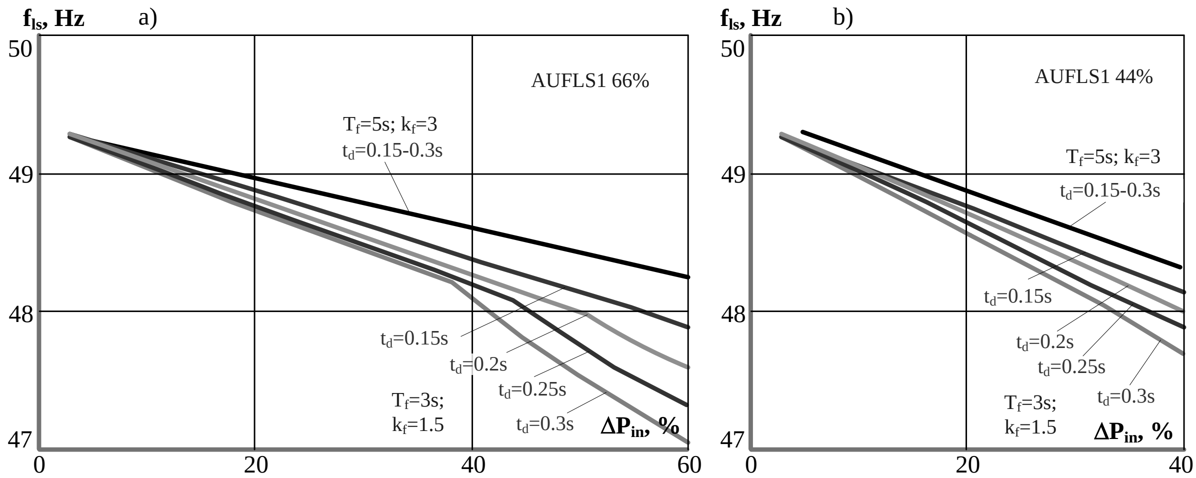


Fig. 3.29. Frequency after operation of the last stage at different power deficits and time delays

Despite the fact that the automatics is provided with feedback, the number of activated stages might vary depending on particular conditions. At large deficits several stages can operate non-selectively; as a result, the load greater than needed is shed. The number of stages that have wrong operated owing to the delay depends on the deficit amount and, therefore, on the frequency decline rate, thus creating additional tripping ΔP_{ls} (power surplus) after operation of the last stage. The stationary frequency variation caused by the power surplus (before the governors start operating) is:

$$\Delta f \uparrow = \frac{\Delta P_{ls}}{D} \tag{3.66}$$

As a result, after their operation at minor deficits the frequency stabilises at the minimum values (Fig. 3.30), while at greater deficits the frequency is tending to rise owing to operation of several excessive stages.

To control generating sources it is necessary to define the minimum frequency values after operation of fast-acting AUFLS and the zones of frequency changes depending on the deficit size, the load to be shed and the time delays. During the analysis, the results for large deficits have been obtained, which are arranged in a graphical form to be used in practice. In the case shown in Fig. 3.31, where the initial deficit changes up to 60%, to 12 stages of the shedding automatics the load $P_{AUFLS1} = 66\%$ is connected; in turn, Fig. 3.32 shows the case when at initial deficits up to 40% the load connected to 8 stages is $P_{AUFLS1} = 44\%$.

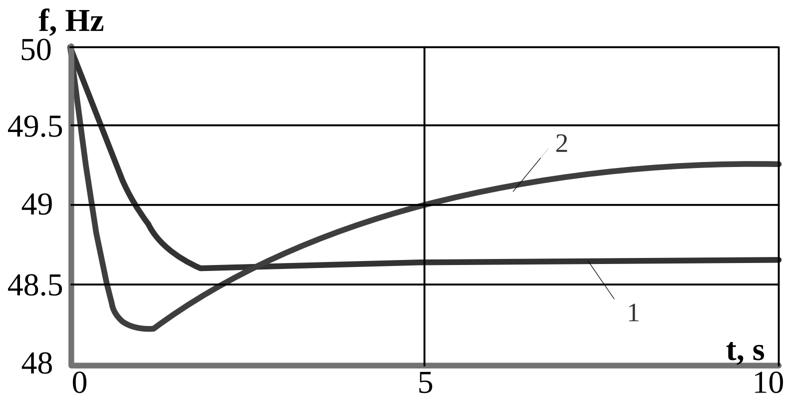


Fig. 3.30. Frequency variation after AUFLS1 operation

1 – at moderate deficit (17%);2 – at large deficit (54%)

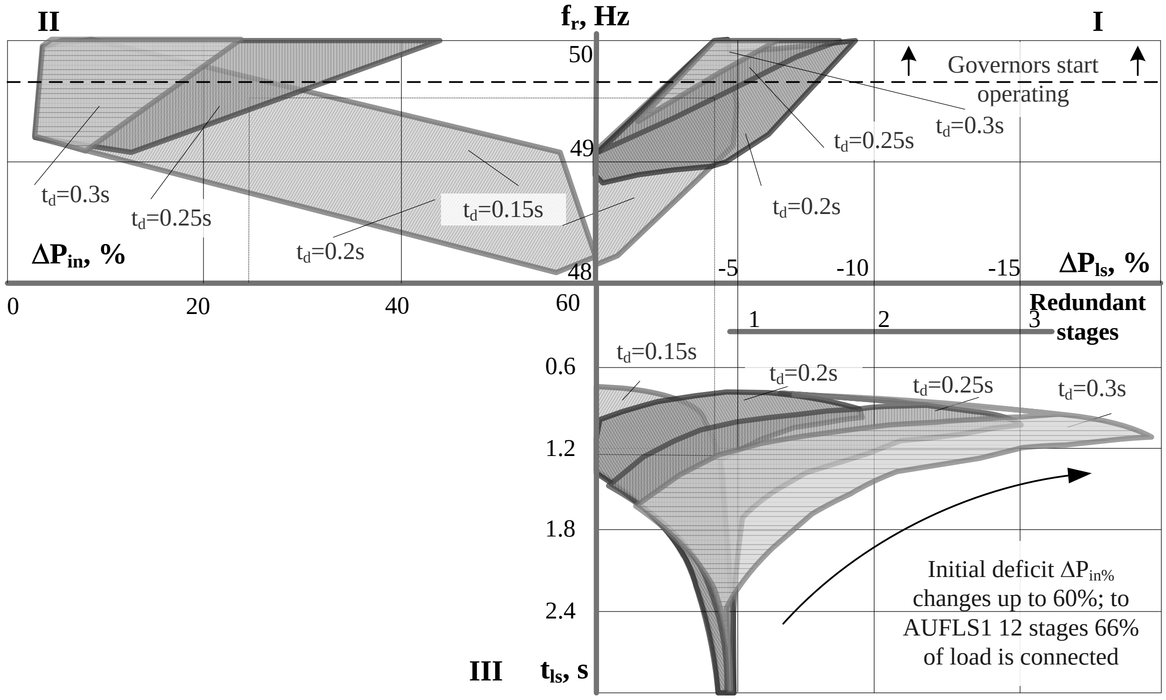


Fig. 3.31. Relationships between the power surplus ΔP_{ls} after operation of the last stage, the frequency recovery values f_r and the operation time t_{ls} of AUFLS1 at different time delays t_d (for deficits up to 60%)

The resultant images (Fig. 3.31 and Fig. 3.32) consist of three quadrants each. In the first quadrant the frequency recovery value f_r is shown in dependence on the power deficits ΔP_{ls} (and the number of stages that have operated non-selectively) after operation of the last stage. The second quadrant shows the f_r value *vs.* the initial power deficit ΔP_{in}. In turn, the third quadrant displays the relationships between the operation time moments t_{ls} and power surpluses ΔP_{ls} after operation of the last stage.

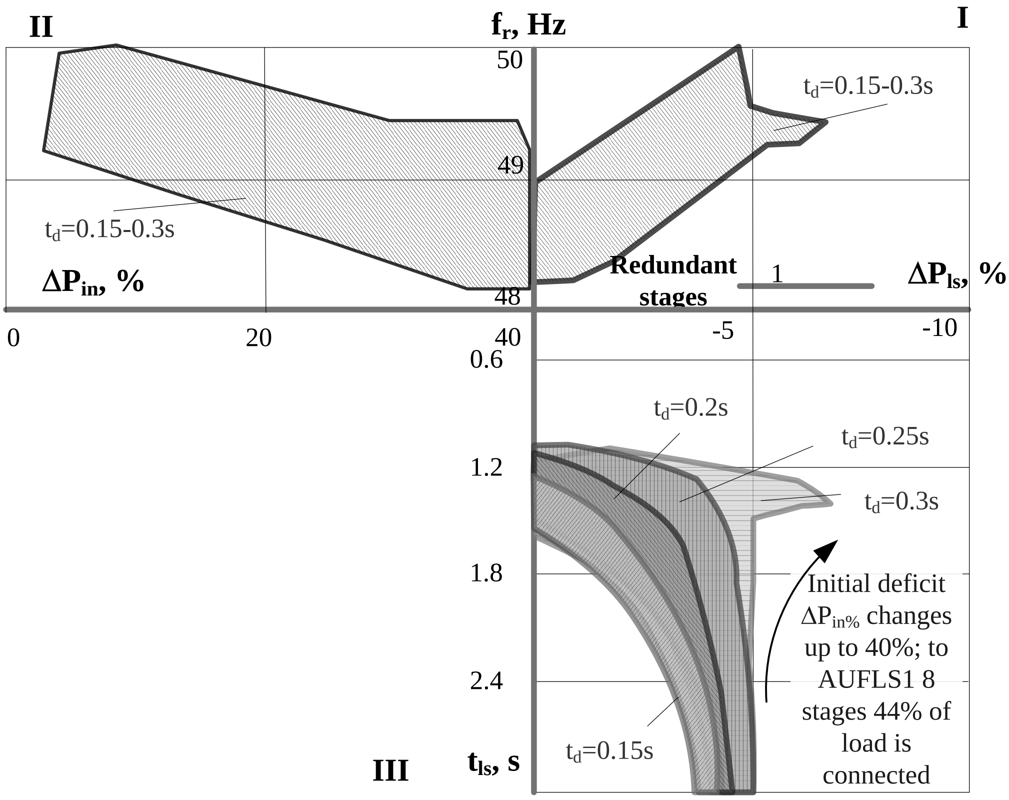


Fig. 3.32. Relationships between the power surplus ΔP_{ls} after operation of the last stage, the frequency recovery values f_r and the operation time t_{ls} of AUFLS1 at different time delays f_r (for deficits up to 40%)

As concerns the frequency levels, from Fig. 3.31 and Fig. 3.32 it could be inferred that a worse situation is for minor deficits, whereas at large deficits it is improved fast, before the operation of slow AUFLS2.

To reduce the non-selectivity of load shedding caused by delays and prevent a deep frequency drop at large deficits, a more suitable AUFLS1 version is used in which individual stages react to the rate of frequency changes [22], [88]:

$$a = \frac{df}{dt} = \frac{1}{T_f} \frac{\Delta P_{\%0}}{k_f} \frac{f_{nom}}{100} e^{-\frac{t}{T_f}} \qquad (3.67)$$

The use of additional stages operated by the rate of frequency changes allows a forced load shedding at large frequency drops thus improving the security of transient process. In turn, the stages reacting to frequency deviations ensure precision and selectivity.

In the cases of small and moderate deficits, after AUFLS1 operation the frequency is kept at a reduced but allowable for power plants level, which retards restoring the normal operation. In turn, in the cases of large deficits to maintain frequency in the range allowable for power plants it is necessary to use the load shedding stages that react to the rate of frequency changes or to the deficit size. To summarise, if the AUFLS1 settings for frequency are selected properly − i.e. with observance of its possible changes and load shedding rates, then the frequency would not come out from the allowable range.

In many power systems the task of restoring the frequency and system integrity is committed to the personnel; this retards elimination of disturbance. To exclude the interference of personnel in the process it is necessary to employ the PS self-restoration mechanism.

The frequency deviations determine to a large extent the discretivity of settings for

load shedding automats, owing to which the number of operated stages depends on the frequency variation rate. The higher rates correspond to greater deficits. Respectively, at greater deficits − after operation of fast-acting AUFLS − the frequency recovery proceeds slower or does not occur at all.

DISTRIBUTED GENERATION BEHAVIOUR DURING BLACKOUTS

Currently, the distributed generation in major power systems reaches many thousands of MW, which influences their operation under emergency conditions to ever increasing extent [7].

The distributed generation plants are linked to the distribution grids, or − in the case of wind turbine parks − to the secondary windings of step-down transformers; these plants operate in a network which structurally is attributable to distribution grids, with their specific configuration and protections; the system operators are unable to control them. Taking into account the properties of grid protection, in the cases of faults in distribution grids the distributed generation units must be fast tripped. After the fault is cleared these units are re-closed and resume the normal operation.

Since the distributed generation is poorly controllable, the only possibility to avoid its negative influence on the major systems' operation under emergency conditions, for the corresponding units the mandatory protection standards have been worked out. Such protections should be able to distinguish between their "own" faults and those occurring in other places.

From the viewpoint of distribution generation, disturbances in a transmission grid could be divided into three groups:

- faults occurring within a distribution grid;
- interrupted voltage supply to a distribution network;
- transmission system's under-frequency emergency with power deficit.

In the first case, the distributed generation plants of the corresponding distribution grid should be tripped.

In the second case, the distributed generation plants of the distribution grid should be tripped by fast frequency decline.

In the third case, the frequency decreases much more slowly, which can serve as the indication that there is no need to trip these plants.

Thus, for example, in the European power system's blackout ([91]; see also Appendix I) at a frequency decline in its deficient part 15 GW wind power plants were tripped, which led to further frequency decrease and consumers' disconnection for its recovery in order to secure synchronisation and system integrity restoration. At the same time, in Denmark due to correct settings the wind turbines were not tripped.

CONCLUSIONS

The cascade processes triggering the blackout development − stability loss, voltage avalanches, thermal and mechanical overload of lines, frequency avalanche or out-of-step operation − cause dangerous deviations in operating variables; as a result, cascade-wise tripping of generating sources occurs. The main task when a blackout is developing is to keep such sources operating, which ensures fast restoration of a power system to normal state.

Analysis of the most often employed protection means reveals their incompleteness. In some cases a power system has no efficient protections − for example, against mass-scale load loss owing to reduced voltage, or against transmission line overload.

The process of cascade-wise blackout development is complicated, and gathers force very rapidly; therefore protection should be fast-acting and preventive, being oriented towards the complete automation of the process.

Of importance is that in power systems the protection complexes exist whose operation principles, after minor correction, could be used for new purposes. By integrating them into the proposed complex a rational protection structure is formed, whose centralised component is responsible for fixing the situation and preparing the conditions for operation of local protections. This solution allows for the use of the accumulated working experience, which would remove doubts about the effectiveness of the new protection complex and overcome the psychological barrier of its implementation.

4. STABILITY OF THERMAL EQUIPMENT AT GENERATING SOURCES

Security of power system operation is to a high extent determined by the reaction of thermal generating sources to frequency deviations under emergency conditions. The opposing reactions of steam-generating plants and steam-consuming turbines to these deviations create conditions for static stability loss, assuming the form of tripping the generating sources. Since the considerations of keeping these sources operational are of primary importance for security of a power system and its subsequent self-restoration, this issue deserves thorough examination. In this section, the interaction of thermal plants is studied, and the methods for system control under reduced frequency are described.

SELF-REGULATION OF A GENERATING SOURCE

The emergency events are characterised by mass-scale tripping of generating sources. Therefore, self-restoration of a power system is possible under the condition that these sources are kept operational. The secure operation of such a source is determined by that of its elements: power boilers, nuclear reactors, steam and gas turbines, as well as auxiliary equipment, and is described by the interaction of static characteristic curves. From the energy point of view, the power boilers, nuclear reactors, and gas turbines are the feeding elements of a power system, whereas steam turbines are its consuming elements.

It is known [24] that every element of a generating source possesses its own character dictated by its physical properties. The capabilities of equipment that are determined by its design specifications and promote the post-emergency restoration of balanced work without external intervention are called self-regulating or self-controlling, which create internal feedbacks of the object (Fig. 4.1a) [64].

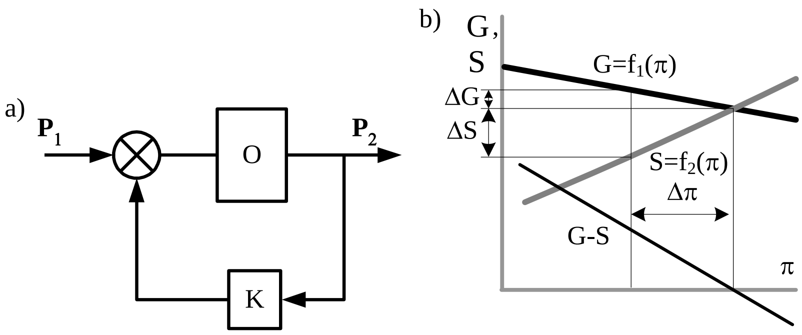


Fig. 4.1. a) The character of feedback in a non- controlled object; b) characteristic curves of an energy object

As seen from Fig. 4.1b, the characteristic generation curve $G = f_1(\pi)$ is a function of an emergency variable designated by π: pressure, frequency or voltage. In turn, the loading dependence on the variable under consideration is characterised by the load curve $S = f_2(\pi)$. The running of a non-controlled object depends on the interaction of properties of both the characteristic curves [92]. Stability is maintained if the following inequality is valid [24]:

$$\frac{\Delta G}{\Delta \pi} < \frac{\Delta S}{\Delta \pi} \qquad (4.1)$$

where G, S are the characteristic values of feeding and consuming elements, respectively. Therefore, we can judge the stability of a generating complex by the condition:

$$\frac{\partial(G-S)}{\partial\pi} < 0 \tag{4.2}$$

In the case when the interaction results in a positive feedback, the operational capability of a plant can be ensured only by automatic control, which compensates for the absence of a natural negative feedback. This situation calls for higher than usual attention and weakens the security of system operation.

In the structural scheme of an energy unit the feedback is important and should be accounted for.

TURBINE OPERATION UNDER NORMAL CONDITIONS

The structural scheme of turbine speed governors is shown in Fig. 4.2 [86]. The frequency variations in power systems are displayed in Fig. 2.7. The frequency variation spectrum contains several components. Speed governors are mostly associated with low frequency variations; since any governor possesses a dead band, to the frequency variations the turbines react for which these variations are beyond the limits of insensitive zone. Therefore to a frequency rise one group of turbines reacts, whereas to a frequency fall – another group. As a result, they keep the frequency in the required zone, which is additionally corrected by the secondary control [93].

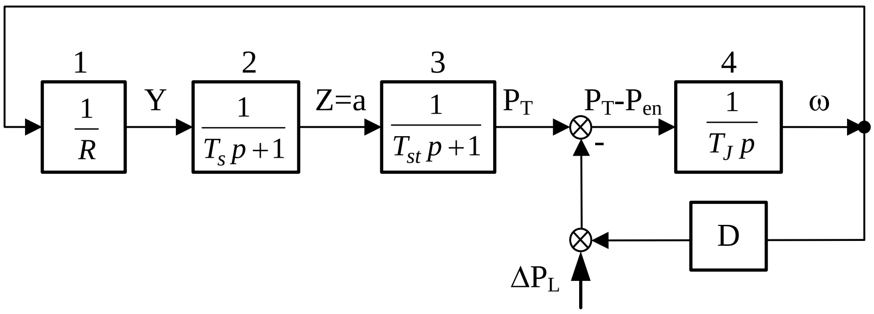


Fig. 4.2. The block scheme of a turbine speed governor

1, 2, 3, 4 –respectively: transient function of the governor, servomotor, turbine's steam volume and generator

The turbine receives power owing to the heat accumulated by boilers; the pressure fluctuations are there smoothed by self-regulation [94], [95]. As seen in Fig. 4.3, load surge (1) proceeds in two stages. The first stage – to the maximum point of curve (1) – takes place at a pressure decrease owing to increased steam consumption when the boiler's accumulating capacities are realised. The second stage is characterised by the consumption decrease and is lasting up to the level shown by intersection of curves (2) and (4), when all the steam load surge is covered by the boiler's output. After that, a steam pressure recovery begins [95].

This process in the case of emergency caused by reduced frequency possesses another character associated with the properties of auxiliary equipment for generating units, to which we relate feed pumps for boilers, compressors for gas turbines, and circulation pumps for nuclear reactors.

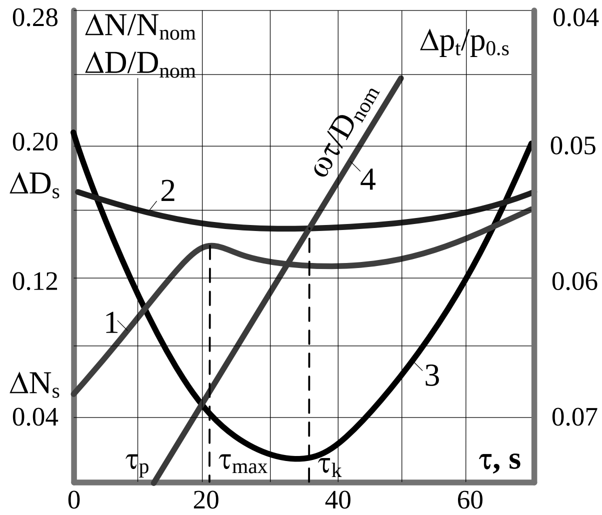


Fig. 4.3. Transient process of load surge:

1– electric load surge; 2 – relative steam load surge; 3 – relative pressure rise; 4 –the boiler steam output rise; ΔN *- the initial load taking up;* $\Delta N_{\max}$ *- the maximum load taking up;* $\tau_{\max}$ *is the time up to the maximum load taking up*

THE PROPERTIES OF FEED PUMPS FOR BOILERS

The most important auxiliary mechanisms are feed pumps for boilers and the mechanisms required for starting and stopping the turbines. The feed pumps supply water, operating against backpressure and opening a shut-off valve. The pump power depends on the rated data of a steam boiler. Thus, for example, the feed pumps of 300MW units have 10÷12MW power, whereas the total power of these pumps serving a high-power (800÷1200 MW) unit is 34÷41 MW [87].

For starting such feed pumps the turbines and asynchronous motors can be employed. If for the control a turbine is used, the rotational speed could be governed, and the output of a feed pump is in this case independent of frequency. However, for this purpose more often high-power asynchronous motors are used; in these cases the output of a feed pump depends on the frequency and is [24]:

$$q = \left(\frac{n_v - n}{n_v - 1}\right)^p \tag{4.3}$$

where n_v is the rotational speed at which, with the pump's pressure decreasing, the boiler's valve returns back; p is the exponent (usually $p<1$):

$$p = \frac{1}{\left(\ln M_v / \ln n_v\right) - 1}. \tag{4.4}$$

with M_v being the torque of a working wheel at the valve opening, pu. For a particular pump [24], at $n_v = 0.812$ and $M_v = 0.35$, $p = 0.247$.

The output characteristic curve can be approximated with the equation (Fig. 4.4):

$$q \approx q_0 - a \cdot n/n_{nom} - b \cdot n/n_{nom}{}^2 \tag{4.5}$$

where q_0 is a constant, and a,b are empirical constants.

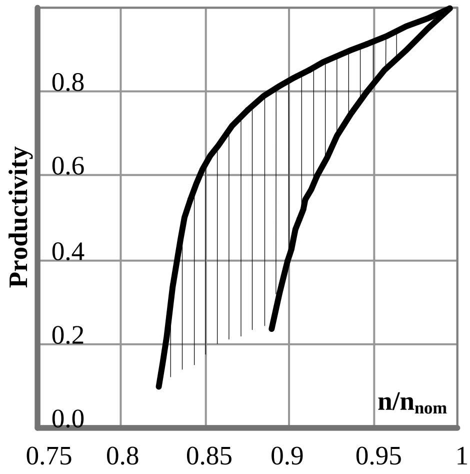


Fig. 4.4. The productivity of a pump working against backpressure in dependence on the rotational speed

Under the conditions of power deficit, at a 7-8% frequency decrease the pump productivity becomes insufficient for the unit's functioning; the steam pressure falls, and, on operation of technological protection, the power plant will be tripped [95]. Taking into account that similar situation is observed simultaneously for several plants, this can trigger a system blackout. The only way out is to use the fast AUFLS for frequency maintenance.

OPERATING CONDITION OF A BOILER-TURBINE GENERATING COMPLEX AT FREQUENCY FALL

The operation of a generating complex is described by the set of characteristic equations of all its elements.

Thus, such equation for the turbine governor is:

$$\Delta f + R\Delta P = 0, \tag{4.6}$$

where $R = (\omega_0 - \omega_{nom}) / \omega_0$ is the speed droop.

Approximation for the feed pump will be:

$$\Delta q \approx \alpha_1 \Delta f + \beta_1 \Delta f^2 \tag{4.7}$$

In turn, the boiler's power dependence on the frequency is:

$$P_b \approx P_0 + c \cdot q \tag{4.8}$$

The process should be made more visual using the nomogram shown in Fig. 4.5, where to the initial condition curve 1 corresponds, and to the emergency one – curve 2. At a frequency decline by Δf, according to (4.6), the turbine power rises by ΔP_t (IV quadrant); at the same time, the yield of the feed pump depending on frequency is decreasing by Δq (I quadrant), which results in a boiler power decrease by ΔP_b (II quadrant) in compliance with (4.8).

As seen from Fig. 4.5, ΔP_t of the turbine as a steam consumer and ΔP_t of the boiler as a consumer of steam generator's power, are changing at frequency drop by Δf in the opposite directions, and, according to (4.2):

$$\frac{\partial \left(P_{k_{(-)}} - P_{t_{(+)}} \right)}{\partial f_{(-)}} > 0 \tag{4.9}$$

These changes result in a pressure fall, to which the technological protections respond by tripping the thermal plants in the stability loss process.

Taking into account that the steam units are the main generating sources whose off-loading enhances the frequency variations, in this case a fast enough frequency recovery by AUFLS is needed. Apart from that, by frequency decline the turbines could be switched to the steam pressure control.

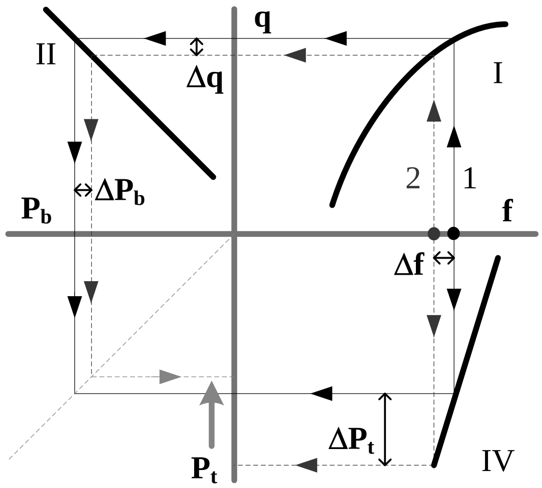


Fig. 4.5. The nomogram for co-operation of boiler and steam turbine:

I quadrant – characteristic curve (c/c) of the feed pump output; II quadrant - c/c of the boiler output; IV quadrant - c/c of the turbine governor output; to the initial condition curve 1 (continuous) corresponds, and to the emergency condition – curve 2 (dashed)

A short-term load relief is required for the steam turbines operating in a combined cycle, since gas turbines react sharply to frequency variations (the application for patent by J.Barkāns and D.Žalostība, [58]).

PROPERTIES OF A GAS TURBINE COMPRESSOR

The influence exerted upon gas turbines by frequency decline is specific. It is known that the running of these turbines is restricted by the temperature of exhaust products in the zone of working wheel blades, which depends on the power. At a low frequency the speed governor of a turbine raises the power in compliance with (4.6). If the speed decreases at a frequency fall, the output of the compressor which is located on the turbine's shaft also decreases [87] (Fig. 4.6).

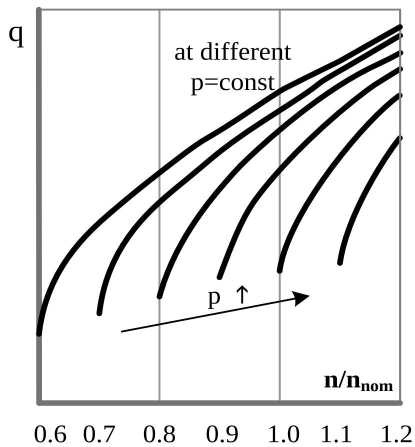


Fig. 4.6. Dependence of gas turbine compressor output on the speed at varying pressure

The dependence of this output on frequency variations can approximately be given by the equation [96]:

$$\Delta q \approx \alpha_2 \Delta f + \beta_2 \Delta f^2 \tag{4.10}$$

where α_2, β_2 are the polynomial coefficients.

The compressor under 1.7 MPa pressure feeds air into the combustion chamber and for cooling down the blade zone. In the zone of a turbine working wheel's stage the air deficit causes a rise in the temperature of exhaust products $\Delta T = f(P, \Delta f)$, to which the temperature control protection responds by tripping the turbine.

In a combined cycle, along with gas turbines, also the co-operating steam turbines are tripped. Thus, for example, in the Italian event of 2003, in under-frequency decline conditions the gas turbines with the total power of 600 MW were switched off, which led to the system blackout triggered by stability loss at thermal plants [97]. A similar event occurred in Australia (the blackout of 2005 [62]).

OPERATIONAL CONDITION OF A GAS TURBINE AT FREQUENCY DECLINE

The running of a gas turbine can be characterised by the nomogram shown in Fig. 4.7, where the initial condition is described by curve 1 and the emergency one – by curve 2. When frequency decreases by Δf, the turbine power increases by ΔP_t (IV quadrant), and the compressor output decreases by Δq (I quadrant); the cooling condition becomes worse, and the temperature rises by ΔT (II quadrant) thus creating the possibility of fault.

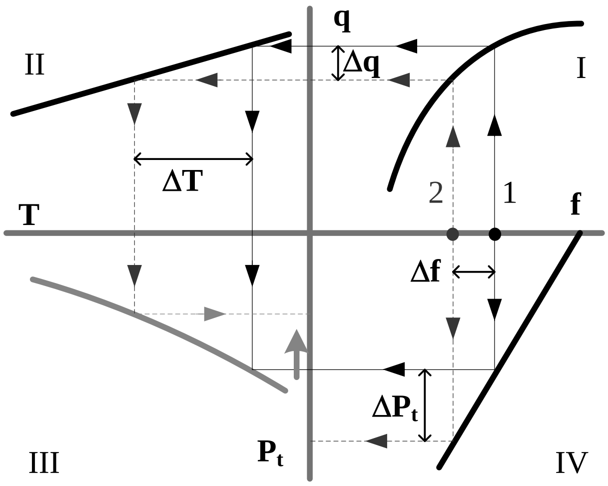


Fig. 4.7. The nomogram for co-operation of gas turbine and compressor:

I quadrant – c/c of the compressor output; II quadrant – c/c of the blade zone temperature variations; III quadrant – the desirable power change; IV quadrant – static c/c of the turbine speed governor: to the initial condition curve 1 (continuous) corresponds, and to the emergency condition – curve 2 (dashed)

The producers of gas turbines make provision for equipment trip in these cases, which under power deficit can lead to a system blackout. To avoid such a situation and keep the generating sources operational, for maintenance of allowable temperature the turbines should be partially off-loaded by frequency drop indications (J.Barkāns, D.Žalostība, patent LV 13944 B, [57]). This, in turn, would affect the frequency, which must be saved by short-term tripping of consumers (with the help of AUFLS). Quadrant III shows the limits of power changes allowed for temperature maintenance to avoid tripping the turbine by protection at the blade temperature rise.

