PROTECTION OF GENERATING UNITS AT DEVIATIONS OF PARAMETERS BY SECTIONING A POWER SYSTEM AS A TOOL FOR BLACKOUT PREVENTION

ĢENERĒJOŠO IEKĀRTU DARBĪBAS AIZSARDZĪBA NO PARAMETRU NOVIRZĒM, IZMANTOJOT SEKCIONĒŠANU KĀ PRETSABRUKUMA LĪDZEKLI

J.Barkāns, D.Žalostība

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Introduction

As known, the development of blackouts in power systems is usually provoked by large overloads (in GW) of cross-sections, when tripping of heavily loaded lines occurs followed by mass scale ground faults due to sagging of wires, voltage avalanches with mass scale tripping of generators and load reject, loss of stability, chaotic division of power systems into parts, frequency avalanches, and large-scale outage of generating stations. The only effective protection against such a collapse is fast-acting unloading of heavily overloaded cross-sections, with *optimal preventive short-term sectioning* [further *sectioning*] of the system at the places through which there is a power flow needed for keeping the overloaded cross-section in operation under safe load [1]. The properly composed anti-emergency automatics meant for frequency avalanche prevention makes possible self-restoration of the operating condition in a power system within about 100 s by means of automatic synchronization [2], which, together with re-closing of the tripped lines, will eliminate the possibility of blackout.

At the operation of preventive automatics short-term deviations of regime parameters occur, to which the power plants can respond differently. To ensure effective automatic self-restoration of the power system without personnel participation it is necessary to keep the generating units operating. In the following sections the response of different generating units to emergency deviations of parameters is considered along with the measures that would allow keeping such units in operation in the self-restoration process in the power system.

The features of feedback in generating units

The generating units should be protected against deviations in the emergency parameters. It is necessary to coordinate their operation with that of emergency protection system, for which purpose a common complex should be formed. The generating units can be composed of power-generating boilers, nuclear reactors, steam and gas turbines and generators. All the mentioned units respond not only to internal but also to external troubles arising in the system and possessing an energetically-electrical nature.

The emergency conditions of external origin are:

- frequency fall;
- frequency rise;
- voltage fall;
- voltage rise.

The safe operation of a generating unit is determined by the schematically-physical/physically conditioned behavior of its feedback (

Fig. 1, a). The controlled object is denoted with O, the power at its input and output with P_1, P_2, and the feedback factor with K. Thus, for example, if we additionally load a boiler then due to pressure fall the pressure in the pipes is decreasing. In this case there is a direct negative feedback, which favoring load relief ensures self-control. The situation can be illustrated by the turbine and load characteristics displayed in

Fig. 1, b. The working regime will be stabile under the condition that the total change is decreasing at the parameter value increasing:

$$\frac{\partial\left(P_g - P_l\right)}{\partial f} < 0 \text{, or } \quad \frac{\partial P_g}{\partial f} < \frac{\partial P_l}{\partial f} \qquad (1)$$

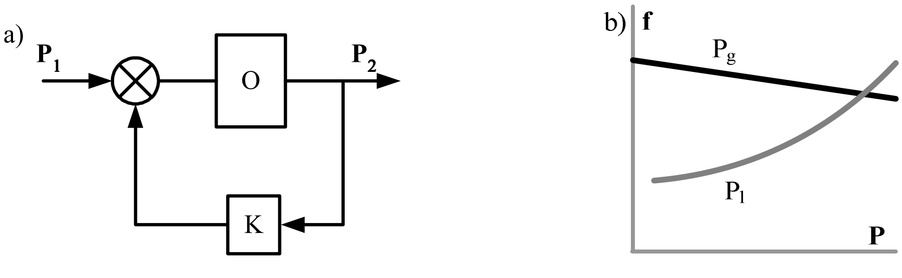

Fig. 1. Feedback behavior a) in the absence of automatic control; b) negative feedback

If the physically conditioned feedback factor is positive, the unit does not possess self-control property, and at the load increasing it is not unloaded but, vice versa, is additionally loaded. In the emergency processes with sharp deviations in parameters such units can lose their working abilities and become tripped by the technological protections. Stabile operation of these units will be achieved if we use automatic regulators with negative direct feedback. For the units with positive direct feedback the automatic regulators are obligatory working elements without which a unit's operation becomes impossible.