At a combined-cycle generation, as the steam generating element with respect to the steam turbine a gas turbine serves. Under frequency decline a disproportion arises between the steam turbine's and the steam-generating unit's (gas turbine) operating conditions. For matching these conditions the producer-installed automatics is applied, whose algorithms do not contain emergency conditions. From the producer's point of view the main task is to prevent damage of the equipment but not to keep it running under emergency condition. To maintain the gas turbines and therefore the combined-cycle steam turbines functioning under emergency conditions the control should be concentrated on the steam-generating equipment, whereas to the steam-consuming equipment (turbines) a subordinate role should be assigned. For this purpose, by frequency decline, the steam turbines should be switched over to the steam pressure regulation, which would provide a close energy connection of both kind installations (J.Barkāns, D.Žalostība, patent application, [58]). After that, the control should be concentrated on the gas installations, with the aim to prevent deterioration of cooling (J.Barkāns, D.Žalostība, patent LV 13944 B, [57]).

PROPERTIES OF CIRCULATION PUMPS AT NUCLEAR REACTORS

The character of a nuclear reactor's feedback is determined by several operating variables: the demanded power, the active zone temperature, and the steam generation parameters of the reactor. Depending on the reactor type, some of these relationships possess a positive feedback, which puts forward strong requirements as to their exploitation and fast-acting control.

Since there are no, as of yet, converters for high-power circulation motors, these latter do not possess rotational speed control, so their output is frequency-dependent [98]. The circulation of a cooling agent is provided by the corresponding tools: for water – by circulation pumps, and for gas – by circulation fans. The productivity of circulation pumps is directly proportional to the number of turns [24]:

$$q = b \cdot f \tag{4.11}$$

where b is a proportionality coefficient.

A decrease in the productivity causes cooling deterioration and temperature rise in the active zone. In turn, the thermal capacity of a nuclear reactor is determined by the difference between the temperatures of cooling media at the reactor's input and output (Fig. 4.8):

$$P_R = a(T_2 - T_1) \tag{4.12}$$

where a is a coefficient; T_1, T_2 are the temperatures at the reactor's input and output, respectively.

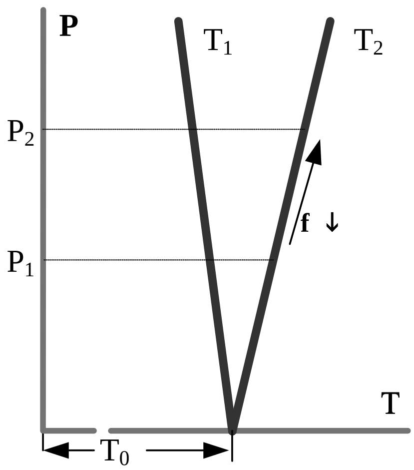


Fig. 4.8. Temperature dependence of power rise in a reactor active zone

If a reactor before the frequency decrease operated with rated load, then owing to frequency deviation at worsened cooling it becomes overloaded, thus causing operation of the protection, which trips the reactor (see in Appendix: the blackout of USA PS in 2003[65]).

OPERATIONAL CONDITION OF A NUCLEAR REACTOR AT A FREQUENCY DECLINE

The nomogram of Fig. 4.9 describes the operational condition of a nuclear reactor at frequency decline. As was mentioned before, at frequency reduced by Δf under emergency conditions the circulation pump output decreases thus worsening a reactor's cooling; this results in temperature rise ΔT in the active zone of the reactor (I quadrant), and its operating variables shift to the zone of higher temperature difference, which causes the output power rise by ΔP_{out} (II quadrant, curve a). If before the emergency a reactor operated at nominal power, under emergency it will be overloaded; since the temperature at the reactor's input changes, the action of its protection will precautionarily follow, tripping the reactor by cooling degradation (as it happened at the Nine-Mile nuclear power plant (USA) in 2003, see Appendix and [65]).

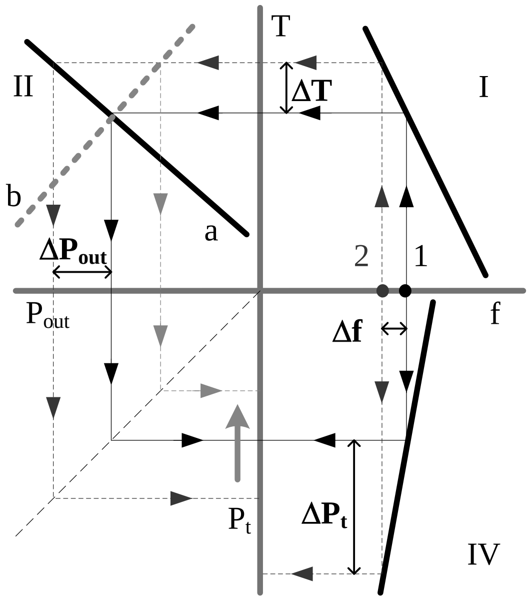


Fig. 4.9. Nomogram of reactor operation:

I quadrant – frequency dependence of circulation unit; II quadrant – factual (a) and desirable (b) power changes at temperature rise; IV quadrant – characteristic curve of the turbine governor output; to the initial condition curve 1 (continuous) corresponds, and to the emergency condition – curve 2 (dashed)

To improve the situation and to keep the reactors operational, by frequency decline indications the turbine should be shifted to the steam pressure control (J.Barkāns, D.Žalostība, patent application, [58]). After that the control should be concentrated on the reactor in order to prevent its overloading due to worse cooling, reducing slightly the power by frequency decline indications [57]. The sought-for power change is shown in Fig. 4.9b in II quadrant of the nomogram.

CONCLUSIONS

Frequency declines under active power deficit create conditions for static stability loss to the thermal units of generating sources, followed by mass-scale their tripping. The situation is especially dangerous in the cases when a frequency decline acquires a protracted character. To prevent such a threat, first of all the steam turbine's reaction to frequency deviation should be accounted for. Therefore, by frequency fall indications the turbine control should be shifted from frequency to steam pressure (“before self” or input control). In this case the turbine is closely linked to the steam-generating unit, obeying the latter’s control up to the time of frequency recovery, thus preventing the static stability loss to the generating sources and keeping them operational. This is especially important for combined-cycle thermal and nuclear plants.

5. SELF-RESTORATION MECHANISM

This section discusses the possibility to integrate the self-restoration mechanism into the new protection complex. This mechanism has so far been successfuly employed for frequency fault liquidation and the main principles of such a solution remain to be valid. Particular attention should be given to the frequency normalisation in both parts of a power system. These issues are considered in detail below.

POST-EMERGENCY FREQUENCY RECOVERY

As was mentioned in Ch.1, the mechanism for frequency fault elimination was worked out in 1963. In the Latvian power system, as in other power systems of the former USSR, blackouts occurred every year, mainly owing to power deficit and weak intersystem links. Jecab Barkans/ (Jēkabs Barkāns), the Chief Dispatcher of Latvenergo, performed classification of emergency events and revealed that all of them proceed identically. As a result, a solution of the problem was proposed according to which the existing fast automatic under-frequency load shedding (AUFSL1) had to be complemented with the following three elements:

- slow-acting under-frequency load shedding automatics (AUFLS2) for restoring the frequency, consisting of several stages with various time delay settings (e.g. 8-10, 15, 20, 25 s, and so on) and with a high setting for start (similar to the first stage setting of the fast-acting AUFLS), which serves for adjusting the retiming setting to the rated frequency after the start. The slow-acting AUFLS2 begins its operation of restoring the frequency up to the normal level after the fast AUFLS1 has been completed its operation (Fig. 5.1);
- automatic re-integration of split parts of a power system at a minor difference between their frequencies, using the available on all lines synchronism-check relays of automatic re-closing (ARC) devices;
- automatic re-closing of consumers' lines by the normal frequency, exerting the control over frequency variations.

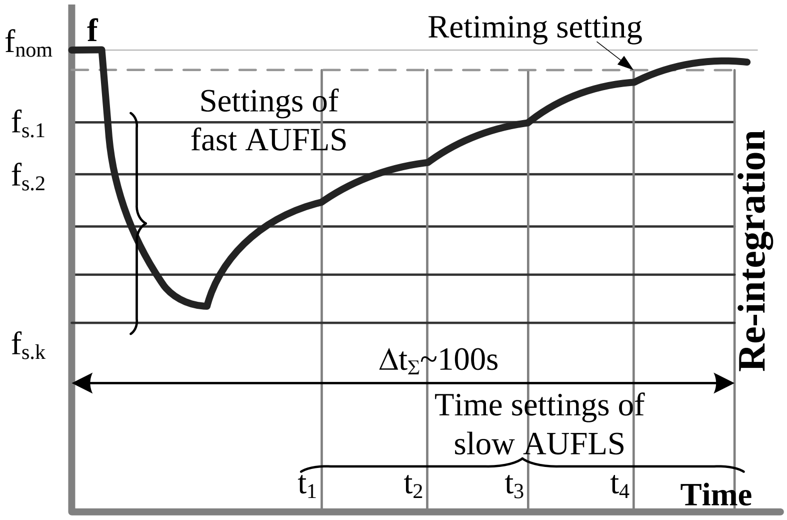


Fig. 5.1. Frequency variations at operation of anti-emergency automatics

Owing to the cooperation of relay protection engineers, it was not very difficult to implement this idea, although this was job of a large scale. For slow AUFLS the existing equipment could be used after minor upgrading, while for consumers' re-closing the standard solutions already employed on the lines turned out to be suitable. The support of relay protection engineers allowed implementation of this idea at the end of 1964. For comparison: before that time the post-emergency system restoration took two hours, whereas the event of 1 October, 1965 was self-liquidated automatically within 100 seconds. In 1967, a series of four emergency events in the Latvian PS occurred in one day; each of them required 100 seconds for self-liquidation. This meant that the frequency avalanche disturbance transformed into an unnoticeable transient process, which could be exploited not only in its direct form but also as the inverted process.

The results of our work published in [5] were appreciated by the technical administration of the Energy Ministry of the USSR, and the key elements were included into its anti-emergency guiding instructions, which secured a wide implementation of our solutions in the territory of Soviet Union. In Latvia, since 1965 this system had operated about 20 times until a reliable inter-system network was built.

SELF-RESTORATION THROUGH FREQUENCY FAULT LIQUIDATION

While applying the mechanism of self-restoration, two most important its properties emerged:

First, owing to a short time of fault self-liquidation this proceeds unnoticed for the majority of consumers.

Second, owing to perfection of the frequency automatics and its newly-introduced slow load relief, the automatic synchronisation and the automatic re-closing for consumers, a frequency disturbance from a dangerous blackout threat for a power system has become the means for its self-restoration to normal state.

Despite the inclusion of this conception into guiding instructions and the experience of its many-years' successful exploitation, this has not been investigated thoroughly. Therefore, one the purposes of the present work was to study the issues associated with frequency normalisation in separated system parts, their automatic re-integration and electricity supply resumption.

REQUIREMENTS FOR SLOW LOAD SHEDDING AUTOMATICS

For slow AUFLS the settings of 5-15 s are specified in order to eliminate over-regulation. To ensure the frequency recovery to the normal value for re-integration purposes, the slow load shedding automatics is provided with automatic change of the retiming setting after simultaneous starting of the protection stages. This is performed through the action on the frequency setting timer using the starting signal (Fig. 5.1).

In compliance with the chosen conception, the operation setting for slow AUFLS2 is a tool for triggering the self-restoration mechanism. The frequency for such operation should be chosen slightly lower than nominal, which cannot be done under normal conditions.

ADAPTIVE FREQUENCY LOAD SHEDDING AUTOMATICS

In this chapter, proposals are set forth that concern upgrading of AUFLS in order to achieve faster frequency recovery by its specific reaction to frequency deviations.

5.1.1. Adaptive AUFLS with dependent time delay

To reduce the influence of time delay on the frequency recovery process as well as to provide sequential tripping of important consumers, the AUFLS with dependent time delay can be used [99], which would integrate the AUFLS1 and AUFLS2 functions. The load shedding stages will be started if the frequency decreases down to the starting frequency, after which the changes in the operation of stages begin according to the characteristic curves whose shape is close to that of frequency variation with time (Fig. 5.2).

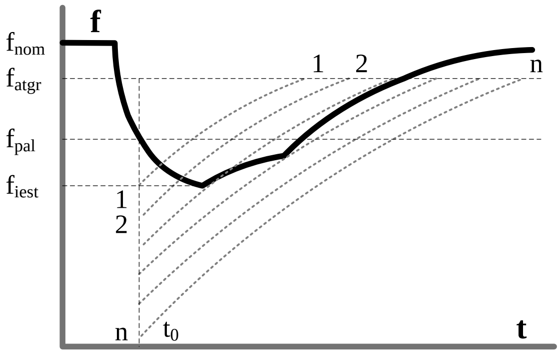


Fig. 5.2. The frequency variation at operation of AUFLS with dependent time delay

As seen in Fig. 5.2, the stages with lower frequency possess smaller operation time.

5.1.2. Adaptive AUFLS with settings of frequency and frequency rate variations

According to the proposal set forth in [100], the settings of the load shedding automatics respond not only to a frequency deviation but also to the rate of its variation (Fig. 5.3).

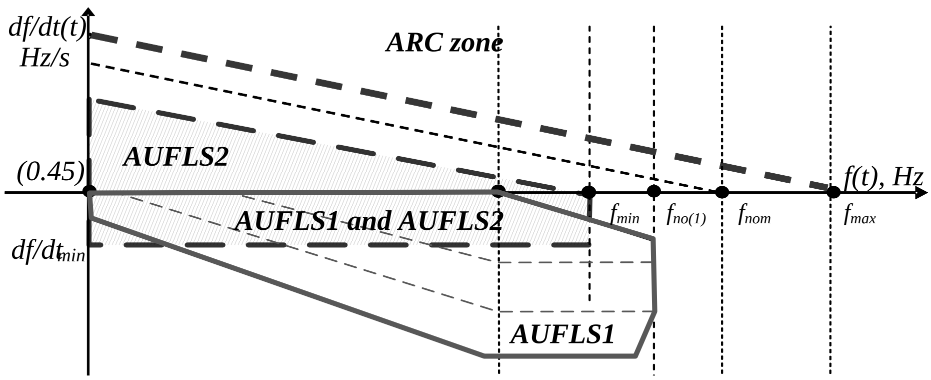


Fig. 5.3. Operation zones of adaptive AUFLS settings

AUFLS1 - zone of power deficit liquidation; AUFLS 2 – zone of the frequency recovery process; ARC – consumers' automatic re-closing (dynamic control)

Taking as an example the Italian blackout [100], [101] (deficit 24%, inertial constant 14 s, load factor 1.6), the frequency variations applying different AUFLSs were modelled; the results are shown in Fig. 5.4.

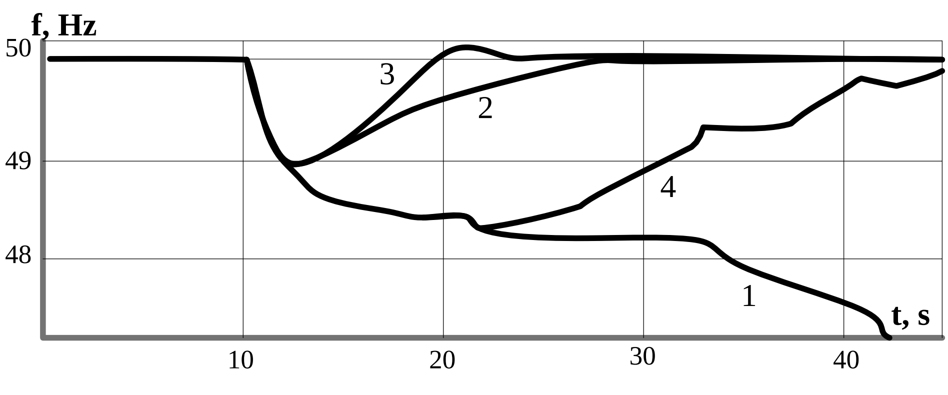


Fig. 5.4. The frequency variations at operation of different AUFLSs

1 – frequency variation under fault; 2 – frequency variation at the use of adaptive AUFLS without dynamic control; 3 – the same with dynamic control; 4 – frequency variations at operation of AUFLS 1 and AUFLS 2

As seen in Fig. 5.4, the use of adaptive load shedding automatics makes the process of frequency recovery faster and more precise (see curves 3 and 2) and allows achieving this within ~ 8-18 s.

5.1.3. Two-level adaptive AUFLS

Publications [46]-[50] contain a proposal to include into the anti-emergency complex a two-level adaptive AUFLS system, which, depending on the deficit extent, uses the principle of load shedding automatics response either to the frequency deviation in the case of small deficit or to the rate of its changes at large deficits (Fig. 5.5).

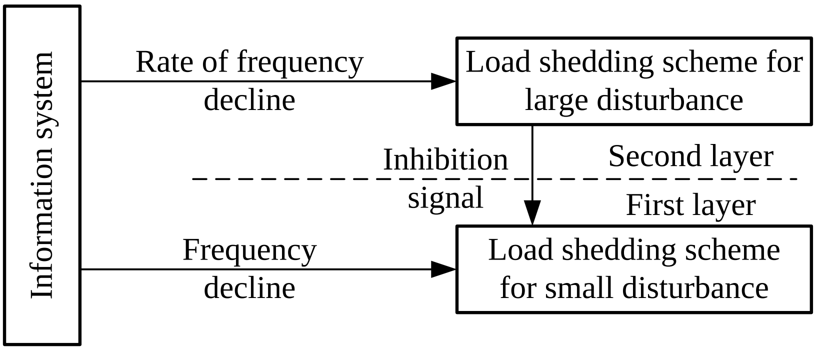


Fig. 5.5. A two-level model for the load shedding scheme

The system has been tested using a 179-busbar model with 29 generators. When the start of a fault is fixed, after 0.2s the power system is split. Depending on the power deficit, the first- or second-level scheme of load shedding is applied.

FREQUENCY CHANGES AT POWER DECREASE

After splitting, in the system part with power surplus a rise in frequency occurs, where, as distinguished from its deficient part, the speed governors are operating. Assuming a simplified scheme of the processes (see Fig. 4.2), the transient function and characteristic equation could be written in the following way [86]:

$$\frac{\omega(p)}{\Delta P_L(p)} = \frac{R(T_s p+1)(T_{st} p+1)}{R(T_s p+1)(T_{st} p+1)(T_j p+D)+1}$$

$$T_s T_{st} T_j p^3 + \left(T_s T_{st} D + T_{st} T_j + T_s T_j\right) p^2 + \left(D\left(T_s + T_{st}\right) + T_j\right) p + D + 1/R = 0 \tag{5.1}$$

where ΔP_L is the load change, p is the Laplace operator, R is the speed droop, D is the load-damping factor, T_s, T_{st}, T_j are, respectively, time constants of the servomotor, the turbine's steam volume and the rotating mass (inertia), seconds (for example, in [86] the following typical average values are given: $T_s = T_{st} = 0.25s$, $T_j = 10s$).

The coefficients of the characteristic equation at the 3rd and 2nd powers of operators are numerically by an order of magnitude smaller than those at lower power operators. Applying the small parameter method, the transient process is mainly determined by the rotating mass constant, turbine speed droop, and the load-frequency dependence. Then the constant of a frequency rise process will be:

$$T_f = \frac{T_j}{D+1/R} = R_s T_j \tag{5.2}$$

where R_s is the PS speed droop.

In practice, the process has an exponential (and, consequently, non-periodical) character (Fig. 5.6).

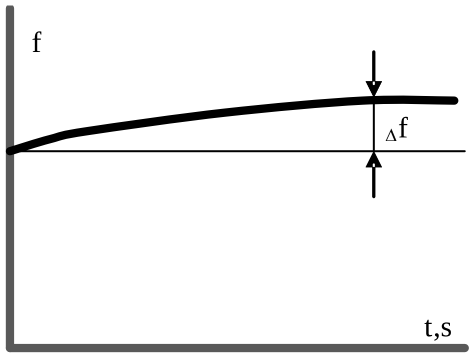


Fig. 5.6. The frequency behaviour under power decrease conditions

The frequency rise triggered by load loss is an important pre-requisite for the following synchronisation process and can be written as:

$$\Delta f = \frac{\Delta P_L}{1/R_s + D}\frac{f_{nom}}{P_s} \tag{5.3}$$

where ΔP is the load change, MW; P_s is the system power, MW; R is the speed droop; D is the load-damping factor, 1/%.

Thus, for example, if the system power is 20 GW and the load loss is 1 GW, then its specific weight (surplus) in the total power value is 5%; In turn, at $R = 5\%$ and $D = 2$ the frequency will rise by $\Delta f \uparrow = 1/(2 + 1/0.05) \cdot 5 = 0.227\%$ or 0.1135 Hz.

NORMALISATION OF THE FREQUENCY LEVEL BEFORE RE-INTEGRATION

For successful synchronisation it is necessary that the difference of frequencies in the split system parts is as small as possible. In the part with power surplus the frequency might be slightly elevated, which could retard the synchronisation process. A similar situation (an elevated frequency) can be settled in the deficient part if during the load shedding, as a result of non-selective AUFLS1 operation, too large number of consumers become tripped. Such being the case, for frequency normalisation a local forcing of its secondary control could be used with the aim to speed up the transition to the normal frequency (J.Barkāns, D.Žalostība, patent LV13881 B [55]). To do this, by frequency rise indication the speed governors of several turbines are forced up to the normal frequency level using the scheme shown in Fig. 5.7.

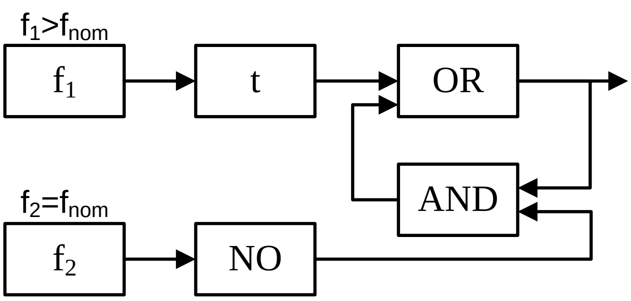


Fig. 5.7. Scheme of forcing the secondary control

In this figure, f_1 and f_2 stand for the elevated and nominal frequencies; t is the time delay element at the output of which a pulsed signal appears; and logic elements NO, OR, AND. The frequency rise is fixed by f_1 element, which by a pulsed signal activates the OR element to change the turbine's setting thus promoting frequency normalisation. This element, having a pulsed signal from t element, remains operated on receiving the input signal from its output through AND element; this latter receives both the input signals since f_2 element by that time has not operated. As soon as f_2 has operated, the signal from NO element disappears, and OR element returns to the initial position, with its action on the speed governor setting interrupted. The forcing is short-term, since after re-integration the normal running of the turbines is resumed by nominal frequency indication.

The forcing of secondary control can be performed under integral control as shown in Fig. 5.8, where k_{r2} is the amplification coefficient, and T_{2r} is the integration time constant.

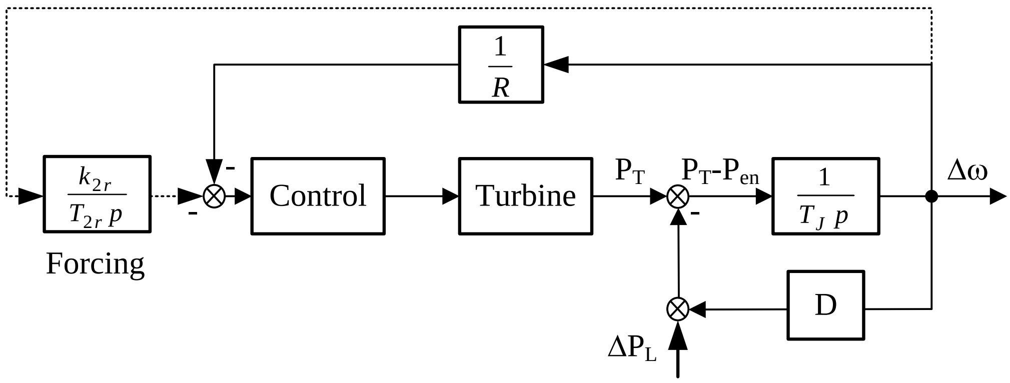


Fig. 5.8. Block scheme of forcing the secondary control

For modelling the secondary control forcing, the *Matlab Simulink* program was used. This is illustrated by Fig. 5.9, where curve *1* for the governors operating in a system part with surplus ($T_j = 10s,\quad D = 1.5,\quad R = 5\%$) shows: (a) frequency rise to 50.12 Hz at 5% load loss; (b) frequency rise to 50.23 Hz at 10% load loss, which can retard the automatic synchronisation. Using the proposed solution in the integration domain at $T_{2r} = 2s$ and $k_{r2} = 4 - 5$, the frequency is normalised in the time of 30-35 s (curve *2*).

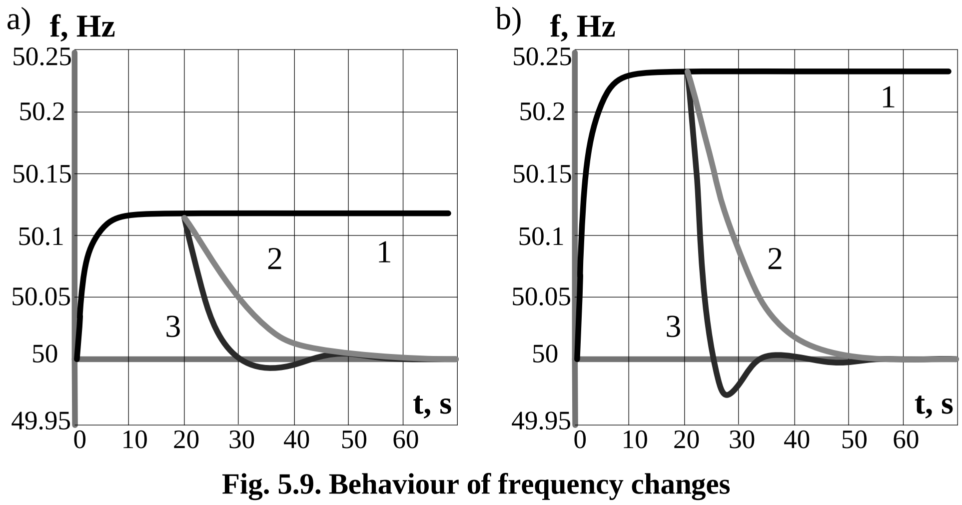


Fig. 5.9. Behaviour of frequency changes

a) 5% excess; b) 10% excess: 1 – without forcing; 2 – with forcing; 3 – over-regulation

In (a) variant, at the beginning the frequency change rate is 8mHz/s, and in (b) variant – 15mHz/s, which allows for synchronisation with the help of synchronism-check devices. At these coefficients the process stability is preserved if the speed droop variations are in the range 5-8% at $T_j = 8 \div 10s,\quad D = 1.5 \div 2$.

The over-regulation at greater k_{2r}/T_{2r} ratios is removed approx. within 25 s, which is shown in Fig. 5.9 with curve *3*: a) for $k_{2r}/T_{2r} = 5$ and b) for $k_{2r}/T_{2r} = 10$.

SELF-RESTORATION MECHANISM IN THE NEW CONCEPTION FRAMEWORK

The fault liquidation and self-restoration proceed in a fast and controllable manner, which thus can be considered as a stable transient process. Therefore, this method can be used for elimination of other disturbances leading to blackouts, e.g. to eliminate a dangerous grid overload by short-term sectioning of a power system with its subsequent automatic self-restoration.

The scheme of self-restoration mechanism functioning is shown in Fig. 5.10. When a system is split as was mentioned above, in one its part a power deficit and a frequency decrease take place, while in the other – a power surplus and a frequency increase.

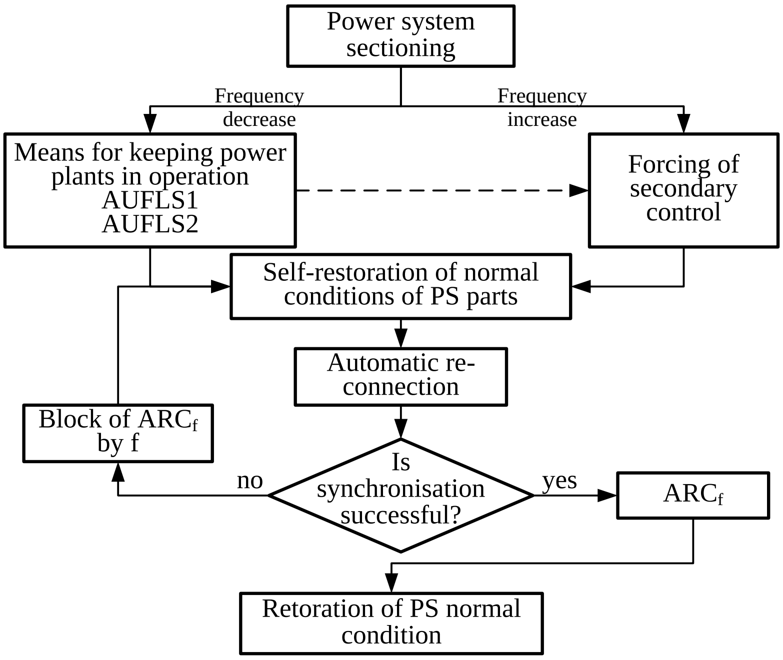


Fig. 5.10. Local systems with feedbacks in the self-restoration mechanism

Under the conditions of a short-term frequency decrease, in addition to the frequency load shedding automatics the special measures described in §4 should be taken for holding the generating sources operational. The elevated frequency is normalised by forcing the secondary regulation, thus creating favourable conditions for automatic synchronisation (considered in §7). When the system integrity of the power system and the carrying capacity of the grid are restored, a step-by-step consumers' automatic re-closing with frequency control (ARC$_f$) is performed. Therefore, owing to local systems with feedbacks the fault self-liquidation can be done fast.

CONCLUSIONS

From the considered above it is obvious that the frequency recovery and its equalising in both the separated parts of a power system create pre-conditions for its automatic self-restoration, which proceeds within ~100 seconds and remains unnoticed for most of the consumers. By directing the development of a blackout towards a frequency fault it is possible to ensure its fast elimination.

6. THE PROTECTION COMPLEX AGAINST BLACKOUTS

CHOICE OF THE STRUCTURE OF THE PROTECTION AND SELF-RESTORATION AUTOMATIC COMPLEX FOR ELIMINATION OF SYSTEM BLACKOUTS

6.1.1. Requirements to the protection complex against blackouts

The protection and self-restoration automatic complex intended for elimination of power system blackouts has to execute the following functions:

to effectively remove a dangerous overload of a transmission grid cross-section;

- to provide fast actions of the protection at performing the preventive functions;
- to simultaneously trip of all transmission lines of the cross-section at the system splitting;
- after off-loading, to provide that the grid cross-section remains operational, preserving as much as possible its carrying capacity thus minimising the sheddable load;
- to involve local systems with feedbacks into the fault elimination process using the self-restoration mechanism;
- to attentive to the psychological aspects of implementation (simple principles of operation and adjustment), using to the greatest extent the known and proved efficient means for new purposes.

6.1.2. The centralisation level of the control system

Examples of successfully and unsuccessfully operating control systems could be met in the nature as well as in economic and technical activities. It is known [5], [29] that the excessively centralised (total) control systems are difficult to implement and, besides, inefficient; at the same time, the systems with optimal structure of centralised and local elements (terminals) have proved to be efficient. Classification of the control methods [12], [24] gives the following two groups: control by deviation and by action. For the former, the use of feedbacks is characteristic, which ensures high precision and reliability. However, to employ the properties of feedbacks, in each following action the dynamics of the preceding process should be observed, for which certain time is needed, which is absent when the actions should be taken fast. In such cases it is necessary to resort to the control by action, which is usually centralised for ensuring high speed of operation. From the viewpoint of creation of an optimal control structure, the task of a centralised control system element is to activate the feedbacks of terminals. In this case the following run of the process should be delegated to the local system elements, which are capable of functioning accurately without external interference.

6.1.3. Structure of the protection complex against blackouts

Based on the analysis of blackout processes it could be concluded that these are triggered by faults occurring in particular places of a power system, with the following cascade-wise propagation throughout the whole system. As a rule, an emergency process begins with tripping of the grid elements, which creates the unallowable overload in the dangerous cross-sections. After that, for various reasons, a mass-scale tripping of generating sources begins.

Such situations give rise to tripping of mutually dependent or independent system elements. Relatively rarer are situations when simultaneously a group of elements are tripped owing to busbar faults or circuit-breaker failures. Busbars are usually safeguarded with fast-acting differential protection. When it fails, the load re-distribution among the same or lower voltage lines occurs. Such being the case, it is necessary to remove overload from these lines.

In the case of a circuit-breaker failure, the busbars are switched off by their backup protection (SBA); during its operation, the dynamic stability requirements must be fulfilled. The situation is worse in the cases of a protection failure, when busbars are tripped by the protection of the opposite line side (in the major objects the problem is solved by providing circuit-breakers with doubling protection).

To prevent the spread of an event bringing threat of blackout, special countermeasures should be taken to keep operating the lines of overloaded cross-section (with as large as possible power flows) and the generating sources. Applying the optimal short-term system splitting (sectioning) at the cross-section through which the power close to the overload is flowing, the grid remains operational, with loaded (but not overloaded) transmission lines; that is, secondary faults potentially leading to blackouts are in this case prevented. This action should be fast and simultaneous for several objects of the cross-section, which determines the regionally-centralised character of such protection. In particular cases, when the number of lines in a cross-section is limited, the control system can be of local character. The information about the overload extent and splitting place can be sent through fast-acting communication channels in the form of logic signals. The structure of the proposed complex is shown in Fig. 6.1.

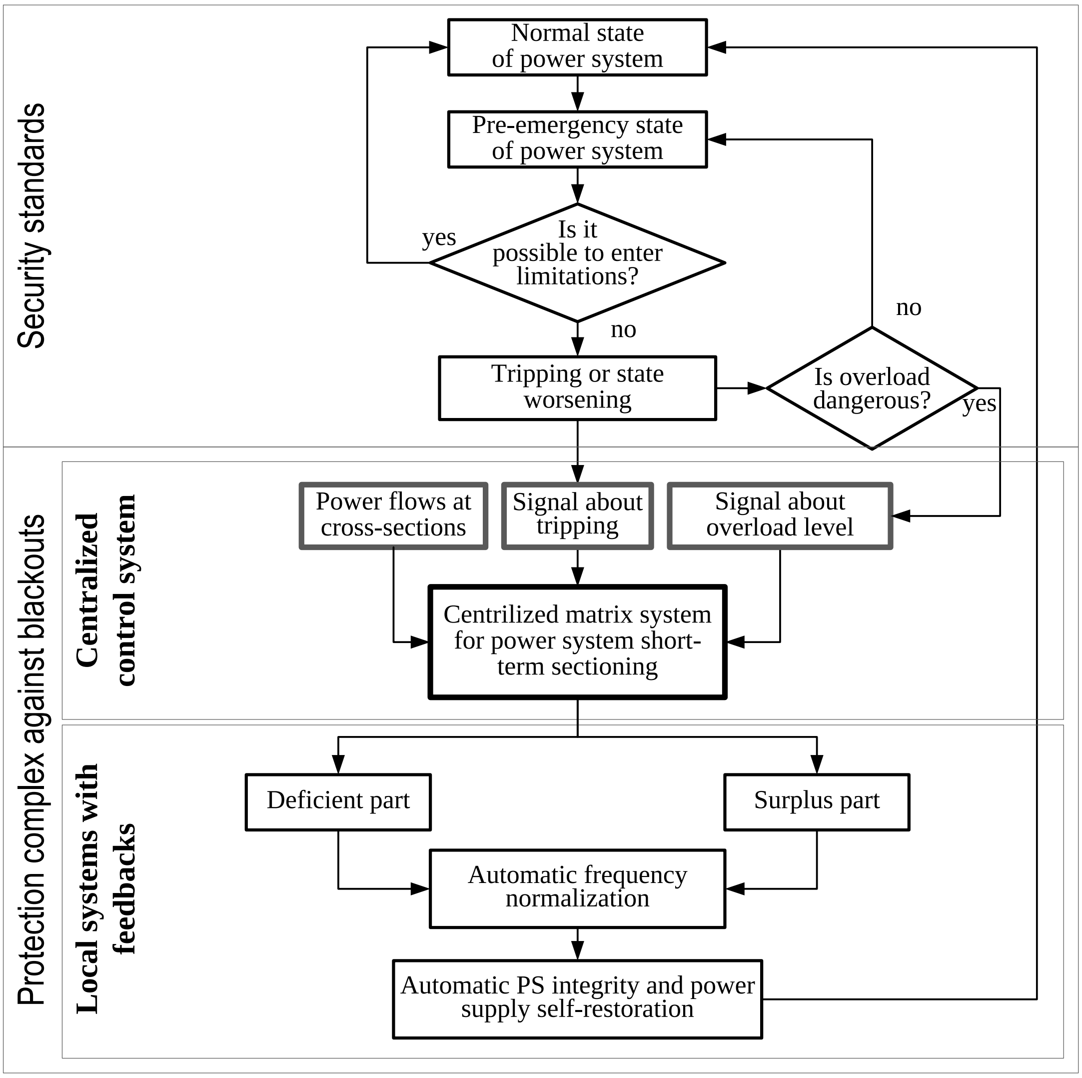


Fig. 6.1. Structure of the proposed anti-emergency complex

The task of centralised control is to involve into the process the existing local systems with their inherent feedbacks providing a high reliability. The above mentioned mechanism of system self-restoration via frequency fault removal ensures the full – or in some cases a partial – its restoration to the normal state.

Employment of local automatic systems relates to both parts of a system: in one of them a power decrease occurs, whereas in the other – its increase. In the system part with power excess the speed governor of turbines maintains the frequency level, and in its deficient part the same result is achieved using the under-frequency load-shedding automatics. If necessary, for frequency normalisation the described above forcing of secondary control should be used. Further run of the process depends on the restoration of the grid carrying capacity as a result of automatic re-closing the transmission lines. After that, within approximately 100 seconds the power system integration follows, with automatic re-closing of tripped consumers' lines. In the case the desired carrying capacity has not been restored, the process of consumers' re-connection delays until the situation normalises.

In order to raise the reliability of the centralised control system its functions should be the narrowest possible. In the case when prevention of transmission grid's overload is performed by splitting the power system into parts at the cross-section place the power flow through which is closely corresponding to the overload, then the centralised complex functions are to be limited – even to the point that we should give up some calculations (see the patent of J.Barkāns, D.Žalostība LV 13913 B, [56]). The information on the overload place and extent can be obtained from the discrete setting levels in the form of logic signals using fast-acting communication channels (see the mentioned patent [49]); in a similar manner, sending the necessary actions to the splitting addresses should be organised.

In the major power systems the splitting can sometimes be performed at pre-defined places (J.Barkāns, D.Žalostība patent LV 13881 B, [55]); this permits giving up the action addressing through branched channels, which would simplify the protection complex. Taking into account that blackouts occur rather seldom and their development, using mentioned proposals, could be stopped fast (although with short-term tripping of the greater consumers' amount), such sectioning at a pre-defined place should be considered possible, especially for major power systems with deficits incomparable with their overall power.

OPTIMAL REMOVAL OF OVERLOAD IN GRID CROSS-SECTIONS

In the case when a grid cross-section is overloaded owing to emergency disconnection of a loaded line, in the protective method of line overload elimination the preventive centralised matrix-shaped structure [12] is used. As distinguished from the conventional, the centralised structure is intended for a new purpose – overload removal using the short-term system sectioning in the place through which the power corresponding to the network overload level is flowing (J.Barkāns, D.Žalostība, patent LV-13772B [54]). By this, a load relief in the cross-section is performed, owing to which it remains operational, with its carrying capacity retained.

Since the dynamic stability can be lost within seconds, the protective actions must be fast. The task is solved using a two-parameter matrix-shaped structure (see Fig. 6.2a).

The first parameter of the proposed matrix is the power flow over a dangerous cross-section as the indicator of the operating condition severity. It is monitored continuously under normal operation, simultaneously using the system's mathematical model for calculation of the grid overload when one of its elements is tripped. The corresponding values are fixed as the places of optimal sectioning under emergency conditions. The second parameter is the signal about an element's tripping, which arrives by a fast communication channel. This means that the protective action coincides in time with the first element's emergency disconnection. The matrices correspond to a definite structure of the grid cross-section. When this structure changes, a change in the matrix scheme follows (Fig. 6.2b).

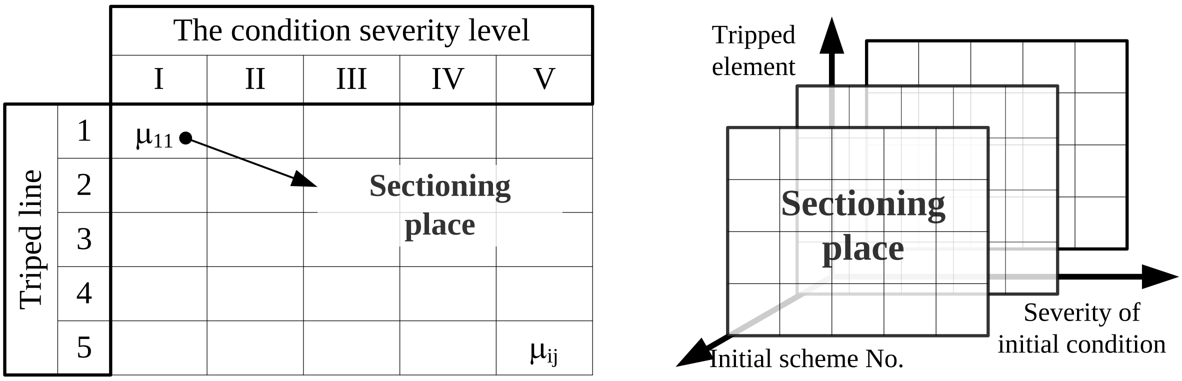


Fig. 6.2. A matrix of PS sectioning places

DETERMINATION OF THE SECTIONING PLACE

The splitting place can be determined assuming in the mathematical model a virtual generator at the power receiving end, where the power is regulated in such a way that its flow through a cross-section is close to the maximum allowable. In this case the splitting place corresponds to the power convergence point (Fig. 6.3) (J.Barkāns, D.Žalostība patent LV 13663 B, [53]).

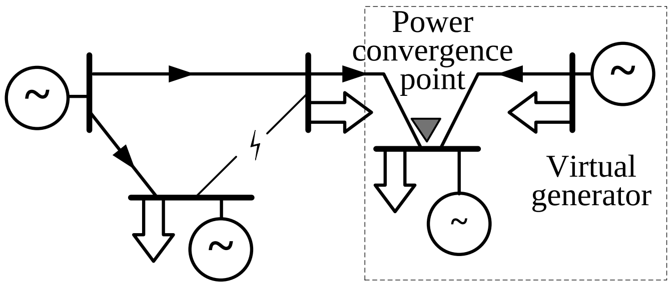


Fig. 6.3. Choice of the optimal splitting place

The optimal splitting is provided by monitoring under normal condition the power flows in the zone of possible splitting.

OPTIMAL SECTIONING WITHOUT A MATHEMATICAL MODEL

As distinguished from the method described in §0, a solution free of complicated calculations deserves attention (J.Barkāns, D.Žalostība patent LV 13913 B, [56]). This solution requires that the centralised protection receives through the logic channel a signal characterising the extent of grid overload (Fig. 6.4).

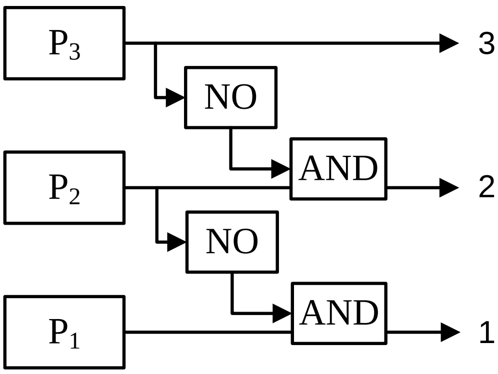


Fig. 6.4. The logic scheme of protection with multi-level settings

Task of the kind is fulfilled by local protection with power settings of several levels so that the action of the highest setting and the transfer of a proper signal are provided. Such a signal is marked with the transfer address(es) and the number(s) of setting level.

In this case to the centralised matrix-shaped structure a scheme of Fig. 6.5 corresponds with the following two parameters:

- factual grid overload ΔP fixed by a cross-section's protection ($\Delta P = P_{fact} - P_{\max}$ where $P_{fact}, P_{\max}$ are, respectively, the power value determined by protection and the maximum allowable its value, which can be considered constant);
- power flows in the cross-sections behind the overloaded grid part in the flow direction, which are determined in real time by the initial system state before the emergency.

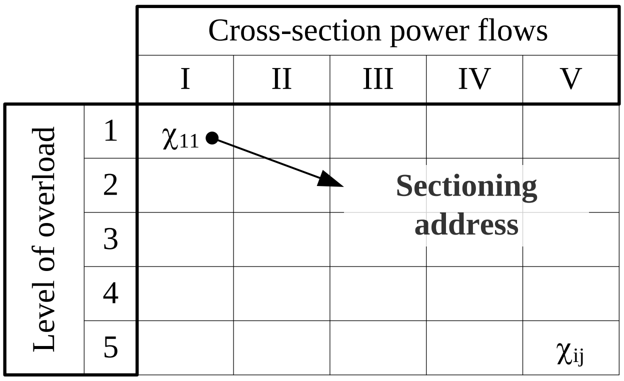


Fig. 6.5. Matrix of sectioning addresses

To every overload level a cross-section corresponds in which the splitting should be performed. When protection has operated, over a communication channel the command on tripping is sent to the cross-section place with the power flow close to ΔP, which corresponds to the least tripping of consumers. In such a way the overload is removed, with the cross-section's carrying capacity kept operational. Thus both the dynamic stability loss and the voltage avalanche initiation are eliminated. If signals arrive over several channels they are summed up. A simplified algorithm of the centralised system's operation is shown in Fig. 6.6.

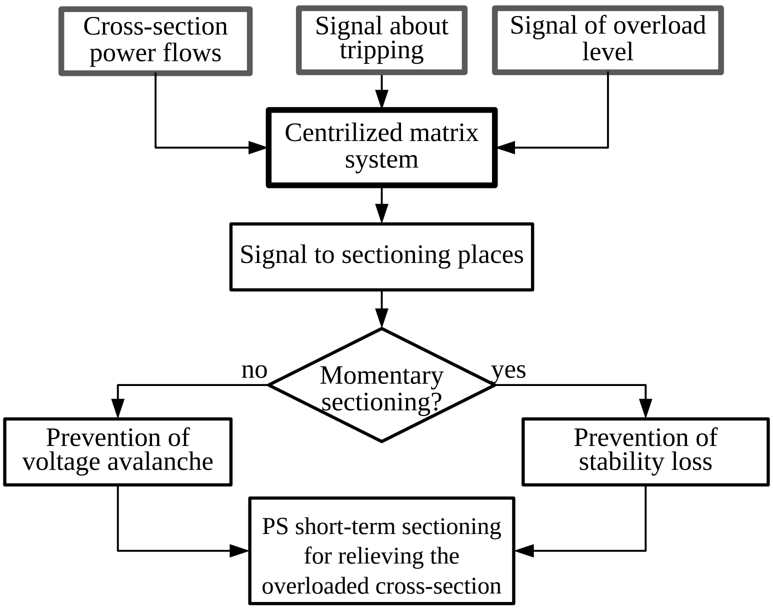


Fig. 6.6. A simplified algorithm of the centralised system operation

The speed of protective actions is dictated by a signal about the tripping of a grid element. This signal evidences that the grid overload can lead to the loss of dynamic stability, which means that the protection should be fast-acting. At the same time, if such a signal is absent, then a voltage avalanche could be expected, and the protection, for the sake of higher reliability, can act with a time delay, since the overloaded generators will be tripped in the 10-20 s time.

INFORMATION FOR THE PROTECTION AGAINST POWER SYSTEM COLLAPSES

The protection against PS blackouts needs centralised information, which could be provided using the real-time mathematical model of the power system. For this, the following tasks should be fulfilled:

1) To estimate the system condition (including the measurement errors removal);

2) To determine in real time the maximum allowable power flows through dangerous grid cross-sections, observing the (n-1) principle at tripping of one element.

3) To obtain instructions in the pre-emergency conditions when urgent countermeasures are to be taken for prevention of cascading emergency development.

4) To control automatically the power flows over the dangerous cross-sections (known beforehand), and to determine preliminarily, under normal conditions, the overload extent in dependence on the real power flow for different lines at their tripping, entering into the memory the type of action.

CONCLUSIONS

Based on the proposed principles and conception, it is possible to introduce into practice the worked out protection and self-restoration complex for blackout prevention. By short-term sectioning of a power system, the overloaded grid cross-section can be fast relieved to the allowable level. Such splitting creates in one system part a short-term decrease of power, while in the other – its increase by the same amount. The emergency situation can be liquidated within ~100 seconds with the help of the advanced self-restoration mechanism. The use of local systems with feedbacks ensures its high reliability and precision.

Different techniques of sectioning and the possibility to employ already existing solutions make the complex simple and easy to introduce.

7. POST-EMERGENCY AUTOMATIC RE-INTEGRATION OF A POWER SYSTEM

The re-integration of a power system is an essential element of its self-restoration. If this task is executed by staff, complicated switchings are required at manipulations with the devices for synchronisation, which retards the process inadmissibly. Since blackouts occur rather seldom and the frequencies in both parts of a split power system are equalised fast, it is admissible, as an exception, for its post-emergency re-integration to use the synchronism-check relays of automatic re-closing devices already existing on the lines. The aim of this section is to show the possibilities for application of this approach in the framework of the proposed protection complex against blackouts.

TRAJECTORIES OF THE RE-INTEGRATION PROCESS

Based on the V.Hachaturov investigation into the non-synchronous switchings-on in a power system [63], a transient process of synchronisation can be described in a simplified manner, using phase plane trajectories in the ($\delta;\Delta f$) system of coordinates. These trajectories are defined by specific system and switching-on parameters: the turbine torque, the synchronous and asynchronous torques of the generator (the damping and excitation effects), the motion acceleration of PS parts, and the switching-on angle [102].

As seen in Fig. 7.1, the limiting trajectories narrow the successful synchronisation domain: trajectory (2) is limited by δ_{max} − the angle maximum allowable in a transient process from the viewpoint of voltage decrease, and trajectory (3) − by practically used switching-on angles [103]. The synchronization is successful in the case when the switching-on point ($\delta;\Delta f$) is located in the coordinate system's area limited by boundary trajectories (2), (3).

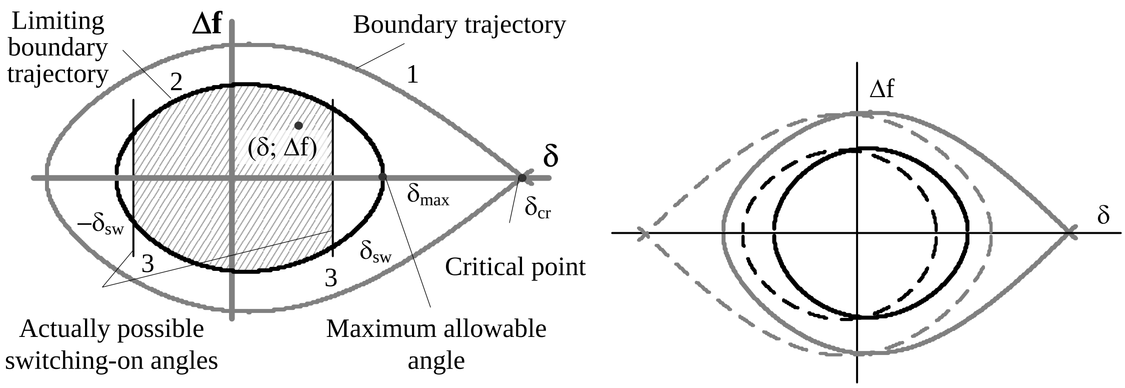


Fig. 7.1. The phase trajectory of a system with acceleration

(1) boundary trajectory asymptotically approaching the equilibrium-unstable or critical point, i.e. $s \to 0, \delta \to \delta_{cr}$, and separating the stable and the out-of-step system states; (2) and (3) limiting boundary trajectories

The trajectory shape is essentially changed by acceleration of the system to be synchronised, which arises under the power deficit or surplus at the frequency recovering up to the normal level [104]. If this acceleration is favouring the synchronisation, then the boundary trajectory extends; if otherwise, it narrows.

The trajectories $\Delta f = f(\delta)$ are symmetrical relative to the δ-axis in the presence of acceleration and also to the Δf axis in its absence. At the same time, the boundary trajectory can be extended by damping, which raises the probability of a successful result.

For a structurally simple system, possible pulling of a generator in synchronism can, in a first approximation, be defined based on the equation of generator rotor motion [6]:

$$\frac{T_{j.r}\Delta\omega_*^2}{2} = \int_{\delta}^{\delta_{\max}} \left(P_{m_*} \sin\delta - \frac{a}{f_0} T_j \right) d\delta \tag{7.1}$$

where a is the uniform acceleration, Hz/s.

In view of $P_{m_*} = \dfrac{E_* U_*}{x_{\Sigma_*}}$, by transforming we obtain:

$$\begin{gathered} \frac{T_{j.s}\pi\Delta f^2}{f_0} = A = \frac{EU}{x_\Sigma}(\cos\delta - \cos\delta_{\max}) - \frac{a}{f_0} T_{j.s}(\delta_{\max} - \delta) \\ \Rightarrow \Delta f = \sqrt{\frac{EUf_0}{x_\Sigma \pi}(\cos\delta - \cos\delta_{\max}) - \frac{a}{\pi}(\delta_{\max} - \delta)} \end{gathered} \tag{7.2}$$

where $\Delta\omega$ is the difference between angular frequencies relative to the rated value; T_j is the constant of system's inertia, s; ω_0 is the rated angular frequency; P_m is the maximum transmitted power, pu; x_Σ – reactance to synchronisation place, pu; the left side of the motion equation equals the kinetic energy A.

POST-EMERGENCY SYSTEM MERGING USING THE SYNCHRONISM-CHECK RELAYS

On frequency normalisation the system integrity is to be restored. In order not to retard the self-restoration of normal operation, the process should be fully automatic, without personnel participation. The use for this purpose of automatic re-closing with catching synchronism devices is impeded by the circumstance that it is unknown beforehand where the merging will take place, while the number of cross-sections where proper devices should be installed is large enough; besides, for successful operation of these devices specific requirements should be met, which essentially retards the process and even call for the staff interference. Therefore, in the cases of rare blackouts, for automatic re-integration it is advisable to use the automatic re-closing devices with synchronism-check relays widely used in power systems. In such cases a non-synchronous re-closing might be expected, and for successful synchronisation it is necessary to ensure that the difference between the frequencies of separate parts is small enough, with the switching-on angle being adequate [103].

Usually, the lines are re-closed at one line end by voltage absence indication, and at the other end − by synchronism indication, with synchronism-check relays started at the angle difference of $\pm\delta$ and operating when the time delay t_d expires [22], [28]. In turn, when used for post-emergency system merging purposes, these relays are in the holding mode on the lines that were disconnected at one end by system splitting, so for successful re-closing it is necessary that during the delay time the voltage vector[1] would be in the allowable range of angles (Fig. 7.2). On the first line's re-closing such a relay would work in the synchronism catching mode, while the remaining transmission lines will be re-closed by synchronism indication.

[1] Considering the motion of voltage vectors, we can assume the system voltage vector U_s to be immovable, and voltage vector U_g of the deficient system part – as rotating about U_s with angular frequency $\Delta\omega=\omega_g-\omega_s$: The positive direction of the vector rotation is chosen counter-clockwise.

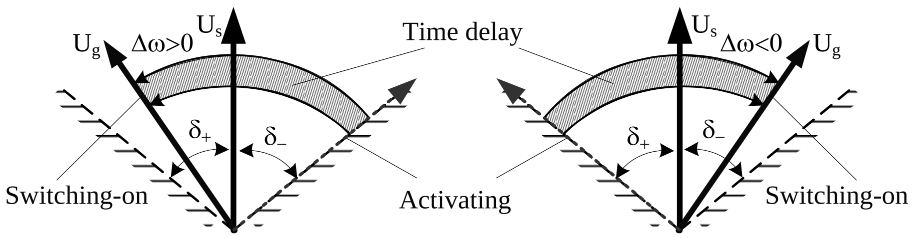


Fig. 7.2. The operation zone of a synchronism-check relay

We will assume that the motion of vectors is uniform: $\Delta\omega = const$; $d\Delta\omega/dt = 0$; then for synchronisation to be successful it is necessary that the following conditions are fulfilled:

$$\begin{cases} \delta_- - \delta_+ \le t_d \cdot 360 \cdot \Delta f_-, & if \quad \Delta\omega < 0 \\ \delta_+ - \delta_- \ge t_d \cdot 360 \cdot \Delta f_+, & if \quad \Delta\omega > 0 \end{cases} \qquad (7.3)$$

Here and further, unless otherwise specified, the time and time constants are expressed in seconds, the angles – in degrees, the angular frequency – in radians; the meaning of indices is: r – for the quantity expressed in radians, * – per unit, pu, + – for a positive value, – – for a negative one; for transition from radians to degrees, Hz and seconds the following formulas are used:

$$\Delta\omega = 2\pi\Delta f \quad \Delta\omega_* = \frac{\Delta\omega}{\omega_0} = \Delta f_* = \frac{\Delta f}{f_0} \quad \delta = \left(360^\circ / 2\pi\right)\delta_r \quad t_* = \omega_0 t = 2\pi f_0 t = 314t \qquad (7.4)$$

At a 1s time delay and ±40° angular range the device switches on successfully under the condition that in the post-emergency state the frequency difference does not exceed 0.22 Hz, i.e.:

$$80 \ge 360 \cdot \Delta f \quad \Rightarrow \Delta f \le 0.22 Hz \qquad (7.5)$$

Decrease in the time delay would make it possible to perform synchronisation at greater frequency differences.

7.1.1. Switching-on angle

Depending on the voltage vector behaviour in the separated system part − whether it is approaching or moving away, is ahead or lags behind − four switching-on variants are possible.

If the switching-on occurs at positive angles, the separated part begins to transfer the active power, whereas at negative ones − to consume it. In turn, depending on the angular velocity difference, there occurs acceleration or deceleration [59]. The switching-on angles in the 1st approximation can be estimated as

$$\delta_{sw} = \begin{cases} \delta_+ + 360^\circ \cdot \Delta f_- \cdot t_d, & if \quad \Delta\omega < 0 \\ \delta_- + 360^\circ \cdot \Delta f_+ \cdot t_d, & if \quad \Delta\omega > 0 \end{cases} \qquad (7.6)$$

The dependence of switching-on angle on the frequency difference Δf at varied time settings is shown in Fig. 7.3.

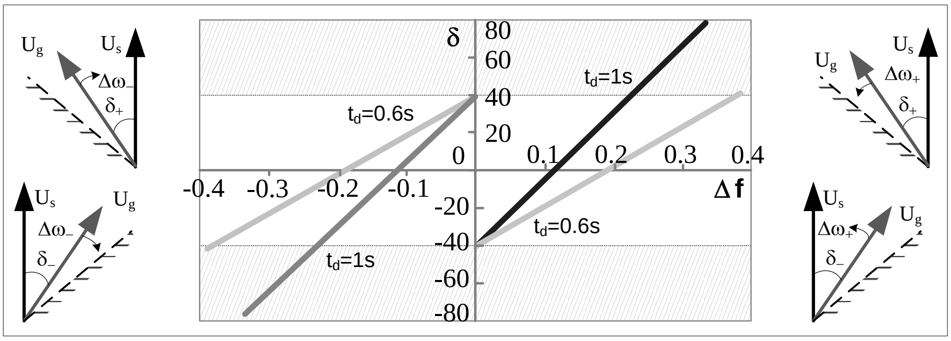


Fig. 7.3. Switching-on angle *vs*. frequency difference and time delay

From the above it follows that if synchronism-check devices with the time delay of 1 s are used, at the frequency difference $|\Delta f| < 100mHz$ and the circuit-breaker switched on, the voltage vectors are approaching each other, whereas at $|\Delta f| > 100mHz$ they are moving apart.

7.1.2. Influence of acceleration on the switching-on angle and post-emergency merging process

The acceleration of a power system's parts affects the switching-on angle, creating its additional change:

$$\Delta\delta_r = \int_0^t \Delta\omega \cdot t_d \cdot dt \quad \Leftrightarrow \quad \Delta\delta = \int_0^t 360^\circ \cdot \Delta f \cdot t_d \cdot dt \tag{7.7}$$

Assuming that the processes are going with a uniform acceleration $a_r = d\Delta\omega / dt = const$, the switching-on angle can be calculated as [105]:

$$\delta_{sw_r} = \delta_{\mp_r} + \Delta\omega_{\pm} \cdot t_d + a_{\pm_r} \cdot t_d{}^2 / 2 \tag{7.8}$$

On passing from radians to Hz and degrees, the switching-on angle (assuming that the direction of acceleration coincides with that of rotation of the separated part's voltage vector) will be:

$$\delta_{sw} = \begin{cases} \delta_+ + 360^\circ \cdot \Delta f_- \cdot t_d + 360^\circ \cdot a_- \cdot t_d{}^2/2, & if \quad \Delta\omega < 0 \\ \delta_- + 360^\circ \cdot \Delta f_+ \cdot t_d + 360^\circ \cdot a_+ \cdot t_d{}^2/2, & if \quad \Delta\omega > 0 \end{cases} \tag{7.9}$$

The variation of the switching-on angle at constant acceleration, various frequency differences and delay times is shown in Fig. 7.4.