Effect of frequency rise on the generating units

The frequency rise in power systems occurs at load shedding and usually the process is aperiodic. Such a transient process is characteristic of steam turbines without re-heating. The aperiodicity of transient processes for the turbines with re-heating is achieved using a special correcting link in the regulator. As concerns hydro-generators, their fluctuating transients in power systems at insignificant load shedding do not cause any considerable complications.

When load shedding takes place, the frequency is determined by the interaction between generation and the load. To characterize such a unit a turbine governor's statism S is employed:

$$S = (\omega_0 - \omega_{nom}) / \omega_0 \text{,} \qquad (2)$$

where ω_0 and ω_{nom} is the rotational speed at the idle operation and rated power of the turbine, respectively.
In practice, with the governor insensitivity not taken into account, $S_{\%}$~4%. This means that at a load changing from idle operation to rated value the rotational speed decreases by 4%:

$$\Delta f_{\%} = \Delta P_{\%} \cdot S = 100 \cdot 0.04 = 4\% \qquad (3)$$

The load is also dependent on the frequency:

$$\Delta P_{\%} / \Delta f_{\%} = k_f \qquad (4)$$

where k_f is the load coefficient by frequency. In practice this coefficient is in the range 1-3. If we know the load shedding $\Delta P_{\%}$, then the frequency rise under stationary operation will be

$$\Delta f_{\%} = \frac{\Delta P_{\%}}{\sum 1/S + k_f} \qquad (5)$$

Taking into consideration that in a power system all turbine governors possess approximately equal statism S, the load shedding will be evenly distributed among the turbines. On the scale of a power system we should take into account the governor's insensitivity, which raises the statism of the power system by up to 10-12%. Then at a 10% load shedding and k_f=2, Δf will be ~0.8% or 0.4Hz. In practice, when sectioning is applied the load shedding does not exceed 2-4% of the total load of a large power system.

Effect of frequency fall on the generators

A frequency fall under the emergency running is sensed by turbine governors, which results in increased feed of steam, fuel and water up to full opening of the turbine nozzle and control device. The operation under reduced frequency is labile, since the power balance can be upset by tripping of generating capacities. Therefore to keep them operating all possible measures should be taken.
For the electric machines working to the grid a relationship exists between the voltage (electromotive force (emf)) in the windings U and the magnetic field in their cores, which makes possible to find magnetic flux density as

$$B = U / \left(\pi\sqrt{2} f \cdot k_W w \cdot s\right), \qquad (6)$$

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

Therefore the induction in the cores is inversely proportional to the frequency and directly proportional to the voltage, since the magnetic permeability is there decreasing ($\mu=B/H$). Taking into account that the magnetic resistance is inversely proportional to the magnetic permeability ($R_{magn}=c/\mu$), the leakage field becomes stronger, which causes overheating of massive design elements. This circumstance is taken into account by limiting the existence time for the frequency fall (Fig. 2), which should be done by protection automatics.