The acceleration narrows the range of synchronisation parameters (in Fig. 7.4 shown by arrows). Therefore, from the synchronisation point of view the process should go at a minor acceleration so that the voltage vector during the delay is held in the operation zone. This can be provided applying the slow AUFLS2.

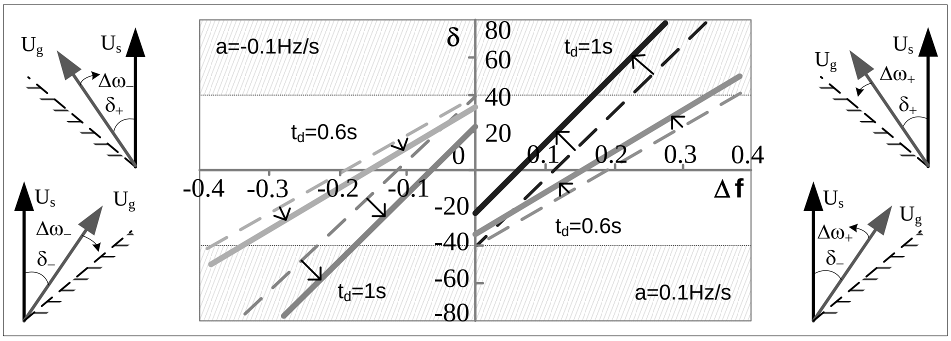


Fig. 7.4. The influence of acceleration on synchronisation parameters

SWITCHING-ON CURRENT EFFECT

If a power system's parts are merged at non-zero angle and frequency difference, the equalising current I_{eq} arises. It is known [22], [63] that, from the viewpoint of operation reliability established for electric appliances, synchronous machines are to stand the impact of three-phase short-circuit I_{sc}. Thus a post-emergency re-integration is possible if:

$$I_{eq}/I_{sc} \le 1 \tag{7.10}$$

According to [63], the switching-on current is:

$$\begin{aligned} I_{eq} &= \left| \frac{\dot{U}_g - \dot{U}_s}{jx_\Sigma} \right| = \frac{1}{x_\Sigma}\left(\left| U_g \sin\delta + jU_g \cos\delta - jU_s \right| \right) = \\ &= \frac{1}{x_\Sigma}\sqrt{\left(U_g^2 \sin^2\delta + U_g^2 \cos^2\delta - 2U_g U_s \cos\delta + U_s^2 \right)} = \frac{1}{x_\Sigma}\sqrt{\left(U_g^2 - 2U_g U_s \cos\delta + U_s^2 \right)} \end{aligned} \tag{7.11}$$

where U_s is the sending system part's voltage, pu; U_g is the receiving part's voltage, pu; δ is the angle between the voltage vectors of system parts at the switching-on time, ^{o}; x_Σ is the equivalent network reactance consisting of the generator sub-transient and the grid external reactances, pu.

Assuming the system voltages to be equal, we obtain:

$$I_{eq} = \frac{U_g}{x_\Sigma} 2\sin \delta/2 \tag{7.12}$$

In turn, the short-circuit current on the generator terminals is:

$$I_{sc} = \frac{U_g}{x''_{d.g}} \tag{7.13}$$

where $x''_{d.g}$ is the equivalent reactance, pu.

Then

$$\frac{I_{eq}}{I_{sc}} = \frac{2\sin \delta/2}{1 + x_{ex}/x''_{d.g} + x''_{d.s}/x''_{d.g}} \tag{7.14}$$

where x_{ex} is the external reactance behind a generator bus.

At the use of synchronism-check relays the maximum value of the switching-on angle would not exceed the angular setting allowable for such a relay ($\pm\delta$, usually ±40°), and the current ratio will be:

$$\frac{I_{eq}}{I_{sc}} = \frac{0.68}{1 + c + n} \tag{7.15}$$

where n is the ratio between the reactances of system parts to be synchronised (it is assumed that the power values inversely proportional to the reactances); c is the ratio between the reactance of cross-section and the reactance of the part to be synchronised.

An example for the ratio between the switching-on current and the short-circuit current at re-integrating the system parts with different power values through a 500kV 400km line at angle of 40^{o} is shown in Fig. 7.5.

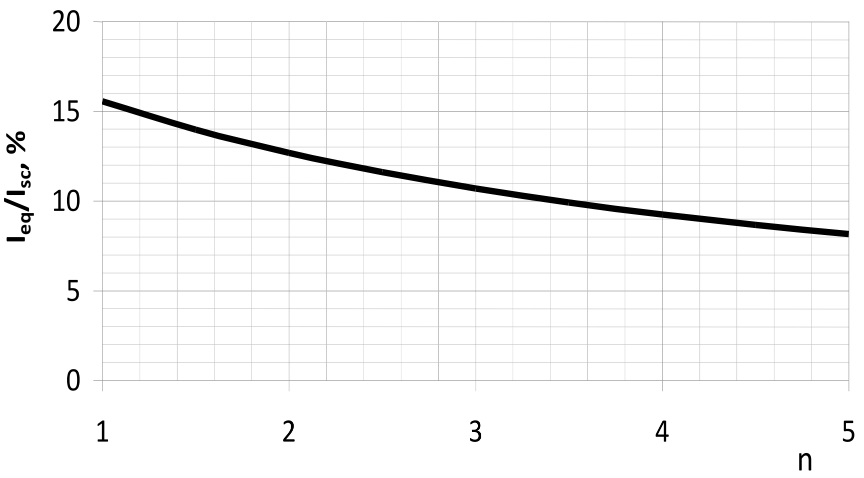


Fig. 7.5. Ratio of currents *vs*. ratio of powers of system parts to be synchronised

As seen, the equalising current is many times smaller than the short-circuit current and is in the limits allowed for transformers and generators.

THE MATHEMATICAL MODEL OF SYNCHRONISATION PROCESS

The synchronisation process of post-emergency merging can be verified on a mathematical model developed by V. Ivanov in the framework of MUSTANG program (1990–2005, Copyright of Vladimir Ivanov Group) [106] for modelling the dynamic processes of the re-integration of power system parts at definite angle and frequency difference.

In this program, the model of synchronous machine [SM] is described by the following equations [107], [108][2]:

$$i_d = \frac{1}{x_d''} \cdot \left[\frac{\omega_U}{\omega_{nom}} \cdot E''_q - U_q \right] \tag{7.16}$$

$$i_q = \frac{1}{x_d''} \cdot \left[\frac{\omega_U}{\omega_{nom}} \cdot E''_d - U_d \right] \tag{7.17}$$

where i_d, i_q are the dq components of current, kA; U_q, U_d are the dq components of voltage, kV; ω_U is the rotational speed of voltage vector, pu; ω_{nom} is the synchronous rotational speed (at the nominal frequency $\omega_{nom} = 1$), pu; $\frac{\omega_U}{\omega_{nom}} \cdot E''_q$, $\frac{\omega_U}{\omega_{nom}} \cdot E''_d$ are the sub-transient EMF components on SM axes, kV; x_d'' is the sub-transient reactance,

and

$$\frac{dE'_{qp}}{dt} = \frac{1}{T'_{d0}} \cdot \left[E_{qe} - i_d \cdot (x_d - x'_{dp}) - E'_{qp} \right] \tag{7.18}$$

$$\frac{dE''_q}{dt} = \frac{1}{T''_{d0}} \cdot \left[E'_{qp} - i_d \cdot (x'_{dp} - x_d'') - E''_q \right] + \frac{dE'_{qp}}{dt} \tag{7.19}$$

$$\frac{dE''_d}{dt} = \frac{1}{T''_{q0}} \cdot \left[i_q \cdot (x_q - x_d'') - E''_d \right] \tag{7.20}$$

where:

[2] Using "Comparisons of synhronous machine models in the study of the transient behaviour of electrical power systems.", T.J. Hammons, D.J. Winning. -Proc.IEE, vol.118, №10,October,1971, the SM equations are written in EDS form (d-q axes).

$$x'_{dp} = \frac{x_d \cdot (T'_d - T''_{d0} + T''_d) - x''_d \cdot T''_{d0}}{T'_{d0} - T''_{d0}},$$

$$T'_d = T'_{d0} \frac{x'_d}{x_d} \qquad T''_d = T''_{d0} \frac{x''_d}{x'_d}. \qquad (7.21)$$

Here: E_{qe} is the *EMF* of the excitation winding (proportional to the voltage), kV; the electro-magnetic time constants $T'_{d0}, T''_{d0}, T''_{q0}$ are given in seconds; the ω_U value in all cases is calculated by the equation:

$$\frac{d\omega_U}{dt} = \frac{1}{T_F} \cdot \left[\frac{d\delta_U}{dt} \frac{1}{\omega_{nom}} - \omega_U \right] \qquad (7.22)$$

where δ_U is the voltage vector's angle with respect to the synchronous rotation axis, rad; T_F is a time constant, s.

Other parameters of the SM model are found as

$$M_e = E''_q \cdot i_q + E''_d \cdot i_d \qquad (7.23)$$

$$P_G = \frac{\omega_U}{\omega_{nom}} \cdot M_e \qquad (7.24)$$

$$\frac{ds}{dt} = \frac{1}{M_j} \left[\frac{P_T}{1+s} - M_e \right] \qquad (7.25)$$

$$\frac{d\delta}{dt} = s \cdot \omega_{nom} \qquad (7.26)$$

where M_e is the SM electro-magnetic torque, MW; P_T is the turbine power, MW; P_G is the SM electro-magnetic power, MW; s_r is the SM rotor's slip with respect to the synchronous rotation axis, pu; δ is the SM rotor angle (i.e. the angle between vector E_g and the synchronous rotation axis, rad; M_j is the SM inertia with respect to the turbine (equal to $T_j P_{G.nom}$), MW·s; D is the damping factor, pu; s_U is the slip of voltage vector U.

For each system part, in compliance with the frequency indicated, the angular velocity reference system for all EMF and voltage vectors is applied. For this, the vectors of the initial slips of SM rotors and of the voltages are introduced in reference to the synchronously rotating axes:

$$s_r = s_u \left(\frac{f}{f_0} - 1 \right) \qquad (7.27)$$

where f is the set frequency, Hz; f_0 is the nominal frequency (50 Hz).

Respectively, the rotor slips of asynchronous motors change by the values of voltage vector slip, i.e.:

$$s_r(f) = s_r(f_0) - s_u \qquad (7.28)$$

where $s_r(f_0)$ is the rotor slip of asynchronous motor at 50 Hz; $s_r(f)$ is the rotor slip at a given frequency.

Into the set of equations describing the motion of synchronous machines, the operation of turbine speed governors & excitation regulators as well as the static portion of the load and asynchronous motors, the own parameter of slip compensation is introduced as:

$$\Delta s = 1 - \frac{f}{f_0} \qquad (7.29)$$

so that in all equations to the s_U and s_r values an extra slip Δs is added. For example, the longitudinal- and transversal-axis equations will read as:

$$
\begin{aligned}
i_d &= \frac{1}{x''}\Big(\left(1+s_u+\Delta s\right)E_q'' - U_q\Big),\\
i_q &= \frac{1}{x''}\Big(-\left(1+s_u+\Delta s\right)E_d'' - U_d\Big)
\end{aligned}
\tag{7.30}
$$

The following equation remains unchanged:

$$
\frac{d\delta}{dt} = s_r 2\pi f_0 = s_r \omega_0 \tag{7.31}
$$

7.1.3. The trajectory computation

The developed program allows for modelling a power system (its generators, excitation systems, control, load characteristic curves, automatics, etc.) with the desired precision; the program also allows the independent choice to be made for the initial frequency differences and switching-on angles, PS accelerations, etc., thus making it possible to obtain a complete picture of the influence exerted by different operating variables on the successfulness of synchronisation.

To define the trajectories of a transient synchronisation process after the introduction of all PS operating variables it is necessary (Fig. 7.6):

1. To calculate the system steady-state condition when the cross-section connecting the parts of a PS is tripped, i.e. the input data refer to their separate operation (in each part at least one control power plant is still in service);

2. To create automatics for re-closing the line. If necessary, to specify the acceleration of the system parts, e.g. by varying load or generation.

3. To choose the parameters to be controlled.

4. To define for each part the desirable values for frequency and switching-on angles.

5. To activate the calculation and estimate the transient process (i.e. the pulling in synchronism).

6. To continue from p.4. The calculation is completed when the required trajectory is obtained, i.e. in the domain of concern the boundary points are found that separate stable and unstable operating conditions.

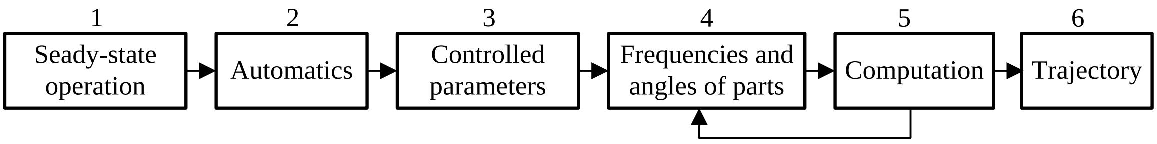


Fig. 7.6. Scheme for calculation of the boundary synchronisation trajectory

To facilitate the choice of initial parameters by p.4, in the first approximation it is assumed that the trajectory is located between two arcs (Fig. 7.7).

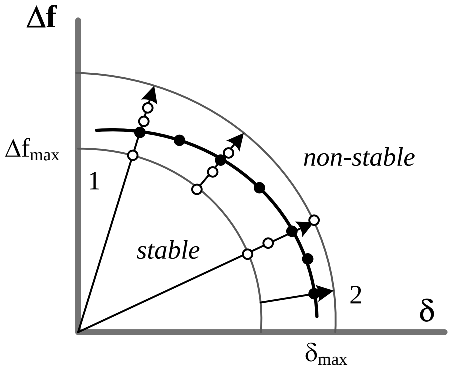


Fig. 7.7. Estimation of a domain's trajectory

The radius of curve (1) is equal to the maximum allowable frequency difference at the zero angle, and that of curve (2) − to the maximum switching-on angle at the zero frequency difference. Then, using the radius-vector we can find the boundary point for the trajectory by moving from the steady-state (i.e. successfully synchronised) domain.

In the case of successful synchronisation the oscillations in a transient process are convergent (Fig. 7.8); otherwise they are divergent.

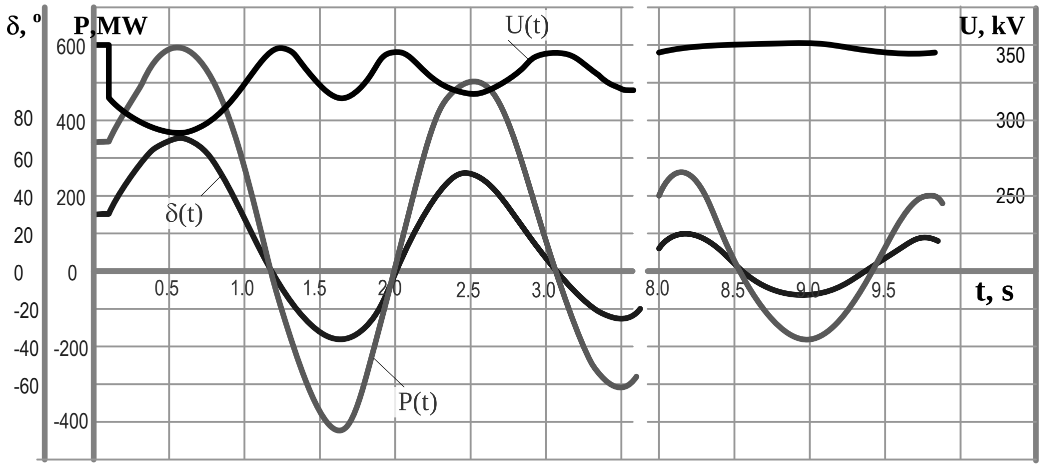


Fig. 7.8. Transient process of successful synchronization

THE BOUNDARY TRAJECTORIES FOR DIFFERENT MERGING SITUATIONS

As was mentioned above, from the viewpoint of stability maintenance the presence of a loaded line in the proximity of the merging point can be a limiting factor for the domain of allowable parameters at post-emergency synchronisation [102], [105]. Although to splitting point no loaded lines are usually connected, in the calculations the presence of such a line is assumed, with its influence on the process taken into account.

We will use the following simplified designations for a power system's parts: PS1− the power sending part, PS2 −the power receiving part, PS3 −the re-connected part. Let us assume that the PS parts have equal power values and are connected by 500kV 400 km lines; the generators have tiristor excitation regulators. Post-emergency re-integration takes place when between PS2 and PS3 a line is closed, with the frequency in PS3 lower than in PS1 and PS2.

Using the mentioned program, the boundary trajectories were calculated taking into account that from PS1 the power is transmitted to PS2, loading the transmission line with $0.56P_{\max}$. At modelling the system re-integration the following was assumed: 1− owing to slow AUFLS2 operation the re-connected part receives -0.3 Hz·s acceleration; 2 − re-integration proceeds without acceleration; 3 − owing to increased load the re-connected part receives +0.3 Hz·s acceleration.

Trajectories for re-connection of the 5 GW and 10GW parts are shown in Fig. 7.9, and that of the 20GW part − in Fig. 7.10. As is seen, the slow AUFLS2 operation (curves 1) favours the pulling in synchronism, whereas the oppositely directed acceleration (curves 3) is narrowing the domain of successful integration.

When analysing the results obtained it can be concluded that in rare emergency cases the synchronism-check relays can successfully be used for automatic re-integration with sufficient reserve.

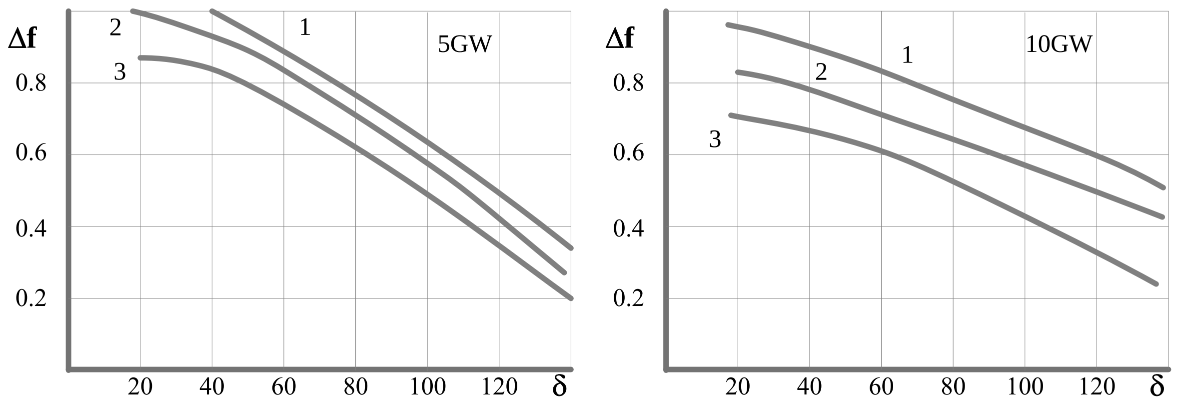


Fig. 7.9. a) Boundary trajectories for the 5GW PS synchronisation; b) the same for 10GW PS:

1, 2 and 3 – acceleration of the connected part, respectively: -0.3, 0, and 0.3 Hz·s

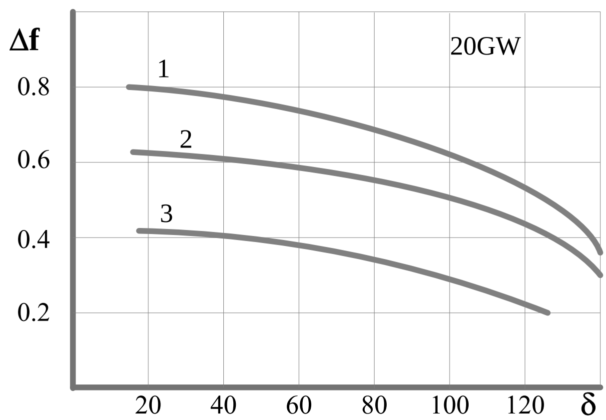


Fig. 7.10. Boundary trajectories for 20GW PS synchronisation

1, 2 and 3 – acceleration of the connected part, respectively: -0.3, 0, and 0.3 Hz·s

7.1.4. Influence of the re-connected part power on the successfulness of synchronisation

With the PS power and frequencies difference values increasing, the range of allowable angles is narrowing (Fig. 7.11).

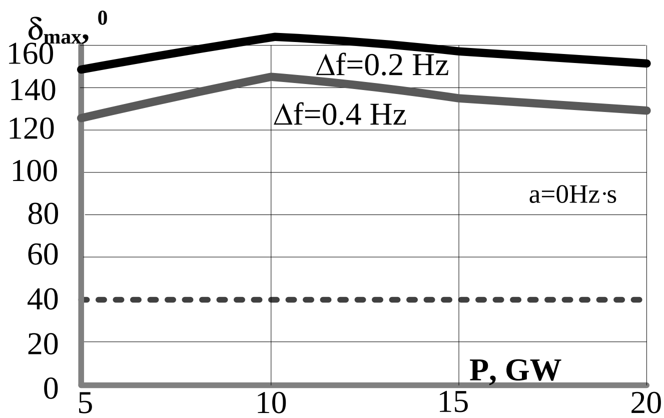


Fig. 7.11.The maximum allowable angle *vs.* the power of synchronised part

The curves shown in Fig. 7.11 were constructed at a frequencies difference of 0.2 Hz and 0.4 Hz. The trajectories characterise the maximum allowable switching-on angles at which pulling in synchronism occurs depending on the power of the re-connected part and on the load of a line close to the re-integration place. The switching-on angle values are limited by the setting of synchronism-check devices (in practice assumed to be $\pm 40^0$). As seen, at normal line loading, even at high frequencies difference, a sufficient security is retained.

THE MAXIMUM ANGLE AND VOLTAGE DECREASE IN A TRANSIENT PROCESS

The maximum angle $\delta_{\max}$ in a transient process depends on the switching-on angle δ, frequency difference Δf and acceleration,□ which should be restricted. The maximum angle $\delta_{\max}$ can approximately be defined using eq. (7.2) but in the absence of acceleration, i.e.:

$$\delta_{\max} = \arccos\left(\cos\delta - \frac{T_j \pi \Delta f^2}{f_0 P_m}\right) \tag{7.32}$$

In this case the equalising power and reactance cause, in addition to the load-related voltage drop, an additional voltage drop:

$$\Delta U \approx \frac{S}{U_g} \sum_{i=1}^{n} x_i \tag{7.33}$$

where U_g is the voltage at the terminals of the generating source, S is equalising power, x_i is reactance.

Considering the processes in a two-machine scheme, the voltage at the transmission point will be [24], [63]:

$$\dot{U}_{tr} = \frac{U_g e^{j\delta} x_1 + U_s x_2}{x_1 + x_2} = \frac{U_g x_1}{x}\cos(\delta) + j\frac{U_g x_1}{x}\sin(\delta) + \frac{U_s x_2}{x} \tag{7.34}$$

where U_s and U_g are the voltages of generating sources; it is assumed that the U_g voltage vector rotates with respect to the stationary U_s vector;

x_1 and x_2 are the reactances from the re-connection point to the generating sources; x is the total reactance, $x = x_1 + x_2$; δ is the angle between the voltage vectors.

As seen in Fig. 7.12, the voltage is falling considerably over a large area around the oscillation centre, which should be accounted for when choosing the synchronisation parameters.

Fig. 7.12. Angular dependence of the minimum voltage in a transient process

The values of voltage in dependence on the angle and connection place are calculable as the modulus of (7.34):

$$\left|\dot{U}_{tr}\right| = \sqrt{\left(\frac{\mathrm{U_g} x_1}{x_1 + x_2}\cos(\delta) + \frac{\mathrm{U_s} x_2}{x_1 + x_2}\right)^2 + \left(\frac{\mathrm{U_g} x_1}{x_1 + x_2}\sin(\delta)\right)^2} \tag{7.35}$$

If $U_s = U_g$ and $x_1 = x_2$, the voltage variations at different angles can be calculated in the following manner:

$$U_{tr} = U_s \cos(\delta / 2) \tag{7.36}$$

As is seen, if in a transient process the angle reaches $\delta_{\max} = 90°$, the voltage will decrease for a short time to $0.707U_s$, and at $\delta_{\max} = 74°$ – to $0.8U_s$.

At known T_j and P_m, using (7.2), (7.35) and (7.32) a nomogram can be constructed to show the changes in the maximum angle and voltage at the connection point of transmission line depending on the switching-on angles and frequency differences (Fig. 7.13).

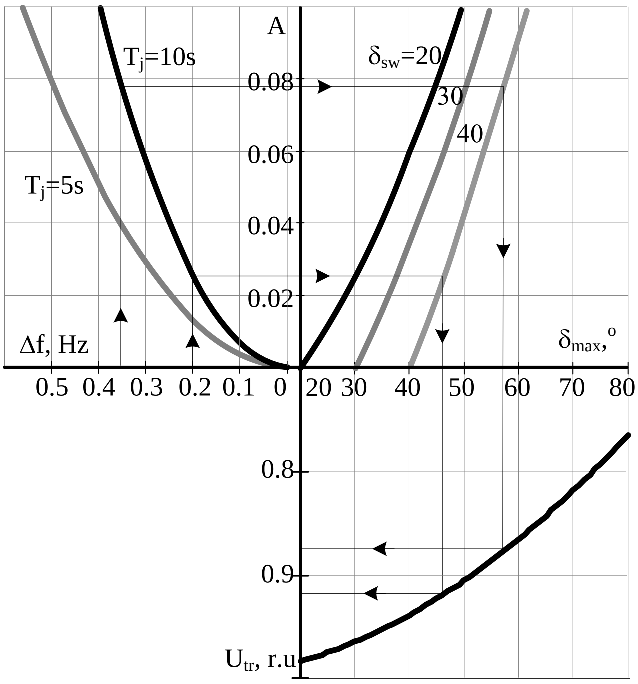


Fig. 7.13. Nomogram for calculation of synchronisation parameters

As seen in Fig. 7.13, the voltage is decreasing in the permissible limits if for merging of system parts the synchronism-check devices are used that allow synchronisation in a small range of frequency differences, at the least accelerations and switching-on angles.

Using the mentioned program, the proposed protection complex against blackouts of power systems has been tested using a 50-busbar model with 25 generators. When the start of dangerous overload is fixed (in a controllable grid cross-section), the power system is split opening 5 lines (in a sectioning cross-section). As a result, the overload is simultaneously eliminated in the overloaded cross-section with the lines kept operating with maximum allowable power flows thus avoiding threat of cascading development. When a system is devided at the cross-section through which power close to overload is flowing, in one its part a power surplus of 4.5 % is observed while in the other – a power deficit of 26 %. As seen in Fig. 7.14, the process of frequency recovery in both parts proceeds without further control (automatic) thus allows achieving automatic re-connection at ~ 64 s. All lines re-closed almost contemporaneously. The oscillations in a transient process are fast-convergent.

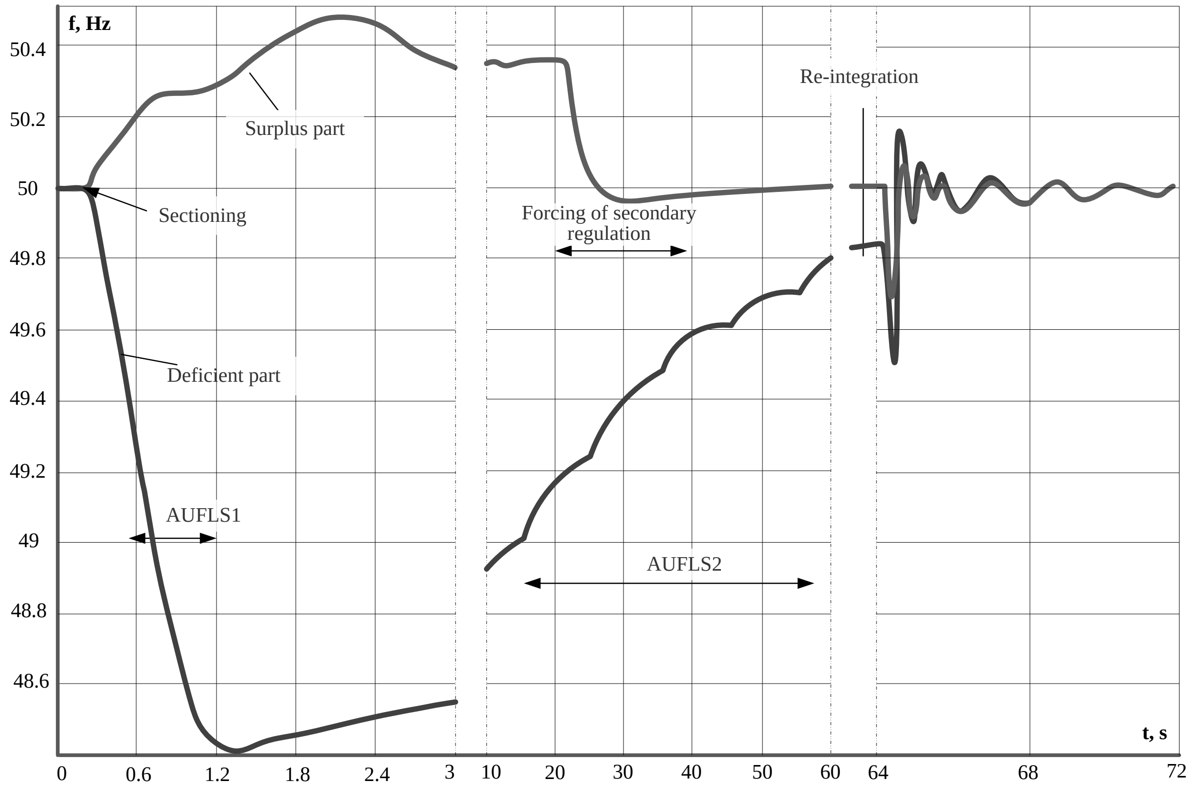


Fig. 7.14. The frequency variations after sectiong (during self-restoration)

AUTOMATIC RE-CLOSING OF CONSUMERS

At system re-integration, the consumers' lines are re-closed using the automatic re-closing by normal frequency indication (ARC_f) [5], [22].

However, the attempt to restore the integrity of a power system with its full carrying capacity could be unsuccessful if there is a stable line fault. To avoid a repeated frequency decline under the unsuccessful re-connection process, the restoration of energy supply should be performed step-by-step (Fig. 7.15). After the first time interval t_{ARC}, if the frequency is higher than f_c, the first consumer group will be switched on. The ARC_f performs frequency control, and, if it is held higher than f_c, then consumers remain to be connected. Within some time (~6s) the following stage operates, and so on. If the frequency falls below the setting, the consumers' re-closing will be delayed, or the process will pass to the expectation mode.

Owing to the frequency control, the threat of repeated frequency faults or voltage drop avalanches in a separated system region is excluded.

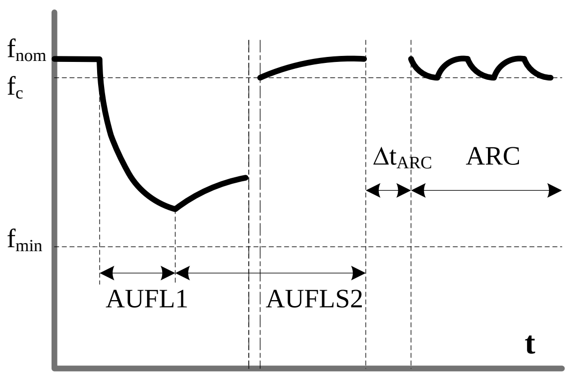


Fig. 7.15. Frequency changes at automatic re-closing operation after unsuccessful re-integration

CONCLUSIONS

Taking into account that the merging should be performed in an undetermined place, in the rare emergency cases for this purpose the already existing on lines synchronism-check relays can be used. At applying them as synchronism catching devices the re-integration process occurs as soon as the frequency in system parts has been equalised (this takes approx. 20 seconds). The re-closing of a first line allows for re-integration in a damping transient process. The remaining lines will be switched on in a usual synchronism-check mode. This ensures that the self-restoration proceeds within 100 s, which will remain unnoticed by the majority of consumers.

The maximum angle in the transient process does not exceed the value at which undesirable voltage drop in the grid could be expected, since the synchronisation proceeds at minor frequency differences provided by a slow-acting AUFLS and at small switching-on angles determined by the settings of synchronism-check relays.

8. SELF-RESTORATION AS A CYCLIC PROCESS

From the above consideration it follows that the protection complex against blackouts consists of elements that prevent development of blackout in a power system and restore its normal operation without personnel participation.

The whole process is therefore of cyclic character (see Fig. 8.1).

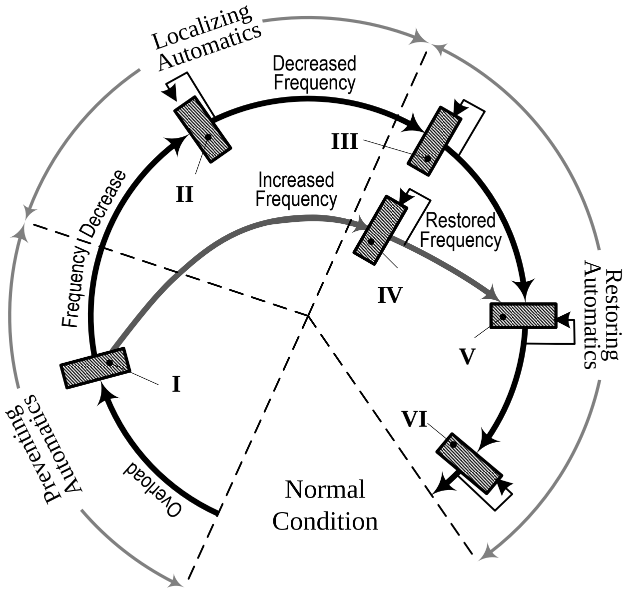


Fig. 8.1. Joint operation of protection devices:

I – elimination of cross-section overload by short-term PS sectioning without feedback; II – operation of fast AUFLS; III – operation of slow AUFLS; II and III operations proceed with the feedback providing higher reliability; IV – forced control; V – PS reintegration; VI – automatic re-closing of consumers' lines

Accordingly, the protection elements can be grouped as follows.

- preventive (warning) – the protection against the network cross-section overload;
- localising – the fast-acting under-frequency load shedding automatics (AUFLS1);
- restoring – the slow-acting AUFLS2, forced secondary regulation, re-integration and automatic re-closing of consumers' lines.

The key protection element of the complex shown in Fig. 8.1 is fast-acting protection (I) against the network cross-section overload performed by short-term PS sectioning at pre-defined places, which momentarily eliminates the overload. When a system is split, in one its part a power deficit and a frequency decline take place, while in the other – a power surplus and a frequency rise. In the deficient part the fast-acting AUFLS1 will operate (II), and the frequency for some time will remain at the reduced level allowed for power plants. Then the slow-acting AUFLS2 restores the frequency up to the normal level (III); in turn, in the power surplus region the frequency normalisation occurs owing to the operation of turbine governors, and, if necessary, for accelerated synchronization a forced regulation (IV) is used. The PS integrity is restored using synchronism-check relays (V); by the normal frequency indication the consumers' lines are automatically step-by-step re-closed (VI).

Thus the emergency situation is eliminated. On the whole, the described complex executes the functions of a PS self-restoration mechanism.

To achieve the serviceable state of anti-emergency automatics it is necessary to keep it ready to act. For this purpose, an interconnected power system needs an analytical centre with definite empowerments for laying out the deployment of protection automatics as well as determination of its amount and settings.

The efficiency of grid overload protection in combination with self-restoration mechanism can be determined considering the emergency development against the background of worldwide blackouts.

APPLICATION OF THE PROPOSED PROTECTION COMPLEX AGAINST BLACKOUTS ON THE BACKGROUND OF PAST EMERGENCY EVENTS

When considering application of the solutions proposed in this work against the background of past emergency events it is worthwhile to examine the data on the worldwide blackouts given in this section and Appendix 1.

1. Blackout on 09.11.1965, USA.

The event was started up when a heavily loaded line was tripped due to erroneous protection setting. Then, under overload, the rest of the cross-section lines were disconnected. On the disconnection of inter-system links the system stability was lost. The trippings going on, the North-American power system was split, and, after the outage of generating sources, collapsed.

Commentary

If a short-term splitting of the overloaded cross-section had been done, the stability loss would not have happened, with the disturbance transforming into a simple power shortage − frequency emergency, which, as we could see, activates the self-restoration mechanism. The emergency in such a case can be eliminated within approx. 100 seconds − that is, unnoticed by the majority of consumers.

2. Blackout on 14.07.1977, USA (New-York).

In that case, lightning during a thunderstorm simultaneously struck two 375 kV lines on a common transmission tower.

Commentary

The event developed as a frequency emergency, which, as was said, with the self-restoration mechanism involved, does not create problems. The complication in that case was caused by the 375 cable capacity, owing to which at the Ravenswood power plant a 1000 MW generator, having lost excitation, was tripped; as a consequence, a repeated frequency disturbance occurred. In the case like that, such a line in the relieved power system should be temporarily tripped on both sides.

3. Blackout on 19.12.1978, France.

The unusually large load significantly exceeded the forecast value. As a consequence, an overload happened in the interconnection line to Germany, which led to a voltage avalanche. This resulted in tripping of generators followed by stability loss and the power system's collapse.

Commentary

If a short-term sectioning had been done with orientation towards the overloaded cross-section, the event would have turned into a frequency emergency followed by self-restoration at reduced load within 10 minutes.

4. Blackout on 04.08.1982, Belgium.

The blackout began owing to overload on a 280 kV line, and led to tripping of 5 generators.

Commentary

If the overload had been eliminated by short-term sectioning, the generators would not have switched off and no emergency event would have happened.

5. Blackout on 14.12.1982, Canada.

During the emergency triggered by the busbar short-circuit of a voltage transformer in the link connecting the *Labrador* HPP with load centres only two 750 kV lines remained. They were overloaded and tripped, with stability lost.

Commentary

If at a proper place a short-term sectioning had been done, no stability loss would have happened, and the lines would have kept operating with a reduced load.

6. Blackout on 27.12.1983, Sweden.

Some incidents caused tripping of two 400 kV transmission lines (from total seven). Owing to their being overloaded, in the southern part of the power system a voltage avalanche occurred, and it was split having lost stability. On the south a frequency disturbance took place, and under the conditions of voltage avalanche the under-frequency load shedding automatics, due to its voltage sensitivity, failed to operate.

Commentary

If the power system had been split for a short time at a proper place, no voltage avalanche with its severe consequences would have happened.

7. Blackout on 08.06.1995, Israel.

The disconnection of a 161 kV two-circuit line caused by fire led to overload on the lines keeping operation, as a result of which in the southern part of the power system a voltage drop and the consecutive stability loss happened. In the swinging process two 550 MW generators were tripped in this system part, with its resultant collapse.

Commentary

In the case the overload had been eliminated by means of short-term sectioning, no blackout would have occurred.

8. Blackout on 02.07.1996, Western power system of USA.

Overloading of a transmission line led to increase in sagging of its conductors. Owing to malfunction of protection, the second line was tripped. As a result, a voltage drop occurred, to which the 3rd zone of distance protection responded. This was followed by a voltage avalanche with stability loss at the system's splitting into 5 islands. Owing to the action on the load and generation, in four islands the power balance was recovered, which helped to restore faster the PS integrity and resume power supply.

Commentary

A correct short-term sectioning would have prevented the voltage avalanche initiation and stability loss.

9. Blackout on 12.01.2003, Croatia-Bosnia.

Commentary

Considering this event, the following could be said. If, in compliance with recommendations, the tripping of the 400/220 kV autotransformer had been used for short-term splitting of the 220 kV link, all generators would have kept operating, with the blackout avoided.

It should be added that at the *Konjsko* substation no busbar and circuit-breaker backup protections were installed.

10. Blackout on 14.08.2003, USA-Canada.

During disturbance caused by line tripping in the overloaded grid there were additional reactive power flow and voltage drop. The distance protections of three lines responded by tripping these lines. As a result, generator disconnections began, with the stability loss in the *New-York* power system; then its collapse followed.

Commentary

If at the grid overload a short-term sectioning of the power system had been done with the aim to relieve the cross-section, the process would have turned into a temporary frequency disturbance at the power receiving end, with tripping of generating sources avoided. The existence in this power system of a self-restoration mechanism would have secured disruption of the emergency process within 100 seconds.

11. Blackout on 28.09.2003, Italy.

This emergency event began owing to increased conductor sagging on the Swiss lines, which resulted in their multiple tripping; then a voltage drop and stability loss occurred on the Hungary bound lines. As a result, Italy was separated from the rest of Europe. After operation of the under-frequency load shedding automatics the frequency was held up at the 48 Hz level for one minute. Then gas turbines were tripped under the lack of compressed air caused by reduced productivity of compressors at lower rotational speed. Since a portion of air is used for cooling turbine blades and combustion chamber, the temperature of working wheels exceeded the allowable level, and the protection tripped them. Under increased power shortage the blackout burst out.

Commentary

If at line overload a short-term sectioning had been applied not to the European links but in the Bologna cross-section, then the majority of those links would have kept operating with the power flow corresponding to the consumption in the northern Italy, with a shortage 1-2 GW instead of 9GW. The gas turbines in this case would have not been tripped, and the frequency level in a transient process would have been close to the nominal. The use of a self-restoration mechanism would have secured the elimination of emergency within 100 seconds, that is, unnoticed by the majority of consumers.

12. Blackout on 13.07.2004, Greece.

At the voltage avalanche initiation, the personnel tried to save the situation by diversified load shedding methods, thus provoking tripping of generating sources.

Commentary

If at 12:25 the power system had been split for a short time with the power flow from north kept at the level allowable for the grid, then on the south a frequency disturbance would have taken place which normally is eliminated by an adequate load shedding; the 400 kV line and the generating sources would in this case have kept operating. After the generator switching-on the situation would have normalised, and the load could have been re-energised.

13. Blackout on 14.03.2005, Australia.

Initially, southern Australia consumed 1500 MW, with 432 MW power flow via the 275 kV Victoria link (on the north), 37 MW Murray link, and from 15 MW wind turbines.

At 6:39 a short-circuit occurred on the 275 kV line near the northern 500 MW power plant. After that the generators' power was recovered, but 400 ms later it fell down to zero. It turned out that the manufacturers installed on the generators of two plants a special protection for stability control (Over-Speed Protection Circuit - OPC), which compares the turbine and the generator powers, and in the cases of too great difference between them in transient processes it performs fast-acting power decrease (turbine fast-valving), which corresponds to the protection using electro-hydraulic devices usually applied against stability loss. The OPC setting turned out to be erroneous, which resulted in the unnecessary turbine off-loading to zero in the transient process caused by short-circuit.

As a result of the reduction of output from power plant, the stability loss happened with tripping of two 275 kV lines and separation of the southern part. Under the conditions of frequency drop to 47.6 Hz on the south there were tripped 80 MW steam turbines and a 100 MW gas turbine together with a combined-cycle 55 MW steam turbine, which led to a blackout of the southern system part, although after operation of the under-frequency load shedding automatics the frequency recovered up to 49 Hz.

Commentary

If at the grid overload a short-term splitting had been done with a partial southern load transfer to the 275 kV lines, no blackout would have happened. Besides, this situation corroborates once more (see above the Italian blackout) the necessity of the gas turbine automatics adjustment for under-frequency operation.

14. Blackout on 25.05.2005, Russia (Moscow).

Commentary

On cutting the power supply to the still operating 220/ and 110 kV transmission grid (i.e. at short-term splitting) the under-frequency shedding automatics could have operated, with the frequency recovery and the following supply resumption at underload. This would have allowed 17 lines and 13 power plants to be kept operating.

15. Blackout on 04.11.2006, European Power System.

A hasty switching caused overload of a middle Germany transmission grid through which 9 GW power was flowing. This led to a deep voltage drop, stability loss, and system’s splitting into three parts. On the action of the under-frequency load shedding automatics the frequency in the deficient part reached 49 Hz. By a lucky chance, no large-scale disconnections of generating sources occurred.

Commentary

At the optimal short-term sectioning this could have been done not at the place of maximum power flow but at the French frontier, with much smaller load tripped. In these cases, the self-restoration mechanism eliminates the fault within some tens of seconds.

9. CONCLUSION

In our research we studied the emergency processes that have occurred in the world's power systems since the second half of the 20^{th} century from the viewpoint of adequate protection means to be created. The research resulted in the following classification:

- stability loss at short-circuits in a grid;
- stability loss at disconnection of a heavily loaded line;
- static stability loss under the conditions of voltage drop avalanche;
- mass-scale equipment tripping under out-of-step operation as a result of stability loss;
- mass-scale outage of generators caused by overloads under voltage drop avalanche;
- multiple line tripping at under-voltage that is recognised by protection as a fault;
- multiple line tripping caused by increased sagging of conductors;
- mass-scale outage of thermal units at under-frequency.

Below, the most significant findings are outlined, which were obtained when studying the mentioned emergency processes, based on the analysis of possibilities to use the existing protective structures taking into account specifics of such processes under new conditions. These results could be presented as follows.

The problem of stability loss caused by short-circuits should be related to the fulfilment of security standards, since the achieved level of transmission grid protection allows for its fast action, practically excluding the occurrence of blackouts (also of those resulting from stability loss due to circuit-breaker and protection failures). In the cases when these standards are not met, this task is delegated to the local (OPC) and centralised (matrix-wise) protections with the turbine load relief functions.

The following two classes, i.e. stability losses at tripping a heavily loaded line and at transmission voltage drop avalanche, are practically connected with transmission grid overloads.

As concerns the massive equipment tripping under out-of-step operation, it was established that similar to the processes going at HPPs during emergencies this occurs at the oil pressure decrease in the NPP turbine speed governors caused by oscillations. It has been proved once more that in such cases the out-of-step operation must be fast disrupted at the angles $< 180^{o}$ by splitting the power system into parts at the asynchronously operating cross-section. In the major loop-wise systems such splitting should be performed not at one but at several cross-sections.

The next two classes − massive tripping of generators under voltage avalanche and of lines at under-voltage (recognised by protection as a fault) − these owe to the transmission grid overloads.

The same cause underlies the multiple lines tripping due to conductors sagging and flashovers at unsuccessful re-closing. In the work a calculational procedure has been elaborated for estimating the sag of conductors and their temperature in the cases of grid overload.

When analysing the cascading disconnections of thermal units at under-frequency it could be concluded that these occur owing to mismatch between the responses of steam generating and steam consuming (turbines) units to frequency, which results in static stability loss to these units. In the work, frequency deviations during these emergencies are analysed along with the possibilities to cope with them using the available protection means and correcting the operational conditions of thermal units. It is established that the main role in the control under power deficit is played by steam generating units. The turbines, as secondary elements, should obey the operating conditions of steam units and be switched from the frequency regulation to that of steam pressure.

Since the primary cause of PS blackouts is the transmission grid overload that triggers the development of cascading processes, in the present work a protection complex against blackouts is proposed that momentarily removes the overload and automatically restores the normal system operation.

For this purpose, as the fast-acting preventive protection, a matrix-wise structure is recommended which is similar to that applied against dynamic stability loss; in this case it is used for new purposes. As a staring up element the overload signal serves, which is sent by a logic channel. Coincedent the protection system contains information on the normal condition. For overload liquidation the grid cross-section is determined through which power close to the overload level is flowing. At this place a short-term PS sectioning is performed, with simultaneous disconnection of the circuit-breakers on all lines of the cross-section on the side where synchronism-check devices are installed. Owing to these measures the overload will be liquidated, and the lines will be kept operating with maximum allowable power flows; the development of secondary faults followed by cascade-wise outage of generating units will be prevented, and the security of PS operation will be raised to a qualitatively higher level.

As a result of sectioning, in the deficient system part the minimum power shortage and reduced frequency are created, to which the under-frequency load shedding automatics responds by activating the self-restoration mechanism based on that frequency fault self-liquidation and system self-restoration first tested in the Latvian power system and afterwards successfully performing many years in several PSs, mostly, of the former USSR. In specific under-frequency cases the proposed methods for control of a thermal unit should be employed. Then in the deficient part, owing to the action of protective means with negative feedback, the frequency restores to the nominal value, whereas in the excessive system part for frequency normalisation, if necessary, the proposed local secondary regulation forcing should be used, which is followed by automatic merging of separated system parts and re-closing of consumers’ lines.

When working out the recommendation as to the use for post-emergency re-integration the synchronism-check devices already operating on the lines, the following aspects were determined and analysed: the successful domains of pulling in synchronism at enlarged angles; the ranges of switching-on current variations in comparison with the short-circuit currents at the merging places; and the character of transient switching-on process. Our investigation confirmed the results acquired in practice. It was revealed that the zone of pulling-in-synchronism process is significantly larger than those corresponding to the limited switching-on angles; at the same time, the switching-on currents are many times smaller than short-circuit currents. This means that a frequency fault can transform into a short-term stable transient process thus securing the power system's self-restoration without staff participation within 100 seconds. For studying this process as well as the performance of the proposed anti-emergency complex the V. Ivanov program Mustang has been used, which provides the possibility to control the transient processes of merging the PS parts operating with different frequencies.

In perspective, the following research directions are conceived: possibilities of using wireless channels in the proposed protection complex; its integration into different voltage grids; and the system's perfection by taking into account the most severe scenarios of emergency development; and some others.

ACKNOWLEDGEMENTS

The World Energy Council/Latvian Member Committee (WEC/LMC) has published many scientific articles on the problems of power supply which were presented and discussed at international congresses and conferences [126]-[139].

It is of importance that the monographs “Peculiarities of Annual Flows of World Rivers” by Prof. J. Barkans and Dr. sc. ing. I. Zicmane (2005, RTU, 211 pp.) and “Rational energy utilisation” by J. Barkans (2003, RTU, 287 pp., in Latvian) were dedicated to the 80th anniversary of the WEC/LMC.

The authors of the mentioned works express gratitude to the Heads of WEC/LMC: Dr. sc. ing. A Davis, Mr. K. Mikelsons and Prof. N. Zeltins, for the support.

APPENDIX 1

Analysis of emergency events

In the world, blackouts of power systems occur regularly. Fig . 1 shows the data on blackouts occurences in the North-American power systems [109], during which a) over 50 thousand consumers were deprived of electricity, and b) the tripped power exceeded 100MW.

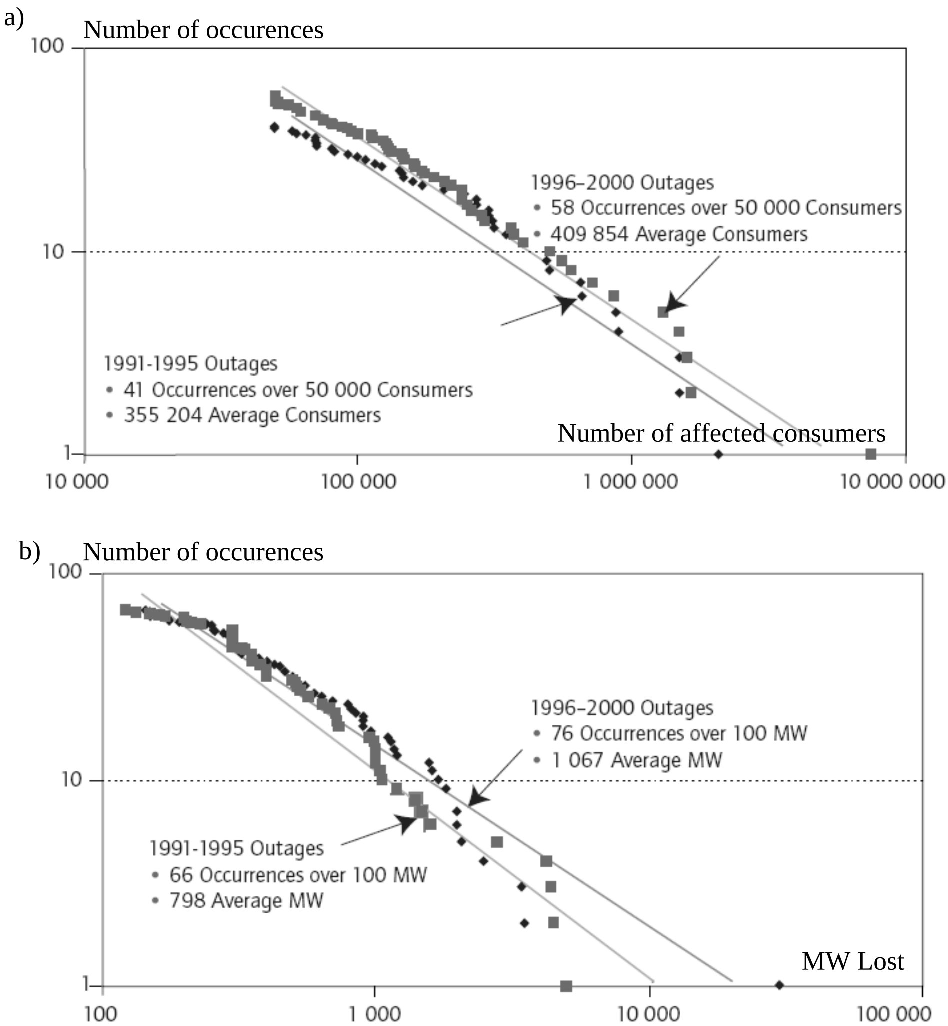


Fig . 1. The data on blackout occurences of 1991-1995 and 1996-2000 in North America

a) over 50 thousand consumers affected, b) the disconnected power exceeded 100MW.

Similar situation is also in power systems of West-European countries, Russia, and many others. Depending on the specificity of power plant operation and the amount of shed load, the restoration of electricity supply can be lasting from several hours to several days.

To the issues of protection against system blackouts numerous scientific works have been devoted; there are many monographs, as well as invented and implemented automatic systems; still, blackouts persist to occur. Obviously, something is wrong in this area, and the problem deserves a deeper analysis in order to acquire a correct notion about blackout processes in power systems; these should be analysed with the aim to find some common features, which would help to improve the relevant technical solutions.

1. Blackout on 09.11.1965, North-East of USA

The blackout occurred in the North-East power system of the USA, in the CANUSE (Canada United States Eastern Interconnection) area. Before the event, 73 % power was generated by TTPs, 26 % was produced by HPPs, and the rest – by internal combustine engines, gas turbines and 3 NPPs [40].

At 17:16 one of the five loaded 230 kV lines was disconnected (from the *Beck* HPP (*Niagara*) to *Toronto*) owing to the erroneous (underestimated) setting. On load re-distribution, in the 2.7s time the backup protection (against overload) tripped the remaining four lines (1500 MW) in the western direction, separating the *Ontario* region load from generation. After disconnection, this power began to flow in the *New-York* direction (Fig . 2) [110].

This was followed by tripping the inter-system links between *New-York* and *Ontario* (Canada), with stability loss between *Ontario* and *Detroit*. As a result, the lines on the south of *Ontario* state were tripped. In the 3.5s time owing to overload the lines connecting the *New-York* state with *Pennsylvania* were switched off. After that, the distance protection, responding to the out-of-step condition, tripped the two-circuit 345 kV line connecting the *Niagara* HPP with *New-York*. This led to splitting of the North-East power system into parts with negative power balance (except the *Maine* state).

Due to the power increase, the Niagara HPP accelerated, carrying along the related TPPs, which, under the increased frequency, were tripped. The vigorous operation of the speed governors of hydro units caused the oil pressure drop in the receivers, which was followed by tripping the units. Some units of the *St.Lawrence* HPP remained supplying the large industrial loads in the vicinity of *Massena*.

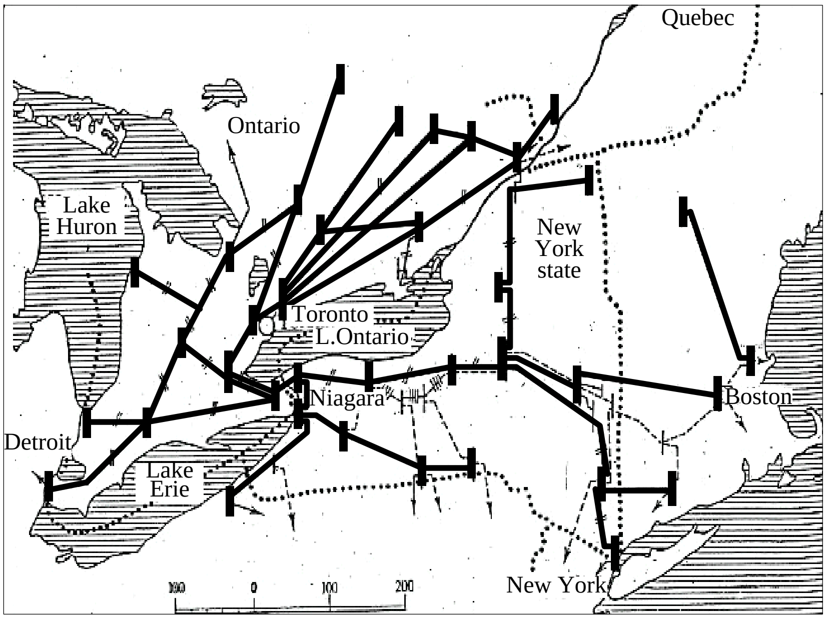


Fig . 2. The feeding scheme of the CANUSE region

Under the conditions of fast frequency fall, in the deficient regions the TPPs were tripped one after another because of under-productivity of their feed pumps. In the outage process three turbines (including a 1000MW one) were damaged. At on of them its main bearing was burned out because of a loss of oil pressure on the bearings when the auxiliary oil feed pump stopped. Only individual consumers kept receiving electrical energy from local sources.

In *New-York*, problems arose with re-closing of a 380 kV cable with high capacitive power, since this could trigger a dangerous voltage rise. So the resumption of electricity supply entailed many difficulties. As a result, this was done only on 10 November, between 3:15 and 6:15. The blackout embraced a territory of 200 thsd km^2 with the population of 30 million.

Table 1. Main causes of the outages

Power plant	Cause of outage
PASNY HPP (Niagara)	Sudden load rejection causing (>) generator acceleration (f↑) > loss of synchronism
Beck HPP (Niagara)	Sudden load rejection > generator acceleration (f↑) > the vigorous operation of the speed governors of hydro units > the oil pressure drop in the receivers
St.Lawrence HPP	Line tripping causing disconnection of 5 from 16 units
Huntley and Dunkirk TPP (Niagara)	Sudden load rejection > generator acceleration (f↑) > HPPs negativly affected TPP operation > protection tripped units to prevent damage of turbine blades due to high speed
TPP (in New York and New England states)	110 MW power shortage (f↓) > under-productivity of feed pumps and other auxillary equipment > power plant outage (at shutting down 3 turbines were damaged due to loss oil pressure drop on the bearings)

Commentary

The causes of this blackout: non-observance of the (n-1) principle; absence of the means for overload elimination; lack of the connected load for AUFLS.

2. PJM blackout on 05.06.1967, USA

At approximately 10:23 on June 5, 1967 the eastern portion of the *Pennsylvania - New Jersey – Maryland (PJM)* interconnection experienced a complete loss of power (the load in the affected area was 9279 MW [45]). Prior to this event, in the area heavy overloads and power transfers were observed.

The blackout started at 10:16, when a 230kV *Nottingham – Plymouth Meeting* line sagged due to heavy loading and flashed over when it contacted a 4 kV circuit. In the next few minutes, line loading increased causing a voltage sagged at various locations of *PJM* area. After separation, the eastern *PJM* part collapsed in the five minutes time. During the blackout 26 generators were tripped; 12 of them − due to loss of field, 6 − due to the unallowable voltage or current, 4 − by turbine protection, and 4 − by other protections.

3. New-York city blackout of 13.07.1977.

Pre-disturbance conditions: the demand for electricity in Con Edison’s service territory totalled 5868 MW, 3008 MW of which was covered by the city’s sources, and the rest − by power flows mainly from north (Fig . 3) [44]. The hot reserve was 1208 MW, and fast-start turbines − 790 MW.