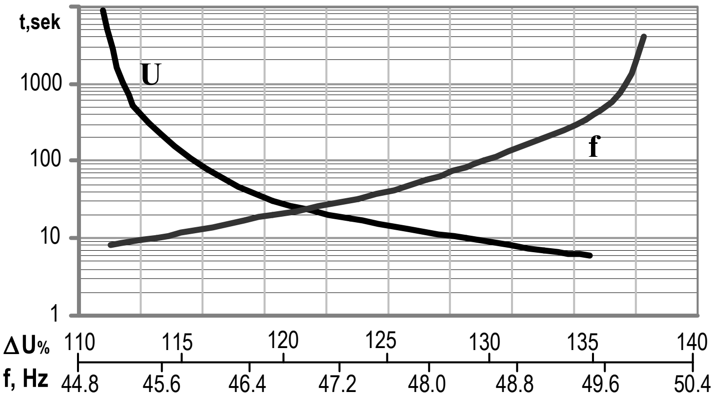

Fig. 2. Time limitations for core overexcitation

Effect of frequency fall on the steam power plants

Since the heating process possesses a comparatively large time constant, it is possible that the protection will operate with time delays greater than the frequency normalization time set by anti-emergency automatics.

When the operation proceeds under reduced frequency we should reckon with possible mechanical resonance of turbine blades, which is avoidable by means of special protection. If the time delays of this protection are not coordinated with frequency normalization time they can become one of the causes of blackout occurrence in a power system.

Frequency drop also affects the operation of steam boilers with their feeding pumps possessing specific features. This is connected with the fact that at a smaller number of pump turns (as is known, high-power asynchronous motors so far do not have RPM (revolutions per minute) controllers) the pump productivity becomes insufficient for the boiler operation (Fig. 3, a); as a result, the pressure in them falls and generating stations are tripped. The situation can be saved by fast-acting under frequency load shedding automatics, which, keeping the frequency at the level safe for boilers, prevents the tripping of power stations.

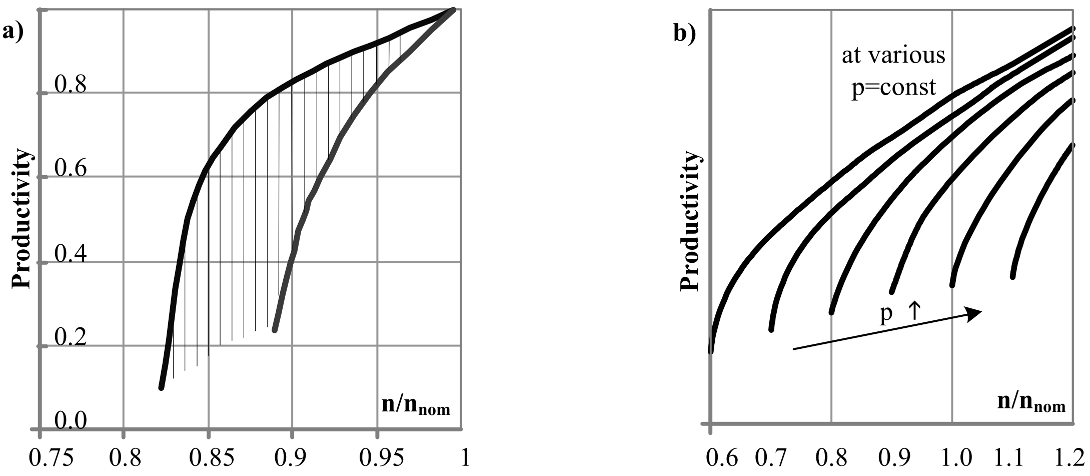

Fig. 3. RPM dependence of the boiler productivity:
a) for pumps working against backpressure; b) for gas turbine compressors

Effect of frequency fall on gas turbines

The effect of frequency fall on the gas turbine is specific. As known, the operating condition of a gas turbine is affected by the temperature of combustion products in the blade zone of its working wheel, which, in turn, depends on power. At reduced frequency the turbine governor raises power. At the same time, owing to RPM reduction the output of the compressor on the turbine spindle falls (Fig. 3, b). This can approximately be expressed as [3]:

$$V \approx \alpha(1-\Delta f)(1+\Delta f)^{n} \tag{7}$$

where n>1 is the index characterizing the degree of non-linearity of the compressor performance curves (equaling to ~4.2), and $\alpha \leq 1$. Thus, for example, when frequency falls by 4% we have $\Delta f=-0.04$, and $V=1(1+0.04)(1-0.04)^{4.2}=1.04 \cdot 0.84=0.87$.

The compressed air is employed not only for fuel combustion but also for cooling the blade zone. Shortage of this air causes the temperature elevation to which the temperature-controlling protection responds within 10-20 s. At a given load and known frequency fall the temperature elevation is function $\Delta\tau=f(P, \Delta f)$, and the protection automatics can trip the turbine by indications of this parameter. Thus, for example, in the blackout of the Italian power system in 2003 [4] under reduced frequency 600 MW turbines were tripped, which led to the collapse of this system. To prevent tripping of gas turbines a special measure must be provided that would respond to frequency reduction.

Effect of frequency fall on nuclear reactors

It is known that the reactor power is connected with the temperature in the active zone as (Fig. 4):

$$P = c(T_2 - T_1)\,, \tag{8}$$

where T_1 and T_2 are, respectively, the temperatures of cooling medium at the input and output of the reactor. The character of feedbacks in a nuclear reactor is determined by various relationships between the changes in the operating condition and other its parameters: the demanded power, the temperature in the active zone, and the steam generation parameters in the case of a single- circuit reactor [5]. Depending on the type of reactor some of the mentioned relationships can possess a positive feedback, which imposes strong requirements on the operating of the reactor and on the speed of action of its control system.

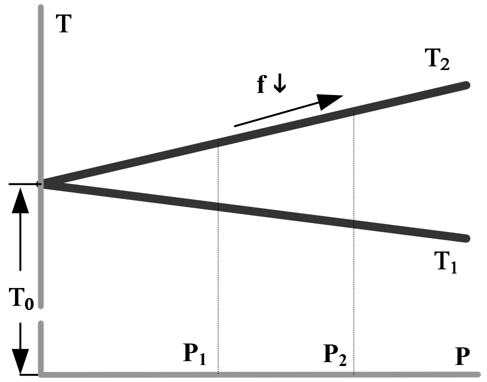

Fig. 4. Effect of temperature elevation in the reactor's active zone on the power

In the cases when in the deficient zone of a power system nuclear reactors are located and the asynchronous motors of their circulation pumps do not possess RPM controllers, the emergency frequency fall affects the operation of these reactors, since the output of the pumps changes proportionally to the RPM reduction. As the result, cooling is hindered, and the temperature in the active zone increases. This means that at a frequency decrease the reactor power grows not only due to the action of the turbine governor, but also owing to the unfavorable influence of the positive feedback. Obviously, special measures are wanted.

Keeping of generating units in operation during a short-term frequency drop failure

Frequency falls occur in a power system under emergency conditions when it is split into parts with power deficit in one of them. As known, for frequency normalization the fast-acting under frequency load shedding automatics [AUFLS1] is used, which for a short time partially sheds the load in the deficient part. The slow under frequency load shedding automatics [AUFLS2] completely restores the frequency up to the rated value so that the reconnection of the separated part of the power system with its self-restoration is possible without personnel participation [6]. The widely spread fast-acting AUFLS1 is known to react to the frequency deviation and its rate (by the derivative). However, improved automatics act more efficiently [7]. Since the automatics reacting to the frequency deviation is met most widely and taking into account that the emergency sectioning of a power system can be used as protection against severe blackouts [8], analysis of possible preventive measures is needed, in which due attention will be given to the proper use of existing means or to their improvement up to the level when the personnel can cope with them. In a power system there are usually many stages of load shedding. Thus, in the above Italian example, there are 19 stages responding to the frequency deviation and 9 – to its rate.