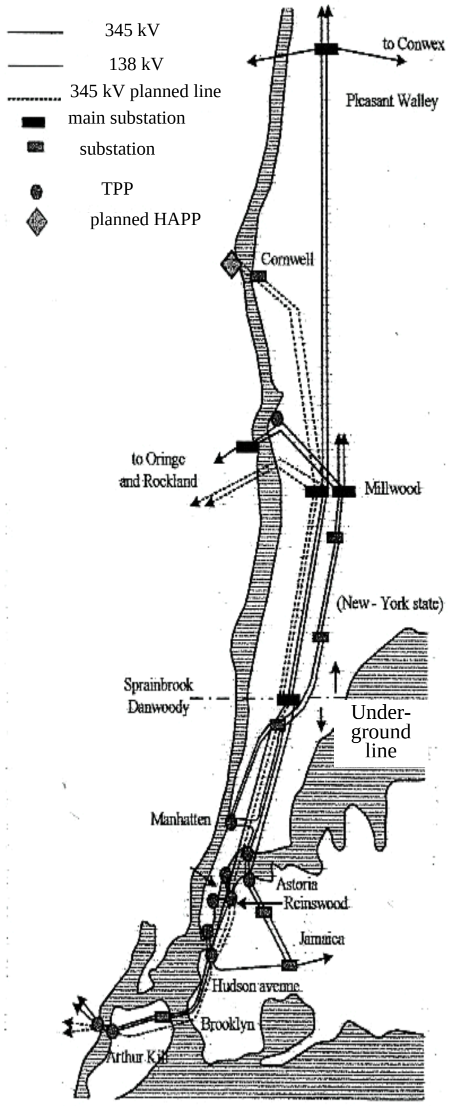


Fig . 3. Scheme of 138 kV and 345 kV grids

At 20:37 a lightning struck a tower carrying two 345kV transmission circuits linking the Buchanan and Millwood substations; in this particular case both lines (97 and 98) flashed over and were tripped by protective relays. Protective equipment automatically shut down the Indian Point 3 nuclear generator (870MW). Line 98 failed to reclose because of inadequate air pressure in a circuit breaker (the result of a loose locking nut). Also line 97 did not reclose. Circuit 88 opened when an improperly designed breaker-failure timer incorrectly triggered a backup relay. At 20:55 a second lightning stroke hit another two-circuit tower, with lines 93 and 99 switched off (Fig . 4). One of them reclosed, whereas the other's re-closing was rejected by the synchronism-check device owing to a large angle. Later on, due to erroneous operation of the distance protection, one-end tripping of one more line occurred, also not re-closed automaticly. As a result of tripping these four lines, for 15 min the *New-York* power system turned out to be connected with other power systems only through three heavily loaded lines: a north-bound 345 kV line, a west-bound 220 kV line, and the 138 kV *Long-Island* line. To eliminate the overload, power reserves were mobilised, and the load was reduced by 8% with voltage drop in the grid; however, the line overloading continued.

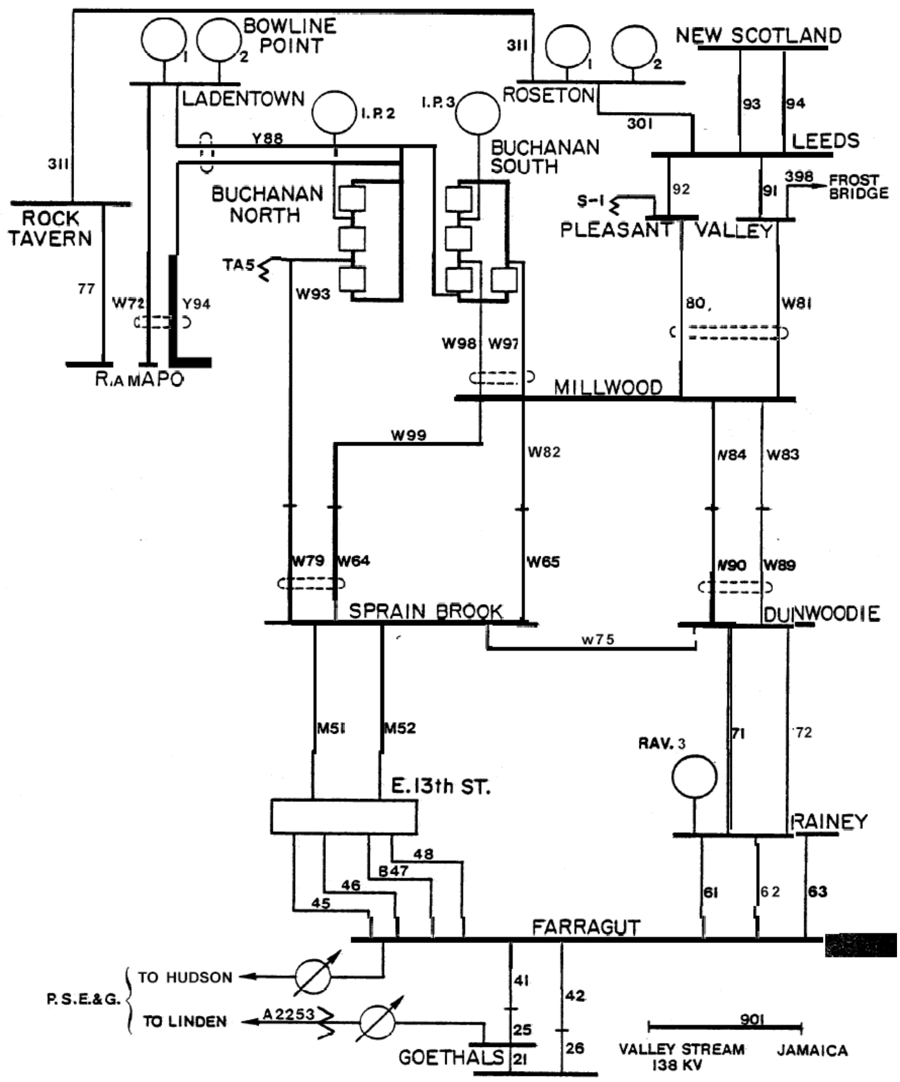


Fig . 4. Scheme of the 345kV system

At 21:19, overload caused line to heat up, expand and sag toward to ground; as a result, the last north-bound 345 kV line (line 92) was tripped (sagging into a tree). At 21:22 the line to *Long-Island* was opened manually, in order to prevent thermal damage of conductors. At 21:23 an attempt was made of its re-connection with north, but due to overload the line was opened again. At 21:29, owing to conductor sagging flashover occurred, and the last west-bound link was tripped.

The *New-York* power system was separated with 1700 MW generation deficit. As a result of under-frequency load shedding automatics (AUFLS) operation, 1830 MW of the consumers' power was tripped; with decreasing active load also the reactive load decreased. The main feeding line in *New-York* is the urban 345 kV cable with high capacitive power (owing to its capacitance), which at reduced reactive power consumption became the cause of a voltage rise. The resultant reaction of generator excitation regulators led to loss of field. For high-power generators (since out-of-step running of generators must not be allowed) the protection decreased the turbine active power; after that, as a response to the field loss, they were tripped. As a result of such protection, the 1000MW generator at the *Ravenswood* urban power station was switched off. The frequency in the system declined again, and, as the AUFLS had already operated, the feed pumps at all urban power plants failed, causing protective relaying equipment to shut down most of the remaining generating units.

Electricity supply was resumed after 26 hours. The circuits of breakers' activation needed compressed air; however this was spent during previous operations. To replenish it, there was required voltage, which was absent in the grid; to switch on the circuit-breakers, it was necessary to find jacks, and so on.

The cable needed cooling by circulating oil provided by pump stations − in turn, they needed electricity. All this aggravated the restoration process.

Failures of protective alarm systems in the city led to rise in criminal acts (marauding), so they had social consequences. Direct losses were estimated to be 10 million $, but, taking into account the criminal acts, they were many hundreds of thousands dollars greater.

Table 2. The main causes of the outages

Power plant	Cause of outage
Indian Point 3	Line tripping > protective equipment automatically shut down nuclear generator
Power plants in the NY area	generation deficiency (f↓) > under-productivity of feed pumps and other auxiliary equipment > automatics shut down power plants generation deficiency > load shedding > reactive power increase > high capacitive power increase due to cable no-load > voltage increase > loss of field > generator tripping

Commentary

Lack of protections against voltage rise caused blackout development.

4. Blackout on 19.12.1978 in France

That time a bitter frost happened, which led to load increase [6], [16].

At 8:00 a.m. the pre-emergency load was 38.5 GW, i.e. by 1 GW greater than the forecast. The power received from Germany and Belgium was 3 GW, which exceeded the planned by 10%. As a result of line overload the voltage in the transmission grid fell from 400 to 370-380 kV.

At 8:25 the load additionally rose by 1-1.5 GW, also at the cost of inter-system power flows. The frequency began to decrease; the AUFLS operated, however the voltage continued to fall, reaching 340-370 kV. During this time the thermal stations' power fell by 500-1000 MW. The personnel tried various measures to keep the voltage level though without success − the voltage in the western regions kept decreasing.

At 8:26 from overload the 400 kV *Bezaumont – Creney* line (east of France) was tripped. After that, triggered by overload, two 400 kV lines that connect the France power system with Belgium were tripped one after another, and the *Reven* HPP near Belgium frontier was lost.

Owing to stability loss the out-of-step condition arose, as a result of which the power system split up into north-east, east, and partly south-east islands, where electricity supply continued. The Spanish links were opened. In the remaining system part a deep voltage drop followed by AUFLS failure took place. 65% of power plants were shut down. Some of them separated and continued to feed the local load.

The large-scale resumption of power supply to consumers began at 9:00. In Paris this was done after 3-4 hours, in other places after 2-4 hours, on the west − after 3-5 hours. Some regions remained de-energised longer.

Commentary

The cause of the emergency event: imperfect AUFLS, which failed at voltage drop. The power plants could be tripped both due to under-voltage and under-frequency. Also, the means for elimination of cascading line overload and voltage avalanche were absent.

5. Blackout on 04.08.1982 in Belgium

The pre-emergency consumption was 5489 MW. The generated active power −5314 MW (23%), the rotating reserve −1290 MW, the consumable reactive power − 2538 MWr, the rotating reserve of reactive power − 835 MVar (33%), import 175 MW, export 95 MW [6].

Owing to the repair works on one of the lines, the state's northern part was connected with its southern part through one 380 kV line with power flows 700 MW and 449 MVar, and through several lines of lower voltage.

The emergency started after the technological protection of one NPP block had been tripped at the power receiving end of the line. The arising power shortage caused overload of other generators. After 2.5-4.5 min the external damage protections switched off 5 NPP and TPP generators. The generation shortage in the northern and central regions was 1809 MW and 1077 MVar, which caused the overload of 85% in the line, and this was tripped by overload protection.

The remaining 150 and 70 kV lines were tripped due to stability loss. In the northern system part the voltage and frequency avalanches arose; under the low voltage the AUFLS failed to operate, which did not allow keeping the frequency in the zone not dangerous for power plants. As a result, all of them were tripped, and the region was blacked out. The consumers were devoid of 2400 MW electricity. The power system resumed the normal operation after 6 hours.

Commentary

The causes: non-observance of the (n-1) principle; imperfect AUFLS (sensitive to voltage); the means for elimination of line overload and voltage avalanche were absent.

6. Blackout on 14.12.1982 in Canada

A simplified scheme of the *Hydro Quebec* PS and its power flows before the emergency are shown in Fig . 5 [6]. The main 735 kV grid is formed by two radial three-circuit transmission lines (over 1000 km) and one DC line through which the electric energy from major HPPs to the regional *Quebec and Montreal* load centres is transferred.

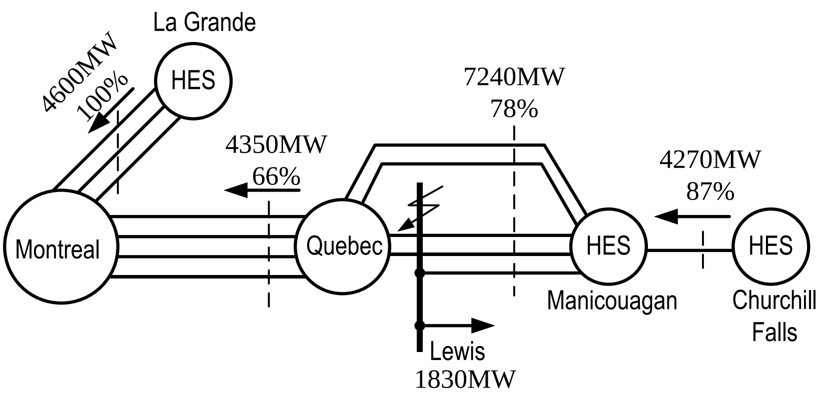


Fig . 5. The scheme of *Hydro Quebec* power system

The total power of the *Hydro Quebec* system in the *Labrador* Peninsula was 15946 MW (16 *La Grande* units, 5213MW; 36 *Manicougan +Outardes* units, 5508 MW*;* 11 *Churchill Falls* units, 5225 MW).

At 13:21 a current transformer burst up at one of the substations, which triggered short-circuit on busbars, which were tripped by the busbar differential protection. After 1.5 s the ingress of ionised gas led to short-circuit on the second busbar system, and it was also switched off by the busbar differential protection. As a result, one of the *Monicougan-Quebec* lines with great power flows became disconnected, and 6000 MW were re-distributed between two keeping operation *Monicougan-Quebec* lines; having lost stability, these were overloaded and 1s later tripped by protection. After one more second, in the same way, three *La Grande-Montreal* lines that had lost stability owing to power rise were overloaded and tripped.

As a result, 2 s after the second short-circuit the *Montreal - Quebec* load centre loses 10000MW; owing to the voltage and frequency drop the auxillary services was lost at thermal plants with a capacity of 1062 MW. The *La Grande – Churchill Falls* lines were isolated for feeding separate loads; however, they were tripped due to overvoltage (1.6-1.8U_{nom}).

Supply for 90% of load was resumed after 5.5 hours; for all other consumers − after 20 hours. 11 thousand of the *Quebec* region's consumers received voltage only at 15:12 owing to the equipment over-voltage damage, which arose under the idle running of the 735 kV line. The losses made up three million $, not counting the expenses of damaged equipment repair and overtime work.

Commentary

The conclusion is as follows. If in the power system there had been preventive division automatics that would have separated the *Monreal- Quebec* lines at overloading of the *Monicougan - Quebec* lines with isolation of *Monicougan* lines with smaller load, these would have been overloaded and voltage avalanche would not have occurred, while on *Quebec* lines, which are on the *Churchill* HPP link, the frequency decline would have been eliminated by AUFLS.

7. Blackout on 22.12.1982 of the USA West cost power system

This blackout embraced a 12.35 GW load area with 5 million populations [65].

A storm turned over a 500 kV line tower, which fell onto the parallel 500 kV line tower thus causing fall of three towers of both the lines followed by their tripping. The line conductors fell onto two 230 kV lines. This resulted in system splitting into four parts. As noted, the protection and personnel were not coordinated and did not correspond to the process running.

In addition, the volume and format in which the data were displayed to operators made it difficult for them to assess the extent of the disturbance and the necessary corrective actions.

8. Blackout on 27.12.1983 in Sweden

The Swedish power system is formed by a grid (Fig . 6) consisting of seven 400 kV line chains with series and parallel compensation [6]. Over this grid large power flows are transferred from the HPPs on the north to the southern load centres, where two NPPs: *Forsmark* and *Oskarshamn* are located.

The pre-emergency system's load was 18300 MW, including the 320 MW export to Finland and 920 MW of electro-boilers' load. This load was covered: on the state's north by HPPs − 10850 MW, on the south −5600 MW, and by the Norwegian import −13500 MW. The north-south power flow reached 5600 MW (93.6%).

At 12:20 one *Oskarshamn* unit, which operated with a power of 490 MW, was shut down. At that time at the *Hamra* substation to the north of *Stockholm* the switchings were performed for repairing an overheated disconnector.

At 12:57 the disconnector was broken when switched, which caused ground short-circuit on the busbars between the power circuit-breaker and the current transformer. Since two 400 kV busbar systems were closely connected, the differential protection, when switching them off, simultaneously tripped four 400 kV lines connected to these busbars, including two north-south transmission lines. This caused overload of the lines keeping operation and voltage drop at the *Hallsberg* and *Kimstadt* substations to 350-360 kV.

At the beginning, the voltage drop caused by load reduction in compliance with static curves, which to an extent off-loaded the transmission grid. Then the voltage regulators of autotransformers restored the voltage in the 220 kV grid, and the load was re-energised.

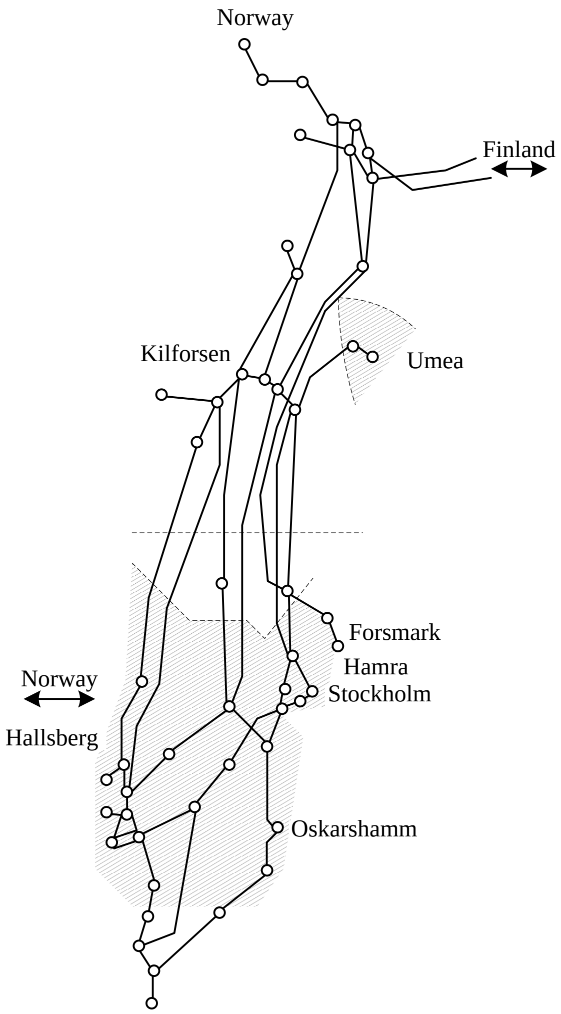


Fig . 6. Scheme of Swedish supply

On tripping the *Hamra* substation due to overload the 220 kV line with power flowing from the north was opened. After 45 s, the overload caused disconnection of the two phases at one end of *Hallsberg-Kilforsen* 400 kV line. Owing to voltage rise, at the disconnected end a one-phase short-circuit happened. Due to mutual induction, the zero-succession currents of faulty lines induced current in a parallel line, which was tripped fast by the protection against ground short-circuits. In such a way, after 10 min from the fault beginning two more 400 kV north-south transmission lines turned out to be disconnected. As a result of transmission overload, in the southern part of power system a frequency decline occurred and the transmission stability was lost, with complete PS splitting into two parts. The power shortage in the southern part was 7000 MW. Apart from that, the voltage and frequency decreased. Most of the AUFLS, being sensitive to voltage, failed. All the NPP generators were tripped by the overload protection, and the southern part of power system appeared to be blacked out.

A two-phase short-circuit tripping of a 400 kV line was made by the protections of neighbouring interconnections, which led to the *Engerman River-Umea River* line disconnection. After that, under overload, a 130 kV line was opened, and the *Umea River* region separated with a power surplus, which caused a frequency rise above the allowable level. The frequency limitation automatics tripped the excessive generator power, and under the conditions of a deep frequency fall the region was blacked out.

In the northern system part a large power surplus formed, with frequency reaching 54 Hz, so the frequency limitation automatics partly switched the generators off. This was followed by separation from Finland and northern Norway.

In the most part the power system's scheme was restored within 1h and 28s. During the emergency, gas turbines and reserve heavy-oil-fuelled TPPs were set in operation. At 21:00 the gas turbines were stopped. The 1st block of the NPP was started up at 23:35, and the last one − in two days' time.

Table 3. The main causes of the outages

Power plant	Cause of outage
NPP of southern part	Generation deficiency (f↓ un U↓) > partial AUSLS failure > tripping of ģenerators by external damage protection due to overload and under-voltage
Power surplus area	Power surplus (f↑) > generator excessive power tripped by protection > f↓ > power plant shut down

Commentary

Causes of the blackout: imperfect AUFLS; absence of preventive automatics, which would remove the overload of transmission grid.

Table 4. Anti-emergency automatics of Scandinavian power system

Country	Action on load, AUFLS	Action on generating units
Sweden	AUFLS: 30% load on 5 stages (48.8, 48.6, 48.4, 48.2 and 48.0 Hz), time setting 0.15s Tripping of water boilers and pumps with time setting 0.15s: 34MW at 49.8 Hz; 25-35 MW at 49.3 Hz; 15-25 MW at 48.6 Hz and 5-15 MW at 49.1 Hz	Mobilisation of generating units: 520MW gas turbines on 3 stages by 0.1Hz
Danmark	East: 50% on 5 stages: simultaneously at 48.5Hz, additionally at 48.7Hz; 20 s at 48.3, 48.5, 48.1, 48.3, 47.9, 48.1, 47.7, 47.9 Hz West: 15% at 48.7 Hz and 25% at 47.7 Hz	Running of 60MW diesel units (60s)
Norway	7000 MW to stages at 49.0-47.0 HZ	
Finland	AUFLS: 10% 48.5 Hz 0.15 s and 48.7 Hz 20 s 10% 48.3 Hz 0.15 s and 48.5 Hz 20 s	Mobilising of 180MW of gas turbine, 15s

Country	Line tripping by frequency	Splitting by voltage variation and line overload
Denmark	Tripping of Swedish interconnection by 47 Hz 0.5 s or 47.5 Hz 9 s	
Finland	Tripping of DC Vyborg interconnection by 52 Hz 0.5 s	
	Tripping of Northern interconnection with Sweden by	

Country	Line tripping by frequency	Splitting by voltage variation and line overload
	50.7 Hz 2s, at import from Sweden over 900MW and voltage lower than 380kV	
Sweden		Two splitting automatics decrease export to continent through DC line at the threat of voltage drop avalanche or overload of important lines. Voltage is measured at various places and protection operates with time delay 2-4s. At voltage decrease in four places one group of lines is disconnected, in two places – other group, as a result transmission grid is relief. The automatics are located Denmark, Germany (two) and Finland
Norway		The Skagerak cable is tripped by 275 and 270 kV voltage, thus relieving grid in two stages by 200 +200 MW
Finland		By critical parameters the interconnection with Sweden is opened at Finland end, decreasing power flow by 200 and 400MW

9. Tennissee blackout on 22.08.1987, USA

On August 22, 1987, during a heat storm, a 115kV switch flashed phase-to-phase while the operator was attempting to isolate a damaged air blast breaker [45]. Because the faulted bus lacked a bus differential protection scheme, the fault continued for more than a second and was eventually cleared by backup relays at remote locations. Due to the long fault duration, motor loads in *Memphis* and the surrounding area began to stall and draw large amounts of reactive power even after the fault was cleared. A depressed voltage condition developed on both the 161 and 50kV systems in Southwestern Tennessee and continued for 10 and 15 seconds. During this time, zone 3 distance relays at several remote substations began to trip. Voltage controlled / restrained overcurrent and distance relays on generators also tripped. This started a cascading effect that eventually tripped all source lines.

10. Blackout on 21.02.1995, USA

On February 21, 1995 a 230 kV lightning arrester on the *Whitpain – North Wales* line failed. The ensuing fault was cleared in 5 cycles by actions of the relays and breakers at the line terminals. However, in addition to the faulted line, 6 other transmission lines incorrectly tripped for various reasons. Approximately 1 second later, at *North Wales,* the line automatically reclosed into the fault. The *North Wales* relays failed to clear the fault, which lasted for 2 seconds before being cleared by the action of relays and breakers at remote stations. During the second, 4 more transmission lines tripped for various causes. In addition, during the second fault, the *Limerick* 1 and 2 generators were tripped by ground overcurrent relays connected to their step-up transformers.

11. Oswego (New-York district) blackout of 26.04.1995.

Pre-disturbance condition: The *Oswego* area is capable of exporting 1700 MW of oil-fired generation from the *Oswego* TPP (Niagara *Mohawk* co.), 2500 MW from nuclear generation of *Nine Mile* and *Fitzpatrik* units and 1100 MW of combined-cycle gas-fired generation from the *Sithe Indepedence* station [111]. On the day of emergency, the *Oswego* TPP and the 2nd unit of *Nine Mile* NPP were out of service.

During the relay calibration, busbar A of the *Volney* substation and the 345 kV line *Scriba-Volney* (Fig . 7) were erroneously tripped. Four minutes later, two 345 kV lines

Scriba-Volney and *Oswego-Volney* were opened due to a phase “B” fault on *Volney* disconnect. Besides, due to erroneous operation of the distance protection at the *Clay* substation the 345 kV line *Nine Mile 1-Clay* was opened.

Dispatching activities and blackout development: first, the command was issued to shut down the 300 MW unit at the *Independence* TPP. Ten minutes later, a 345 kV *Volney-Marcy* line was opened by supervisory control because of arcing on a second *Volney* disconnect. Additionally, 200 MW power at the *Independence* electrical power station was tripped. Next, *Volney* busbar *A* and *Scriba-Volney & Nine-Mile 1-Clay* lines were re-closed. Upon the situation analysis by special power exchange and failure estimation programs it was allowed to raise the power up to 760 MW.

After the disconnect had been repaired, the *Volney-Marcy* line was restored to service and the *Independence* power was raised to the initial.

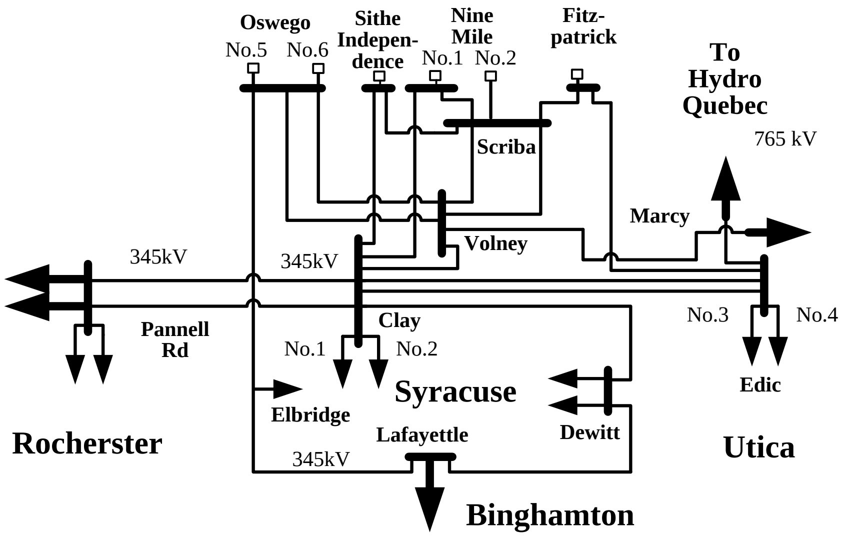


Fig . 7. The main links of 345 kV grid

Commentary

The fact that almost simultaneously two disconnectors failed evidences that at the power flow re-distribution the lines became overloaded, which was inadmissible for the disconnectors at the *Volney* substation. Therefore the carrying capacity of the lines can also be limited by disconnectors when the situation turns out to be bad.

To protect the power system against undesirable consequences, the command was issued to trip the power of the generating station at the power sending end by 500 MW. In the emergency process the grid overload did not reach the blackout level. However, in the cases when such an overload reaches a dangerous level the staff commands will be overdue, and only a preventive anti-emergency fast-acting protection can save the situation.

12. Blackout of the Israel power system of 08.06.1995.

The data on the power system: 400 kV; 161 and 110 kV transmission grids (Fig . 8) [112]. The system condition prior to the power failure: the air temperature $+35^0 C$, the predicted peak demand - 4500 MW; an additional problem was a low voltage profile in the central and southern parts of system.

At 13:15 two generators tripped in the central part of the country owing to a busbar short-circuit, which raised the power flow from north to south. At 13:36, the fire under a 161 kV two-circuit line knocked both circuits out of operation. On the south a voltage drop took place.

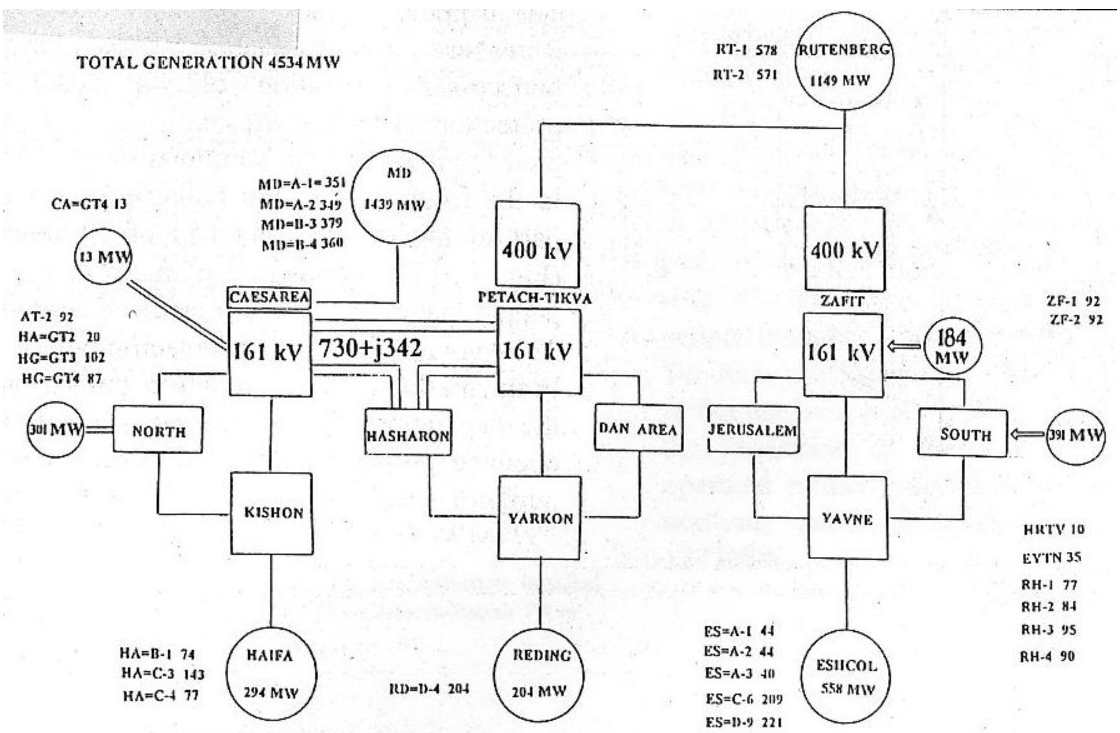


Fig . 8. Scheme of the Israel power system before blackout

At 13:50 in the southern system part the gas turbine was tripped owing to overload (over-excitation). In the overloaded grid the voltage fell deeper, and the stability was lost until the 4th zone of distance protection operated, dividing the power system into two parts. During oscillations two 550 MW units were tripped by unneccessary operation of the stator coolant protection. After the trip, both units still supplied their auxiliaries. In the southern part a 900 MW deficit was created, which caused a frequency decrease and load shedding situation. AUFLS was insufficient, the frequency was held up at a low level, and in this system part all the generating sources were shut down. Three million residents were left without electricity (Tel-Aviv and Jerusalem).

In the northern part three generating plants were tripped under low load.

The southern part's restoration started from actuation of 50 MW gas turbines. Supply for 70% of consumers was resumed at 17:00, with complete system restoration achieved at 18:00.

13. Blackout on 02. and 03.07.1996 in the USA West coast power system

The emergency event occurred in the western power systems (WSCC), which within 35 s time was split into five islands (Fig . 9), having left without electricity about 2 million consumers (load of 11.850 GW) in the USA (*Arizona, California, Colorado, Idaho, Montana, Nebraska, Nevada, New Mexico, Oregon, South Dakota, Texas, Utah, Washington, Wyoming*), Canada (*Alberta, British Columbia*) and Mexico (*Baja California Norte*) [113]. The restoration of normal operation lasted from 30 min up to more than 6 hours [114].