The frequency reduction under the conditions of a power deficit proceeds in three stages. In the first one, at the opening of a turbine governor and power deficit $\Delta P_{0\%}$ the frequency begins to decrease by an exponential with time constant $T \approx 1.6 \div 2.5s$ in compliance with the static load coefficient k_f (4). When the frequency reaches the first setting, for example $f_{s1}=49.2Hz=-1.6\%$, operation of the first unload stage takes place with shedding load $\Delta P_{s\%}$. Besides, to protect the automatic devices against errors at operation caused by electromagnetic troubles there is provided a small time delay $\tau=0.05 \div 0.1s$ owing to which at greater power deficits additional frequency fall occurs. The frequency will fall down to f_1 according to the expression

$$f_1 = f_0 - \Delta f_0 = f_0 - \Delta f_{\infty 0}\left(1 - \exp\left(-\frac{t_1 + \tau}{T}\right)\right), \tag{9}$$

where $\Delta f_{\infty 0} = \frac{\Delta P_{0\%}}{100 \cdot k_f} f_{nom}$ is the resultant frequency change from f_0 (the start of the process) to stationary frequency f_∞ (the finish of the process), Hz; $(t_1 + \tau)$ is the time to the first stage operation, s, which is

$$(t_1 + \tau) = -T \ln\left(1 - \frac{f_0 - f_1}{\Delta f_{\infty 0}}\right), \tag{10}$$

In the process of frequency fall in the range -(1.2÷4)% the settings for unloading stages are defined, each of them will be actuated with operation after time delay τ. Thus, for example, the time interval between operations of the first and the second stages will be:

$$\Delta t_1 = (t_2 - t_1) = -T \ln\left(1 - \frac{f_1 - f_2}{\Delta f_{\infty 1}}\right), \tag{11}$$

where $\Delta f_{\infty 1} = \frac{\Delta P_{1\%}}{100 \cdot k_f} f_{nom}$ and $\Delta P_{1\%} = \Delta P_{0\%} - \frac{f_0 - f_1}{f_{nom}} 100 \cdot k_f - \Delta P_{s\%}$ is power deficit after first stage operating. The frequency will decrease in accordance with the equality:

$$f_2 = f_1 - \Delta f_{\infty 1}\left(1 - \exp\left(-\frac{\Delta t_1}{T}\right)\right), \tag{12}$$

Further, during the second stage, assuming that the process the power unloading in the range of frequency decrease is uniform, this can be presented as the sum:

$$f = f_0 - \Delta f_0 - \sum_i \left(\Delta f_{\infty i}\left(1 - \exp\left(-\frac{\Delta t_i}{T}\right)\right) - \Delta f_\tau\right), \tag{13}$$

where Δf_τ is additional frequency drop due to non-selective operation.

Not taking into account time delays τ of the stages, at unloading the value $\Delta f_{\infty i} = \frac{\Delta P_{i\%}}{100 \cdot k_f} f_{nom} = \frac{\Delta P_{0\%} - i \cdot \Delta P_{s\%}}{100 \cdot k_f} f_{nom} - \sum_i (f_{i-1} - f_i)$ is tending zero, which means frequency stabilization.

However, if we take into account the delays of the unloading stages, several more stages can be disconnected non-selectively, with formation of power excess (see Fig. 5, a) followed by a fast frequency rise. As the result, the character of frequency changes in time will be as shown in Fig. 5, b), when it increases within a few seconds to the level admissible for operation of generating units. If it is below the rated value then slow AUFLS2 will help frequency to approach this value, thus ensuring automatic synchronization and self restoration of the power system. In the case when frequency increases up to the normal level the process will already be close to completion, the turbine governors resume working; acceleration in this case is not too large any more, being in compliance with synchronization requirements.

To achieve that this process is only little dependent on the power deficit uneven distribution of frequency unloading is desirable, when to the first stage a greater users' power is connected then to the last one.

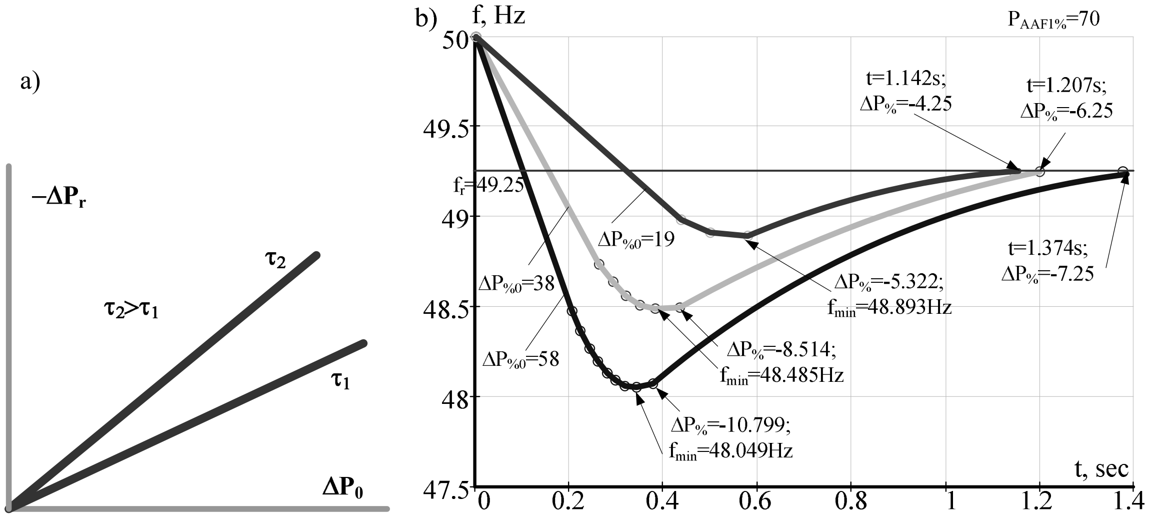

Fig. 5. a) Power excess dependence of initial power deficit at various time delays τ,
b)The character of frequency changes at various initial power deficit $\Delta P_{0\%}$

Effect of voltage fall on the generating units

Disconnection of a heavily loaded line leads to redistribution of power flows among remaining lines, which means that the network cross-section becomes overloaded. This causes additional losses of reactive power giving rise to its additional flow. When the transversal and longitudinal components of voltage drop increase, the voltage level at the receiving side decreases by 15-20%. This is responded by the generator excitation regulators, which leads to overloading of the stator and excitation windings of the generators. When external damage causes operation of the automatics for protection of generators they are massively disconnected, which results in the collapse of the power system.

The overload of a network cross-section can reach thousands of megawatts. To avoid such dangerous overloading various organizational measures are applied, however with a minor success. Therefore radical technical means are required, which at the very beginning of a cascade-like emergency could prevent a blackout without personnel participation.

The only means making possible to achieve that, is fast-acting unloading of the overloaded dangerous network cross-section. For this purpose it is necessary to split the power system by its sectioning into parts in such a way that this overloaded cross-section is kept in operation with allowable power flow [1]. In this case in the separated part of the system a power deficit is created. Following the frequency fall in this part the under frequency load shedding automatics will operate, which restores frequency to the rated level, then automatic synchronization will take place. The previously disconnected transmission and users' lines will be re-closed, and the operating condition in the power system will be restored within 100 s without personnel participation.

The sectioning should be done in the cross-section through which a comparatively small power is flowing (1-2 GW), with the help of automatic protection devices operating in compliance with the tasks prepared under normal conditions and using a logic signal of the fast channel. The requirements as to precise determination of the sectioning place are not excessive. The smaller power flow at the separation point is, the smaller unloading scale is to be expected, and, consequently, no disconnection of the most heavily loaded line will occur [8].

Since in the cases when the voltage fall does not reach the level at which the primary protection will operate the lines are not disconnected, although this can cause intensive sagging of wires, their multiple contacts with earth, and, as a result, stability loss. In the cases when for unloading the overloaded cross-section special protection devices are used, disconnections occur at the places through which the greatest powers are flowing, thus strengthening the serious threat of collapse.