Owing to elevated air temperature (+38^{o}C) the load in the southern *Idaho* and *Utan* considerably rose. The blackout started at 14:24 with the 345 kV *Jim Bridger-Kinport* line (the *Idaho- Wyoming* link) disconnection (Fig . 9, Fig . 10) when conductors sagged into trees. Due to the error of protection a parallel 345 kV line (*Jim Bridger-Goshen*) was disconnected; then the special protection tripped two of the four generators (1040 MW), since the grid cross-section could not transmit the *Jim Bridger-Goshen* plant's power (2 in Fig . 9). As a result, the frequency in the interconnected power system fell to 59.9 Hz. At changed carrying capacity of the grid the voltage began to decrease fast in the *Boise* region (*Kinport*, *Midpoint, Boise,* and others); at the same time, power flow increased in the *California-Oregon* direction (the 500 kV line *Summer Lake – Midpoint*). Under low voltage in the *Boise* surroundings several minor HPPs were tripped.

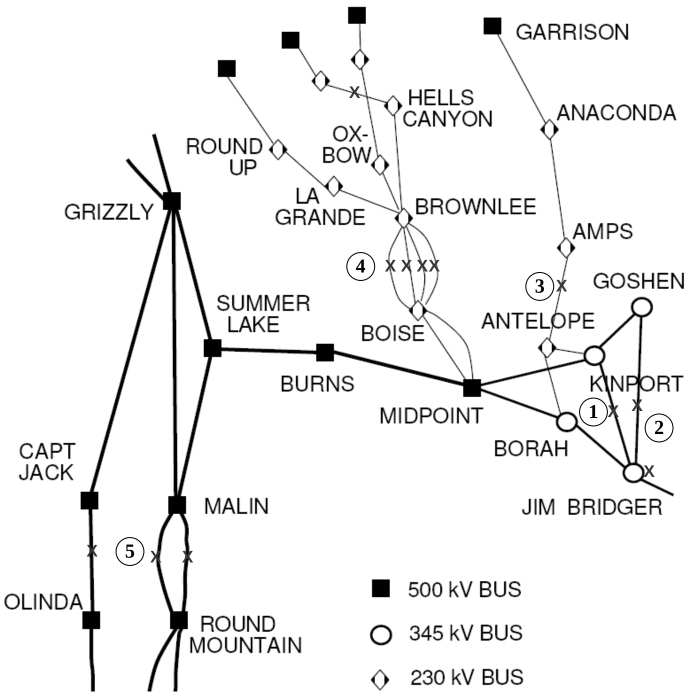


Fig . 9. The main episodes of the blackout

After 24 hours, on the operation of the 3rd distance protection zone (large overload, low voltage) the 230 kV line *Anaconda – Antelope* between *Montana* and *Idaho* states (3) was disconnected, causing fast voltage drop in the *Boise* and *Malin* region followed by tripping four 230 kV *Brownlee – Boise* lines (3rd and 2nd zones of distance protection) (4). Under low voltage conditions the automatics at *Capt Jack* and *Malin* substations operated, switching off three 500 kV - 4000MW lines in the *NW Pacific – California* cross-section (5), which resulted in stability loss (Fig . 10).

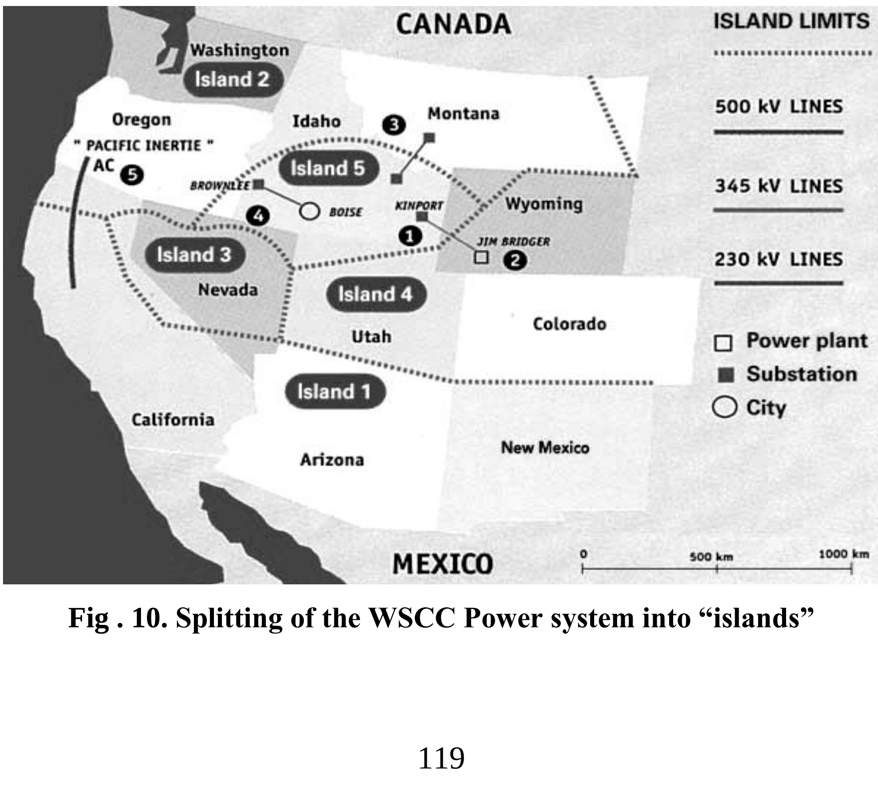


Fig . 10. Splitting of the WSCC Power system into "islands"

The loss of the *NW Pacific – California* interconnection (5) activated the remedial action scheme (RAS), which then switched off 2477 MW generation on the north-west and switched on the dynamic braking. Apart from that, responding to the loss of synchronism, special division automatics was activated in order to stop the blackout process [115]. As a result, the western power systems split up into five islands (see Fig.10). This reduced the amount of consumer tripping and speeded up the power system restoration.

Similar events repeated on 3 July. When in the *Boise* region a dangerous voltage drop began, the operators shed the load manually thus stopping the blackout progress [113], [116].

14. Blackout on 10.08.1996 in the USA West coast power system

The blackout occurred in the western power systems (WSCC), at a high air temperature (+38^{o}C) having left without electricity 7.49 million inhabitants (load 30.9 GW) in the USA (*Arizona, California, Colorado, Idaho, Montana, Nebraska, Nevada, New Mexico, Oregon, South Dakota, Texas, Utah, Washington, Wyoming*), Canada (*Alberta, British Columbia*) and Mexico (*Baja California Norte*) [114]. The electricity supply was resumed after 9 hours.

The power flows via the *California – Oregon* cross-section was 4350 MW, from Canada *B.C. Hydro – Northwest* – 2300 MW, while through the *Pacific* DC link – 2848 MW [117].

Increased sag of conductors into trees on the 500 kV line *Big Eddy - Ostrander* happened (Fig . 11, 0). The grid overloaded, the voltage began to decrease, which led to disconnection of two more 500 kV lines *John Day – Marion - Lana* (0) and one 230 kV line caused by ground short-circuit.

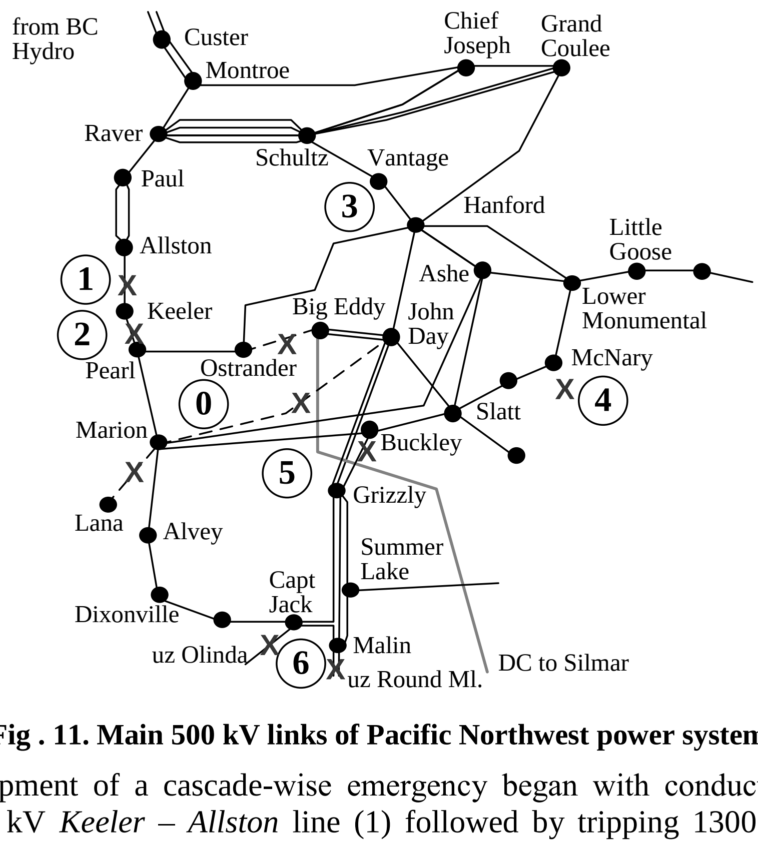


Fig . 11. Main 500 kV links of Pacific Northwest power system

The development of a cascade-wise emergency began with conductors' overlapping trees on the 500 kV *Keeler – Allston* line (1) followed by tripping 1300 MW power. On disconnection of the 500 kV *Allston - Keeler – Pearl* line the power flows were re-distributed among *Hanford* lines (3) and also among 115 and 230 kV grids. Under the overload the voltage in the region of *Hanford, Big Eddy, John Day* and *McNary* substations fell significantly. Under the conditions of voltage avalanche the line tripping began, and the protections of the *McNary* power plant switched off by error all the units (500 MW) (4) thus causing stability loss [113]. On the disconnection of the 500kV *Buckley – Grizzly* line (5), the voltage at *Malin* substation fell down to 315 kV, causing the disconnection of *California - Oregon* links (6). As the cascade-wise disconnections caused by low voltage and loss of synchronism continued, the united power system split up into four parts.

The main causes of generating sources' disconnections (22988 MW) were: long-lasting low voltage, sudden load rejection, power system's oscillations, low frequency, high voltage, and excitation system's problems [45].

15. Blackout of the Bangladesh power system, 20.06.1998.

The pre-emergency load was 1918 MW and the generation 1970 MW [118]. The event occurred at 19:10; at the time of peak load a 230 kV- 226 MW two-circuit line was tripped. In the blackout process 24 generators and a large number of lines were switched off. The power system's operation was resumed 11 hours and 28 minutes later, on the next day.

The complete information on the blackout was not recorded. The large number of disconnections could be evidence for the operation of protective means under deeply decreased voltage or for the sagging of line conductors. Both these cases are indicative of line overload. The generators could have been tripped under voltage avalanche conditions or owing to thermal equipment stability loss at under-frequency.

16. Blackout on 25.06.1998, USA, north-west

This disturbance resulted in the loss of 950 MW load and affected 152 thsd people in *Minesota*, *Montana*, *South Dakota* and *Wisconsin* (USA), and *Ontario*, *Manitoba* and *Saskatchewan* (Canada) [65].

During a thunderstorm a 345 kV line was tripped. Under reduced voltage the line was overloaded, thus adding to system's weakening. Then a lightning struck the second 345 kV line, taking it out of service as well. Following this outage, the remaining lower voltage transmission lines in the area became significantly overloaded, and relays tripped them. This cascading removal of lines from service continued until the entire northern region was separated from the Eastern Interconnection, forming three islands and resulting in the eventual blackout of the northwest *Ontario Hydro* system.

17. Blackout on 11. 03.1999 in Brazil

As a result of a 440 kV busbar short-circuit to ground at the *Bauru s*ubstation five 440 kV lines were tripped. At the beginning, the power system kept operating, but then collapsed owing to erroneous protective actions. This was followed by cascading outages of power plants in the *Sro Paulo* region and later on − by disconnection of DC and 750 kV Itaip lines and 24731 MW tripped. The blackout was felt by 75 million inhabitants for 4 hours [119].

From the system, several still operating parts with 10 GW power separated. Normal condition in the southern region was restored within 49 min. Power supply to *Minas Gerais, Goibs, Federal* region, *Mato Grosso*, and *Ticantins* was resumed in 30 min. However, such restoration in *Federal* cities *Sro Paulo*, *Rio de Janeiro, Espirito Santo* and *Mato Grosso do Sul* proceeded much slower (4 hours) owing to unforeseen problems and equipment damage.

18. Voltage avalanche condition without blackout, 06-07.07.1999, North-West of USA

The load in the PJM system was 51.6 GW [65]. In the system all emergency procedures were used (including a 5% voltage reduction) except manually tripping load, and 5000 MW were imported from external systems to serve the customer demand.

The voltage fell by 5%, and all the capacities available were mobilised; all the foreseen anti-emergency countermeasures were taken in the middle and in the evenings of both days. The voltage in the transmission grid decreased; however, owing to the mentioned measures applied it was possible to hold the voltage. The high reactive power losses in the grid caused higher reactive power consumption owing to large active power flows.

19. Blackout in Croatia - Bosnia on 12.01.2003.

The power system's grid consists of 400 kV EU lines from Slovenia, 220 kV lines and local 110 kV lines. Total loading was 2023 MW (peak value around 2700 MW) [120]. Under bad weather conditions in the *Dalmatia* region, 7 transmission lines were tripped. The main power flow directions are shown in Fig . 12 [43].

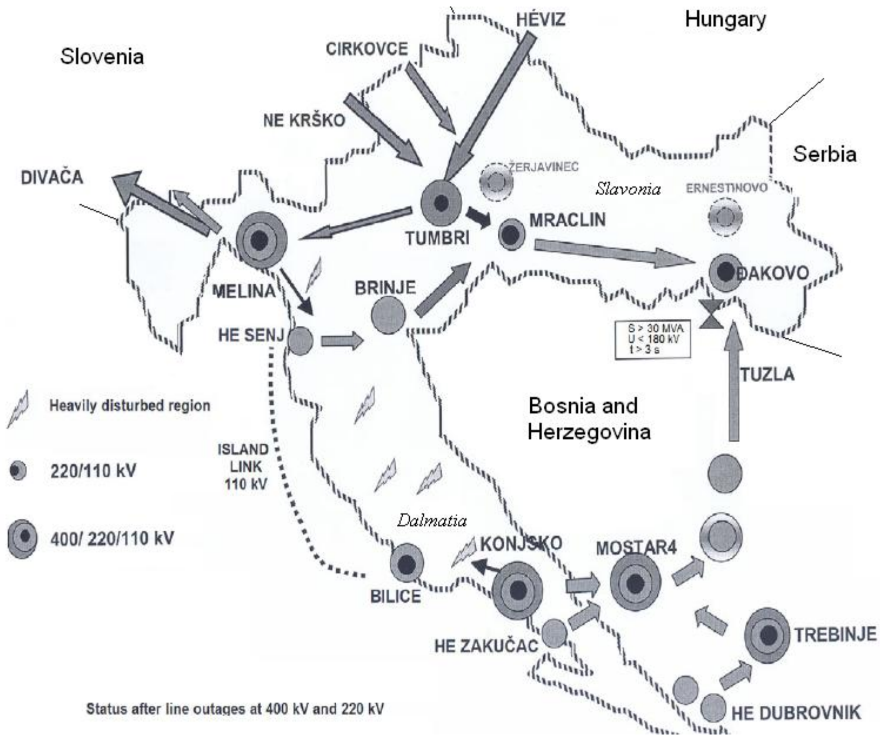


Fig . 12. Directions of power flows in the Croatian PS before blackout

The blackout began with three-phase short-circuit on the 400 kV *Velebit-Konjsko* line. In the power circuit-breaker at the *Konjsko* substation one of the phases failed, and, since the *Konjsko* 400 kV busbar had neither busbar nor circuit-breaker failure protections (SBA), the non-symmetrical operation was not disrupted. This caused cascading disconnections of lines (by distance protections) and power plants within 30 s owing to response of excitation regulators to low voltage in the *Dalmatia* region.

The transmission grid's overload resulted in a voltage avalanche spreading also in the Slavonia region, to which special protection responded by tripping the *Dakovo-Tuzla* northern link and activating the load shedding automatics by the voltage drop indication. This saved the Slavonia region from blackout which afterwards developed in the *Dalmatia* region.

As a result, in the emergency zone in Croatia and Bosnia the generators at several power plants were tripped; due to overload several autotransformers and transformers switched off; under the conditions of power avalanche the 110 kV lines were disconnected.

20. USA-Canada blackout on 14.08.2003.

The weather being hot ($+32°C$) and windless (0-0.6m/s), the load in the *First Energy* controlled region grew by 20% [65]. According to the USA standards, the temperature allowable for a long time span is $t_{al} = 90°C$, and for a short one $t_{\max} = 100°C$. When it is hot and windless, at constant load the conductor temperature can rise from 60 to 100°C, which seemingly was taken into account at establishing the limitations on power flows. The power systems were fitted with 1) load shedding by frequency decline (25-30%) with the settings

59.3 – 57.5 Hz ($\Delta f = 1.16 \div 4.16\%$); 2) load shedding by voltage drop $\Delta U = 92 - 89\%$, with settings of several seconds [121].

At 13:31 (before emergency) the *Estlake 5* (595 MW), power plant was shut down, which was followed by increase in the line load. No additional power flow limitation was set.

At 14:02, the *Stuart-Atlanta* 345 kV lines tripped due to contact with a tree, causing a short-circuit to ground, and locked out (unsuccessful re-closing); at increased load in the grid the voltage fell and reactive power flows grew. At 14:14 the monitoring system (SCADA, EMS) failed. At 14:27 the 345 kV *Star-South Canton* line was tripped (successful AAI). The distribution of power flows at 15:05 is shown in Fig . 13.

At 15:32, owing to increased sagging the 345 kV *Hanna-Juniper* line was disconnected at 88% loading.

At 15:27-41 also the 345 kV *Star-South Canton* line switched off three times for the same reason (conductor sagging into trees) − the 3rd time re-closing was unsuccessful.

The power flows over 138 and 69 kV grids increased. At 15:59, *West Akron* 138 kV busbar tripped due to a circuit breaker failure, which caused the five remaining 138 kV lines connected to the *West Akron* substation to open. At 16:00-09 four 138 kV lines with 160-180% overload and a 345 kV s line (overload possibly 120%) were tripped.

Low voltage. At 16:06-09 three 345 kV lines were disconnected by distance protections, which at under-voltage react to overload as to short-circuit. A cascade of power plants' disconnections (937 MW) started. On one of the lines the reactive power flow grew 10 times, with a voltage drop down to 80% of nominal. On the line to *New-York* power oscillations appeared.

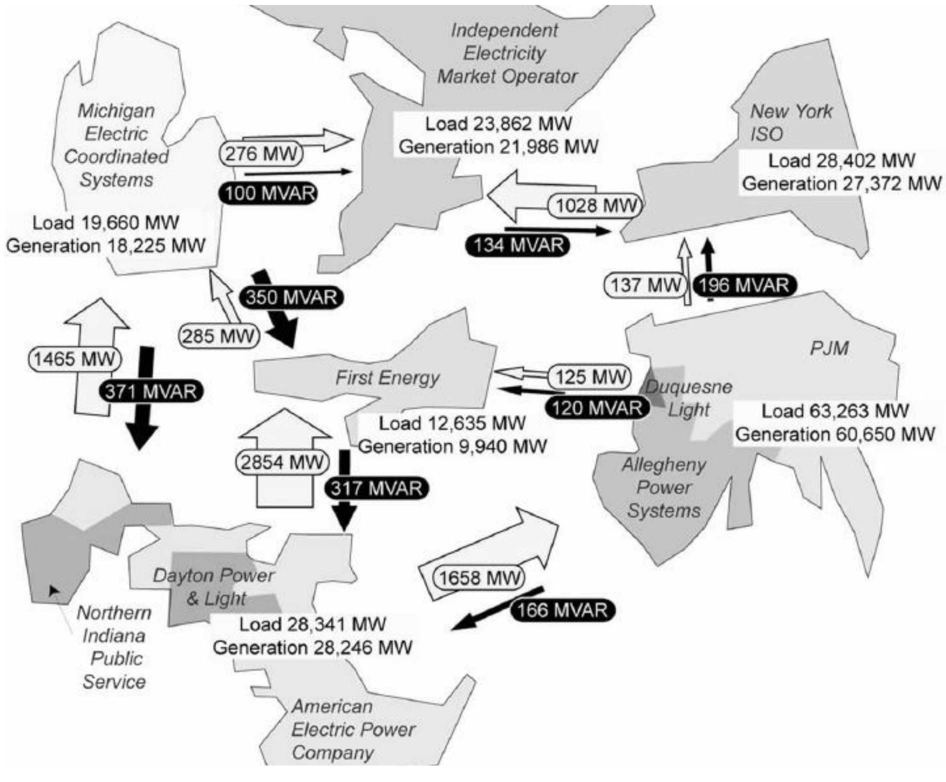


Fig . 13. Generation, consumption and inter-system power flows (USA-Canada 14.08.2003 15:05)

At 16:10 three 345 kV lines and 1200 MW generation were tripped due to low voltage (the grid lacking protection against out-of-step operation in some places). Two more 345 kV lines opened at the angle increasing. The separation of regions continued. One more 345 kV line opened. The frequency decline and AUFLS started. Then 5 more lines and power plants (5059 MW) were tripped. On disconnection of the following four lines the *New-York* region began to separate; three more lines tripped, a full blackout burst out (Fig . 14).

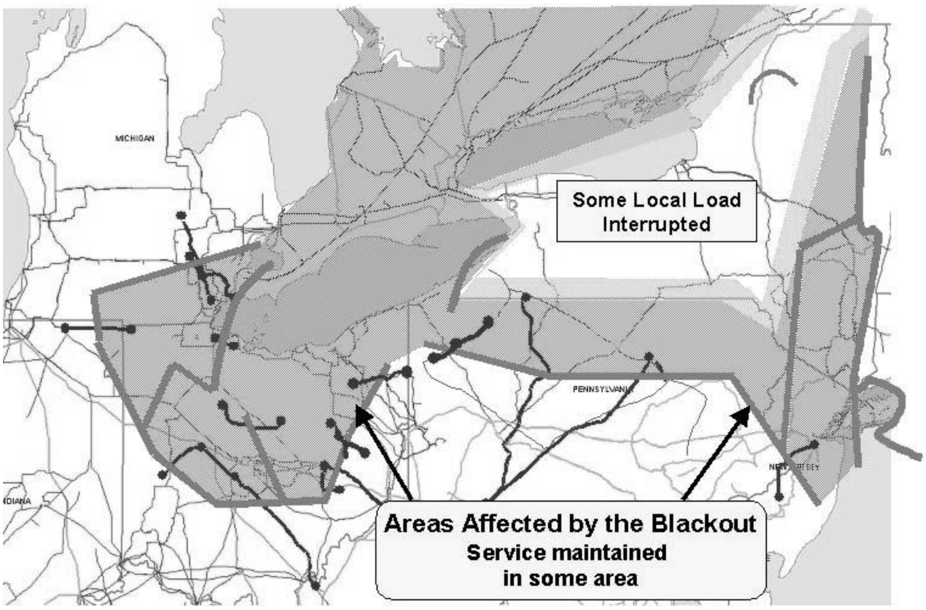


Fig . 14. Regions spanned by the blackout in USA-Canada 14.08.2003.

In total, 265 power plants with 508 individual generating units were disconnected, including 66 thermal power plants; 70 gas turbine power plants (37 of combined cycle included); 101 HPPs; 10 NPPs (7 in USA and 3 Canada) and 18 others. The normal condition was completely restored two days later.

Table 5. The main causes of nuclear power plant outages

Power plant	Cause of outage
USA	
Indian Point-2 (990 MW) New York surroundings	Low grid frequency > reactor coolant pump trips > protection tripped reactor on low flow (high temperature of active zone). The auxiliary bus experienced under-frequency. Offsite power was lost to all the plant auxiliary buses and automatically reenergized from the emergency diesel generators
Indian Point-3 (1010MW)	the same
Perry (1275 MW)	Voltage and frequency fluctuations on the grid > low pressure of speed governor; a generator under-frequency trip signal> turbine control valve fast closure>reactor trip
Nine Mile-2 (1193 MW)	Frequency fluctuations > rapidly manipulating the turbine control valves to control turbine speed > low pressure in the hydraulic system controlling turbine control valves > reactor trip. The safety buses automatically deenergized due to low voltage and automatically reenergized from the emergency diesel generators.
Nine Mile-1 (600 MW)	Frequency fluctuations > fast closure of the turbine valves> turbine tripped on low load > reactor trip. The safety buses were automatically deenergized due to low voltage and automatically reenergized from the emergency diesel generators.
Ginna (487 MW)	Frequency fluctuations > the turbine control valves closed down in response to the changing grid conditions > temperature and pressure transients > over-temperature-delta temperature signal > reactor trip

Power plant	Cause of outage
Fitz Patrick (850 MW)	frequency fluctuations > rapidly manipulating the turbine control valves to regulate its speed > low pressure in the hydraulic system that controls turbine control valves > reactor trip. Offsite power was subsequently lost to the plant auxiliary buses and automatically reenergized from the emergency diesel generators
Fermi-2 (1130 MW)	Large swings > generator field protection trips (overexcitation and loss of field)>turbine trip > reactor trip. Offsite power was subsequently lost to the plant auxiliary buses and automatically reenergized from the emergency diesel generators.
Oyster Greek (629 MW) near Atlantic Ocean	Voltage and frequency fluctuations on the grid > generator trip due to high ratio of Volts/Hz > turbine trip > reactor trip. The plant safety and auxiliary buses transferred from main generator supply to the offsite power supply following the plant trip
Canada	
Pickering (8 reactors 515 MW each)	Pickering A: unit 4 was operating at 12% power in preparation for synchronisation to the grid; it tripped due to heat transport low coolant flow when the heat transport main circulating pumps ran down. Pickering B: unit 5 > large voltage oscillations > manual control of generator excitation > generator tripped on loss of excitation > reactor consequently tripped (low gross flow parameter, low core differential pressure); unit 6 > the same; unit 8 reactor automatically set back on load rejection; unit 7 was coming back from a planned maintenance outage and was manually tripped.
Darlington (4 reactors each 880 MW)	Unit 1 automatically stepped back to the 60% reactor power state upon load rejection. The decreasing steam pressure and turbine frequency > reactor to be manually tripped. Like unit 1, unit 2 automatically stepped back upon load rejection; due to under-frequency on the main primary heat transport pumps, the turbine was tripped manually. Unit 3 experienced a load rejection and during the stepback of unit 3 was able to sustain operation with steam directed to the condensers. The unit was available to resynchronise to the grid. Unit 4 experienced a load rejection and required manual trip > manual turbine trip.
Bruce (8 reactors each 840 MW)	Bruce A (units 1-4) were manually tripped. Bruce B (units 5-8) experienced initial generation rejection and accompanying stepback on all units. All generators separated from the grid on under-frequency. Units 5, 7 and 8 maintained reactor power at 60% of full power and were immediately available for reconnection to the grid. Unit 6 tripped due to insufficient neutron over power margin
Point Lepreau (680MW)	Frequency change > short-term drop in output by 140 MW > excess thermal energy being discharged via the unit steam discharge valves > within 25 min the turbine generator was reloaded to 610 MW

Other *Gentilly-2* nuclear power plants kept operating together with *Hydro Quebec*.

Within the overall cascade sequence, 29 generators (6%) tripped between the start of the cascade and the split; the cause − line overload followed by voltage drop. The next interval in the cascade was as portions of the grid lost synchronism, when *Michigan*, *New-York – Ontario - New England* separated from the rest of the Eastern Interconnection. Fifty more generators (10%) tripped as the islands formed due to loss of synchronism, excitation system failure, with some under-frequency and under-voltage. In the third phase of generator losses, 431 generators (84%) tripped after the islands formed, simultaneously due to loss of synchronism and excitation caused by voltage (6%) and frequency (10%) drops as well as by voltage and frequency rise in other places. Of them, 17 generators switched off due to overloading with reactive power, 14 − due to field loss; 17 units − due to loss of voltage sufficient for in-plants loads. Some generators were tripped by their operators.

Commentary

Absence of preventive automatics against dangerous transmission overload. Overall absence of elementary anti-emergency automatics in the power systems.

Some of the generators had protections, which switched off the former by under-frequency at small time settings (it is not clear if this was necessary). Although the generators had protections which switched them off by swinging indication, the grid lacked fast-acting automatics for disrupting the asynchronous running.

The power systems lacked an analytical centre which could work out an anti-emergency conception.

21. Blackout of 23.09.2003 (Denmark-Sweden)

The initial pre-emergency situation [27], [122] is shown in Fig . 15. For scheduled repair the following DC links were disconnected: between *Zealand* island (*Copenhagen*) and *Kontek* (Germany), and between Sweden and the continent. In Sweden, for scheduled repair two 400 kV links were disconnected: one of them in the direction of western shore and the other between north and south.

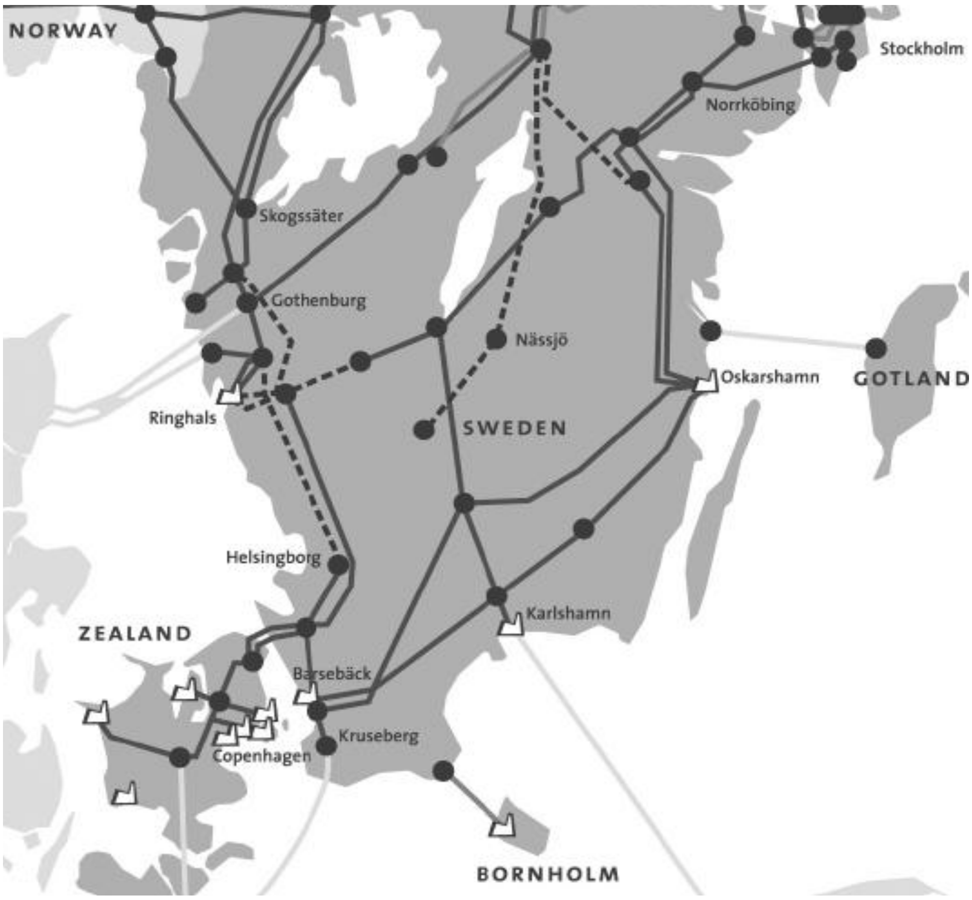


Fig . 15. Scheme of the *Zealand* island grid 10s after short-circuit at *Horred*; the disconnected lines are shown by dots

At the major power plants of *Zealand* island the following disconnections of units were made: *Asnaes* − 4th unit, *Avedore* −1st unit and *Amager* −1st unit (damaged). Apart from those, at *Barseback* the 2nd unit and at *Oskarhamn* the 1st and 2nd units were switched off for thorough revision, and the southern power plant *Karishamn* (operating on liquid fuel) was shut down. Before the emergency the capacity of *Zealand* power plants was 1800 MW and that of wind turbines − 450 MW; the available power was 3300 MW.

At 12:30 the 3rd unit at the *Oskarshamn* NPP switched off owing to damage of the water line gate at power decrease by 1200 MW. By mobilising the reserves the frequency was stabilised at the 49.9 Hz level. The mobilisation time was 15 min.

At 12:35, due to mechanical failure in an insulator of the *Horred* substation, a double busbar fault occurred. As a result, four 400 kV lines were disconnected: one in the western shore direction, another − in the direction towards the northern link; as concerns the remaining two lines, connected to them the 3rd and the 4th units of the *Ringhals* NPP switched off having lost 1800 MW. One more 400 kV south-bound line is radial, so this turned out to be useless under emergency condition. This situation was aggravated when the power stations in Northern Sweden, Norway and Finland increased production still further.

The Swedish transmission was overloaded at the voltage drop in a wide southern territory. In the southern Swedish part a number of 220 and 135 kV lines were tripped. Under low voltage the load decreased, owing to which the frequency was held at the 49.7 level. At the beginning, the power was kept by the major *Zealand* units: the 5th at *Asnaes* and the 2nd at *Avedore* power plants, which were added to the 400 kV lines and were connected with Sweden via the *Eresund* cable. In Denmark, the voltage drop was smaller. Then frequency oscillations began, which lasted for about 10s − the evidence that the power of Danish power plants fluctuated against those of Norway, Sweden and Finland as they continued to work through the Sund cable link. The units of the mentioned power plants at under-voltage were overloaded with reactive power and were tripped by the overload protection. Ninety seconds after short-circuit the separation of the northern and southern Sweden parts occurred, and the voltage fell down to zero, having left the southern Sweden without energy; on the operation of protection the *Eresund* cable was disconnected. Later it turned out that the emergency resulted in damage of the *Asnaes* 5th unit's transformer. The 2nd *Avedore* unit after the emergency was activated, however 5 days later it was tripped due to damage − a result of the emergency that was eliminated within a week time.

The restoration began at 14:57 and went on till 22.07. The consumers were re-closed step-by-step in the process of restoring the system operation.

Table 6. The main causes of nuclear power plant outages

Power plant	Cause of outage
Units of Rihghals NPP	Line tripping > loss of interconnection with power system
Units of Asnaes & Avedore NPP	Deep voltage drop > power plants overloading with reactive power > overload protection tripped units

Commentary

The fact that the busbar fault happened immediately after the disconnection of a 1200 MW unit (*Oskarhamn*) leaves room for doubts whether the emergency event was independent. Sometimes, under the conditions of enhanced power flow, defects of contacts potentially leading to arc appearance are revealed. In Denmark, the disconnections of generating sources could have happened due to stability loss oscillations − e.g. resulting from the oil pressure decrease in the turbine speed governors.

The situation could have been much easier if:

- the Swedish transmission had been secured using the splitting at the place that would allow operation without overload;
- the *Zealand* generating sources had kept operating by splitting the Swedish interconnection in another place, which would allow operation or, in the worst case, by disconnecting the *Erezund* link with Sweden.

22. Blackout of 28.09. 2003 in Italy

The Italian power system is connected with the rest of UCTE grid via six 380 kV (3 – FR, 2 – SW, SL) lines, nine 220 kV (1 – FR, 6 – SW, AU, SL), and a 500 MW DC overseas cable (GR) [123]. The load before the blackout was 27.4 GW, import − 6951 MW (SW – 3610; FR – 2212; SL – 638; AU – 191; GR – 300 MW) [97]. The maximum allowable conductor temperature − +80°C.

At 03:01:42 due to increased sagging of conductors into trees a heavily loaded (86%) 380 kV *Lavorgo-Mettlen* line to Switzerland switched off (Fig . 16: 1). The attempts of single-phase auto-reclosing were not successful. The attempts by the operators to put this line back into operation failed again because of an overly high phase angle (42^0).

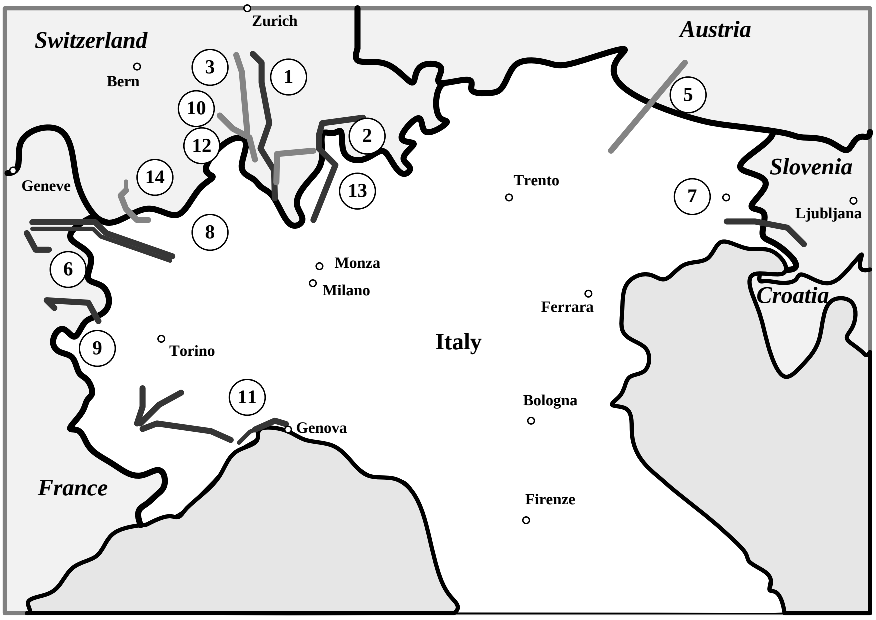


Fig . 16. The development of blackout of 28.09.2003, Italy

The neighbouring lines took over the power flows; the 380 kV *Sils-Soazza* line (Switzerland) became overloaded, and 24 min later this line also tripped after flashover with a tree (2). After 2s the protection tripped the overloaded internal 220 kV *Airolo - Mettlen* Swiss line (3).

At 03:25:26 cascading line disconnections started (4-7) owing to protection operation. On disconnection of the *Cislago-Sondrio* (SW) line the voltage began to fall rapidly, with the reactive power flows (CR, HU) increasing. In a French border region within 7s the voltage fell to the minimum − down to 300 kV. The Italian PS lost synchronism, and, after disconnection of the 220 kV *Avise-Riddes-Velpeline* (FR, 4), 220 kV *Lienz – Soverzene* (AU-I, 5), 2x380 kV *Albertville-Rondissone* (FR, 6), 380 kV *Devaca – Redipuglia* (SL, 7) lines the major links with UCTE were lost. On disconnection of remaining lines (7-13) Italy was separated from UCTE.

Totally, 13x380 kV and 6x220 kV inter-system lines were disconnected. Under operation 196 thermal power plants and 151 hydro stations remained, with the total consumers' load at 03:25:42 being 27568 MW. The own generation − 20594 MW, and the power shortage − 6674 MW (32%).

Italy possesses a well-developed under-frequency load shedding automatics, to which 50-60% of the load is connected. It contains 19 stages reacting to the minimum value of frequency, 5 of them operating in the range 49.7-49.1 Hz (tripping 6000 MW pumps if they work), and 14 stages for each 0.1 Hz in the range from 48.8-47.7Hz that react to the rate of frequency changes with 0.01-1.0 Hz/s steps. After the protection automatics had operated, the frequency was stabilised at the ≈48 Hz level. The under-frequency operational condition is labile, since any additional decrease in generation could provoke a blackout that would be triggered by failure of feed pumps at thermal power plants.

At reduced frequency the output of the gas turbine compressors decreases; the same occurs with the feed of compressed air into the combustion chamber where this air fulfils also cooling function, so the temperature of combustion products at the input of gas turbine working wheel grows as well.

Further, at the frequency of 47.5 Hz the blackout burst out. As a result, the 9924 MW generating power (62 power plants) was tripped. The outage causes of power plants are shown in Tab.7.

Table 7. The main causes of power plant outages

Power plant	Cause of outage
3 units (899 MW)	Voltage collapse > loss of auxillaries' supply > boilers' failure
2 units (306 MW) gas turbines	Power deficiency (f↓) > compressors' under-productivity > reduced flow in the compressor> high temperature of exhaust gases > turbines' tripping
2 units (754 MW)	voltage fluctuations > loss of excitation > generators tripped by protection
2 units (306 MW)	Out-of-step operation and oscillations > loss of syncronism
13 units (1294 MW)	Turbine tripping (mainly due to gas turbine protection)
31 units (5390 MW)	Power deficiency (f↓) > frequency crossed a low threshold > relays by f_{min} tripped units (some of them with erronous settings)
3 units (472 MW)	Line current increase and voltage decrease > U/I essentialy decreased > units were tripped by under-impedance relay operation
1 unit (405 MW)	Voltage drop under minimum allowable > under-voltage relay tripped unit
6 units (12414 MW)	Out-of-step operation > low pressure of bearing oil; under-voltage > sudden load loss; faulty seal of throttle valves

Commentary

The line overload caused increased sagging of its conductors, which led to stabile faults due to conductors' flashover on the trees (bushes) along the lines; as a result, the Italian power systems separated with 32% power shortage. Despite the well-developed AUFLS this was insufficient for maintenance of frequency in the zone not dangerous for power plants. In the emergency development the frequency changed in two steps: first to 48 Hz and then fell further. As a result, the frequency change rate could be comparatively low, and part of the automatics might have not operated. To avoid such situations it would be desirable that the AUFLS stages responding to different parameters would be partially conjuncted.

Despite of the developed AUFLS there was no slow-acting AUFLS for prevention of long-lasting under-frequency operation of a power system and frequency recovery to the normal level.

23. Blackout of 13.07.2004 in Greece

The maximum load in Greece sets up increasing use of air conditioning. The energy arrives from generating sources on the north and south by 400 kV and 150 kV lines through 400/150 kV autotransformers and numerous 150/20 kV transformers [124], [125]. The power system is sensitive to voltage falls.

The first emergency event dates back to 1996, when a voltage avalanche occurred on the south of *Athens* embracing the *Peloponnesus* peninsula. After strengthening the power system by creation of generating sources in the *Athens* region, a 3rd two-circuit 400 kV line in the north-south direction, 400/150 kV autotransformers and the *Peloponnesus* cable connection the situation improved.

By the time of Olympic games, 2004 in Greece, additional upgrading had been envisaged: 400/150 kV autotransformers, capacitor banks, 150 kV links between power plants, a new 400/150 kV substation (*Argiropol)*, and others. Unfortunately, many of these measures were not yet available. On the day when emergency happened, two autotransformers of *Palini* and *Ag.Stefano* substations and many capacitor banks in the Athens & Central Greece were switched off. Besides, owing to repair works and damages, there were tripped: one 150 kV line *Lavrio-Palini*; two 150 kV cables in *Piraeus*, one 150 kV line between a 400/150 kV substation and the ANSG power plant. The grid was thus heavily overloaded, with the voltage already reduced. Besides, the previous day there were disconnected: a 125 MW generator in *Magalopoli* (*Peloponnesus*), which continued to operate with a power of 80MW and another one − in the northern Greece.

At 7:08 of the preceding day (2.07.04) a 300 MW unit of the *Lavrio* power station (Athens area) was lost due to auxiliaries UPS failure. The failure was repaired, however due to starting complications the unit was switched on only at 12:01. By that time the consumption reached 9160 MW and the voltage in *Athens* − 90% of the nominal. After the generator's synchronisation the voltage stabilised. However, under the technical minimum condition during the manual control the unit was lost again due to high drum level.

At 12:25 the operator shed a 100 MW load. At 12:30 a disconnection of 80 MW was performed. This, however, was not enough to stop the voltage decline, so at 12:35 a further load shedding action of 200 MW was requested. At 12:37 due to overload the 3rd unit of the *Aliveri* power plant switched off. At 12:38 the remaining unit of this plant was disconnected manually. On disconnection of the north-south 400 kV line a stability loss occurred, followed by tripping all the generating units, which embraced also the neighbouring zones of the European PS.

The resumption of operation in the main directions took 2-3 hours; some of the loads, for various reasons, were re-energised after 6 hours.

24. Blackout of 14.03.2005 in Australia

In the initial position the southern Australia consumed 1500 MW with 432 MW power flow via the 275 kV link from *Victoria* (on the north), 37 MW from the *Murray* link and 15 MW from wind turbines [62].

At 6:39, line short-circuit occurred not far from a northern power plant (500 MW). After that the generator power was restored. Later, after 49 ms it fell by 20 MW, and then, after 400 ms − to zero but not tripped; at 8:24 the power of each unit from the two recovered up to 200 MW.

As a result, two seconds after short-circuit in the 275 MW grid stability loss took place. During this process, according to records, the transient power reached 900 MW. Two 275 kV lines were tripped, and the southern PS part separated. After the separation, the frequency in that part fell down to 47.62 Hz within a 4.5 s time. Owing to the operation of AUFLS the frequency stabilised at the 49.70 Hz level. Due to frequency difference the synchronisation turned out to be impossible.

On the frequency decline, at the *Ladbroke* power plant (the southern system part) two

38 MW generating units were tripped along with the *Pelikan Point's* 100 MW gas turbine and 55 MW steam turbine operating in the combined cycle. The program of the gas turbine's automatics was not adapted to the under-frequency operation, whereas the latter turbine lost its steam. The power system operation was resumed at 8:25.

The power oscillations of the generating units (the northern part) resulted from operation of a special stability control protection (Overspeed Protection Circuit – OPC, installed by the manufacturer) that compares the turbine and the generator powers. If the difference is too large, the protection rapidly reduces (brakes) the turbine power, thus realising the known function of electro-hydraulic devices for protection against stability loss. In that particular case, the adaptation performed by manufacturers was erroneous, so instead of protective function it caused stability loss.

25. Blackout of 25. 05. 2005, Moscow

In the time of repair works a 4000 MVA autotransformer power and 7 synchronous compensators at several substations were tripped [41].

On 23.05.2003 at the *Čagino* substation with 500, 220 and 110 kV busbars, fault of 220 kV two current transformers and busbar occurred. There, as a secondary factor the main compressed air pipe-line out was damaged (the air flowed) by the porcelain fragments or by the busbar short-circuit current. This resulted in circuit breakers' switching-on. The substation scheme switched off, and the auxilliaries' supply was lost. The issued air could not be recovered due to loss of compressor feeding. At night the substation scheme was partially restored; however, since after starting the compressor its air pressure was not fully recovered, the circuit-breaker could not be activated, and the grid scheme was not complete. During the night, on examination of the grid scheme, the operation maintenance measures were worked out and the situation seemed not to be risky any more.

Nevertheless, in the morning the information was received about a line overload and a voltage drop in the 220 and 110 kV grids. The reactive power and, hence, line current increased everywhere. Later, it became clear that there were stable faults since the overload caused sagging of conductors into ground (bushes).

Owing to overload, at 9:23 the 220 kV *Ochakovo- Choboti* line was tripped (unsuccessful re-closing); at 10:07, due to the same reason, the 220 kV *TEC-20-Akademičeskaja* line was disconnected; then followed: at 10:31 − 220 kV *Baskakovo-Gaļjanova* and *Južnaja-Čertanovo*; the 220 kV TEC23-*Gaļjanovo-1* line (unsuccessful re-closing); at 10:44 − 220 kV *Kedrovo-Očakovo* line (unsuccessful re-closing).

As the sagging increased and flashover occured, the lines were opened. These faults are stable, which explains the unsuccessful automatic re-closing operation. Altogether (with one exception) 28 lines were tripped with unsuccessful re-closing followed. The voltages in the 110 kV grid fell down to 85-90 kV, and in the 220 kV one – to 199-213 kV. Under voltage avalanche 13 power plants switched off when the generators were tripped by overload protection as the response of excitation regulators to the voltage avalanche in the grid.

The emergency was fully eliminated on 12 May, 26.05.05. The total tripped load was 3539.5 MW, including: Moscow PS - 2500 MW, Tula PS − 900 MW, Kaluga PS −100 MW, Ryazan PS − 26.5 MW, and Smolensk PS − 13 MW.

Commentary

The cause: shortage of the means that would allow fast elimination of a dangerous grid overload.

26. Blackout of the European power system of 04.11.2006.

The total load (274 100 MW) distribution in the European PS is shown below [91]. To allow a ship to pass on the *Ems River* to the *North Sea* it was necessary to disconnect a two-circuit 380 kV line. The disconnection terms were changed, so this took place at 21:38 without additional numerical verification of the (n-1) criterion. This resulted in loading the line with 1200 MW. After coupling the busbars the line tripped immediately. This was followed by overloads of other cross-sections with voltage drops at the power receiving ends and disconnection of 15 lines by the 3rd zone distance protections.

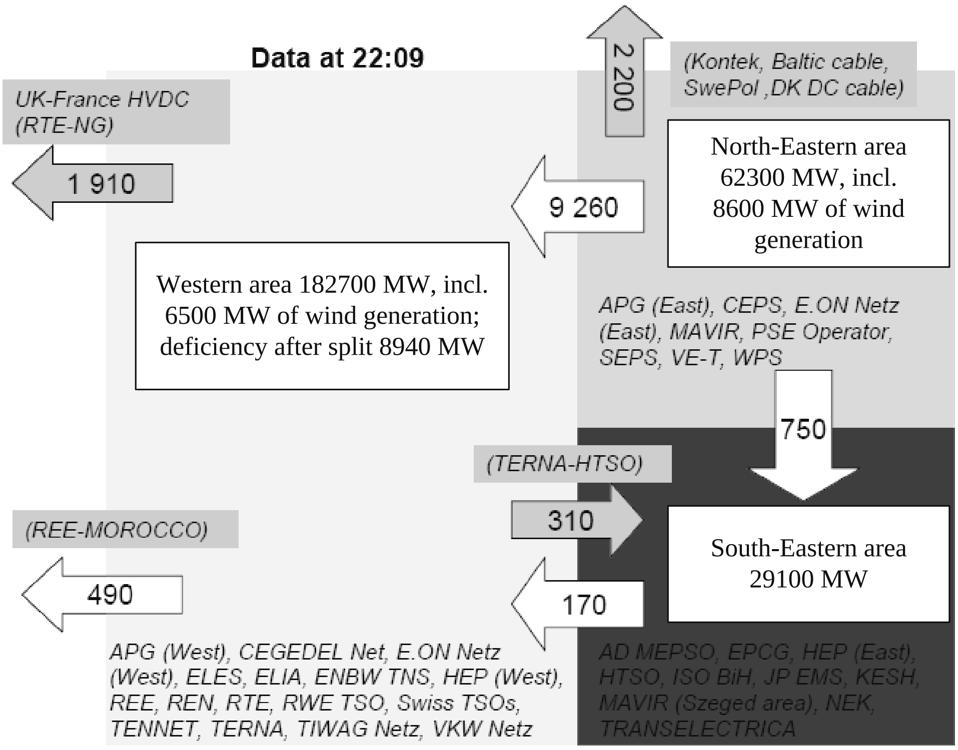


Fig . 17. Generation and power flow distribution among three areas before splitting

To allow a ship to pass on the *Ems River* to the *North Sea* it was necessary to disconnect a two-circuit 380 kV line. The disconnection terms were changed, so this took place at 21:38 without additional numerical verification of the (n-1) criterion. This resulted in loading the line with 1200 MW. After coupling the busbars the line tripped immediately. This was followed by overloads of other cross-sections with voltage drops at the power receiving ends and disconnection of 15 lines by the 3rd zone distance protections.

At 22:10, the Morocco-bound line switched off by the frequency decline indication, and the power system split into three areas (Fig . 18).

In the 1st area a power shortage of 9500 MW formed, and the frequency fell down to 49 Hz. First, on frequency decrease to 49.5 Hz some minor generating units, being plentiful and uncontrolled, were tripped; 40% of them were wind power plants and others − small cogeneration plants; all this aggravated the situation with frequency still more. In Denmark the wind plants were not disconnected. 60% of the tripped wind plants were connected to grid at 22:09. At that frequency (49.5 Hz) the water reservoir pumps (1600 MW) switched off within 8 s; at 49 Hz the AUFLS stages started operating, tripping 17000 MW per 0.4-0.5 Hz. Apart from that, the manual load disconnection was done. For fast frequency restoration, the forcing of generating units was applied, with hydro generators started as well (total 16 800 MW, and the tertiary reserve 18500 MW). On the DC link of Skagerrak to Scandinavia, on frequency decline and load shedding automatics operation the power flow decreased from 2200 MW to 50 MW. At the frequency decline the flow was reduced and later restored applying the tertiary reserve.

In the 2nd area a 10000 MW power surplus was created, with frequency rise to 51.4

Hz. In Northern Germany 5400 MW and in Austria 800 MW of wind generator power was tripped. With the help of turbine speed governors the frequency deviation was corrected to 0.3 Hz, which exceeds the value allowed under normal conditions (0.18 Hz several minutes after splitting). The DC links to Scandinavia preserved their power flows in compliance with the carrying capacity of internal Polish lines.

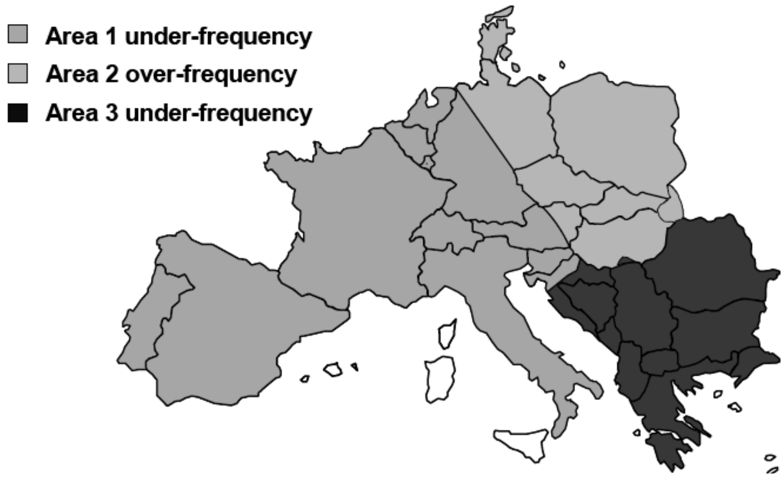


Fig . 18. Schematic of UCTE power system splitting into three areas

In the 3rd area a 800 MW deficiency and a frequency decline of 49.7 Hz were observed. On the Morocco link there was 490 MW power flow before the emergency. When it switched off, at 49.7 Hz the power shortage was partly covered by Algeria and Tunisia (380 MW) with power surplus and frequency of 50.16 Hz. In Morocco 300-350 MW was tripped by the AUFLS.

Frequency stabilisation. It was possible to restore frequency by means of power reserve mobilisation.

The estimated amount of primary control in the Western area was 2050 MW while the total imbalance of this area was close to 9000 MW (approx. 22%); in the North-Eastern area it totalled 250 MW as against an imbalance of over 750 MW (approx. 35%). These figures show that primary control solely was not able to stabilise frequency in these areas. In the Western area frequency was stabilased mainly by load and pump shedding (approx. 18600 MW to cover initial imbalance of approx. 9000 MW as a result of splitting and further generation tripping of 10900 MW), while in the North-Eastern area - by wind generation tripping (approx. 6100 MW).

The secondary reserve is usually put into service by the operator. Under particular conditions this could be done only coordinating the actions of all operators, which was impossible; the task was therefore fulfilled to the extent achievable without mutual coordination.

In the 1st region, additional activation of almost total tertiary reserves available in all control areas close to 17000 MW allowed restoring the frequency to the nominal value. This action was not sufficiently coordinated. In the 3rd region, due to relatively low imbalance the activation of tertiary reserve (100 MW) in Croatia together with LCF in frequency mode in Greece and an accompanying natural decrease of consumption in this area made it possible to restore the frequency.

In the 2nd region it was necessary to reduce frequency by tripping the generation. This also was not coordinated. In two control areas the generation level was reduced manually, while some others sustained the exchange as scheduled. The most critical factor was the increase in generation (the opposite to the expected) observed in the German part of the North-East area which was caused by uncontrolled re-connection of wind farms which tripped in the first moment after splitting. Under such conditions the frequency was restored only by decreasing deeply the generation output in other control areas.

Unsuccessful re-synchronisations

An attempt of re-synchronisation was made already at 22:10, however it was unsuccessful due to a large frequency difference. Then 6 unsuccessful attempts followed, with the use of semi-automatic and automatic devices: at 22:34, synchronisation on the 1st 380 kV *Oberhaid-Grafenrheinfeld* line occurred, accompanied by tripping due to strong oscillations; at 22:38 such a synchronisation attempt was repeated − with the same consequences; at 22:40:09 synchronisation on *Landesbergen-Wehrendorf* line was done at $\Delta f = 0.3\,\text{Hz}$ − consequences identical; the same was on the 380 kV *Conneforde – Diele* line.

Taking into account the experiences from the trials mentioned above operators decided to try to connect as many circuits as possible within a short range of time. At 22:46:23 switching-on both circuits of the 380 kV *Conneforde – Diele* line, which again caused oscillations, ended up after 4 s in tripping both 380/220 kV transformers at the Conneforde substation, the 380 kV line *Unterweser-Conneforde* and opening of the 220 kV busbar coupling in the *Conneforde* substation. The difference of frequencies was about 300 mHz. The attempt to re-synchronise the *Landesbergen-Wehrendorf* line also failed after 3s.

Finally, at 22:47:23 a successful synchronisation was achieved on the 380 kV line *Bechterdissen-Elsen* at $\Delta f = 0.18\,\text{Hz}$ and the angle < 10°. It is remarkable that this line is much shorter than those on the North of Germany which failed before. Further lines were switched-on very quickly.

In the III area, the re-synchronisation process started immediately after successful reconnection of I and II areas (frequencies difference between areas I-II and III was 0.04 Hz). This was completed at 23:57 when the last 400 kV Croatia-Hungary line was re-closed.

Table 8. The main causes of outages

Power plant	Cause of outage
Power plants of Western area	Power deficiency (f↓) > tripping of distributed generation (wind turbines, combined cycle power plants), some at 49.5Hz > worsening operational condition
North-East area	worsening operational condition due to uncontrolled re-connection of wind farms which tripped in the first moment after splitting

Commentary

The blackout was caused by incompleteness of organisational measures with regard to the $(n-1)$ criterion, which was analysed using outdated information.

The major generating stations kept operation. In the process of separating the minor generating plants, the events of a power system's scale were not differentiated from those going in the distribution grid to which these plants are linked; such minor power plants should not have been tripped under the overall power shortage conditions (e.g. in Denmark they had not been disconnected).

In the process of overloading the lines were tripped by protection, which caused the power system's splitting effect with separation of the deficient region in the western zone. The power shortage was eliminated by the fast-acting AUFLS, and, as a result, the emergency was essentially a frequency avalanche without self-restoration.

The power system has no slow-acting AUFLS2, which would automatically restore the nominal frequency within 100 s thus creating the conditions for automatic re-synchronisation. As a result, the process of re-synchronisation dragged on. Therefore this was done manually, without coordination in regard to long lines, at non-optimal places and at large frequency differences; this was followed by heavy transient processes involving many unsuccessful actions.

No well-developed re-synchronisation strategy exists. Indeed, the frequency difference is much more important parameter than the switching-on angles. These can reach 40°, determining only the value of switching-on current, which in the worst case does not exceed one third of short-circuit current if the transient process was successful. In turn, at smaller frequency differences provided by AUFLS2 within 100 s all the lines would have been re-closed in few seconds − i.e. with the disturbance remained unnoticed for the consumers.

27. Byelorussian event of 25.06.2008.

In the initial position, on the Smolensk-Belarus cross-section one 300 kV line was disconnected for repair, so the power flow via this cross-section reached the maximum of 900 MW [42].

When the emergency burst out, at the *Lukoml* power plant one-phase short-circuit in the 8th unit (300 MW) caused its tripping. The short-circuit current (>20 kA), having distributed along the grounding loop reached the pipe with compressed air, in which during the sparking a hole was burnt; the air flowed out of the circuit-breaker control system, and the tripped circuit-breaker after 8 min absence of air switched on. The generator excitation switched off, so this was unable to reduce the speed of rotation. As a result, the resistance turned out to be too low, and, on the circuit-breaker's switching-on, through the circuit of tripped unit the non-total-phase current (>2 kA) flowed. With no time delay the anti-sequence protection of the unit operated, whereas the automatics of protection against failures of circuit-breakers was started up since these cannot be controlled without air. This led to failure of the close backup protection that should have tripped a neighbouring circuit-breaker thus keeping other units operational.

As a response to the current non-symmetry, the current protections of other transformers operated, tripping the remaining 7 300 MW units (total power 2100 MW) and leaving the circuit-breaker of the 8th unit switched on. As a result, all lines connected to the corresponding busbars were tripped at the opposite ends by the backup protections, which caused a loss of 2400 MW and a weakening of the transmission grid ring. The power flow through two lines remaining operational (330 and 750 kV) reached 1400 MW against 900 MW allowed, having overloaded 1.4 times the 1000 MVA transformer at the Byelorussian substation.

On the operation of overload protection with a 5 s setting the 1000 MW Daugava HPP generators were started up; besides, the Byelorussian operator tripped 800 MW, thus reducing the power flow to admissible level in the 45 min time. After an hour the 330 kV line to the Ukraine was re-closed, and the post-emergency condition normalised.

Commentary

The task placed on the protection of generating units is to protect them against internal damage.

When in a power system cascade-wise emergency processes develop at which its external parameters are changing, the system's power balance is threatened: cascading outages of generating stations occur, with possible equipment damage during this time. Therefore it is of importance to keep the generating sources operating when the frequency and voltage change.

To keep the generating sources operational, the pre-emergency control means should be applied in order to prepare the former to the emergency conditions with changed parameters.

Power systems should have special analytical centres that would be able to create automatic anti-emergency complexes and coordinate their work so that it is possible to eliminate emergency without personnel participation.

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