Effect of voltage rise on the generating units

Voltage rise occurs when there is excessive reactive power. This is responded by the generator excitation regulators, which reduce the excitation; as a result, generators can go out of synchronism and become disconnected from the protection. In this case it is necessary to switch on the transversal compensation reactors or disconnect for a short time a high-voltage line which will be reconnected after normalization of operating condition.

Conclusions

1. Short term sectioning of a power system at the optimal places allows unloading of the dangerous cross-sections thus keeping the lines in operation with safe load and preventing initiation of a voltage avalanche.
2. The causes of outages of power plants which are associated with deviations of the working parameters can be eliminated owing to fast self-recovery of normal operation without personnel participation.
3. As a response to the frequency fall, in gas turbines a temperature elevation is observed in the blade zone. In the nuclear reactors, due to worse cooling, a frequency fall is responded by temperature and power increase in the active zone. The tripping of generating units is prevented by fast normalization of operating condition and by under frequency special measures.

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Jekabs Barkans, Professor, Dr.Hab.Sc.Ing.
Riga Technical University,
Faculty of Power and Electrical Engineering
Address: Kronvalda Boulevard 1, LV1050, Riga, Latvia
Phone: 371+67089939

Diana Zalostiba, researcher (PhD student), M.Sc.Ing.
Riga Technical University,
Faculty of Power and Electrical Engineering
Address: Kronvalda Boulevard 1, LV1050, Riga, Latvia
Phone: 371+67089937
e-mail: diki.best@gmail.com

Barkāns J., Žalostība D. Ģenerējošo iekārtu darbības aizsardzība no parametru novirzēm, izmantojot energosistēmas dalīšanu kā pretsabrukuma līdzekli.

Lielo energosistēmu sabrukumu avāriju analīze parādīja, ka parasti avārija izceļas bīstamo šķēlumu pārslodzes rezultātā, kas izraisa sistēmas elementu kaskādveida atslēgšanos. Tas neizbēgami noved pie masveida elektrostaciju atslēgšanās jau pirms stabilitātes zaudēšanas, kā rezultātā energosistēma pilnīgi vai daļēji sabrūk. Vienīgā iespēja apturēt sākušās avārijas attīstību ir tīkla bīstamo šķēlumu atslogošana. Ņemot vērā, ka pārslodzes var sasniegt lielas vērtības, autori piedāvā izmantot preventīvu optimālo īslaicīgo sekcionēšanu, kas ļauj atslogot pārslogoto tīklu, saglabājot darbā pārvades līnijas ar pieļaujamo noslodzi. Tādā veidā bez personāla līdzdalības tiek novērsts sabrukums un nodrošināta režīma pašatjaunošanās īsā laikā. Publikācijā ir izskatītas režīma parametru novirzes iedarbības uz ģenerējošiem avotiem pārejas procesā, kuras var izraisīt to atslēgšanos. Pretavārijas automātikas uzdevums ir aizsargāt ģenerējošos avotus, lai saglabātu tos darba kārtībā, kas ir pamats veiksmīgai un ātrai pašatjaunošanai.

Barkans J., Zalostiba D. Protection of generating units at deviations of parameters by sectioning a power system as a tool for blackout prevention

Analysis of blackouts has shown that emergency situations are usually associated with overloading of dangerous cross-sections, which causes cascade tripping of a power system’s elements. This inevitably leads to the outage of power stations even before the stability has been lost, and, as a result, to a complete or partial collapse of the system. The only possibility to stop the development of such an emergency at its very beginning is to unload the dangerous cross-sections. Since overloads can reach great values, the authors propose to use a preventive an optimal short-term sectioning, which would allow unloading of the overloaded network, keeping at the same time transmission lines operating under the safe load. Such sectioning will prevent the system’s collapse, while its operating condition will soon be restored without personnel participation. The paper considers the influence of deviations in operating

parameters on the generating units in a transient process, which can cause the outage of power stations. The task of the preventive automatics is protection of the generating units with the aim to keep them operating, which is necessary for successful self-restoration of a power system.

Баркан Я., Жалостиб Д., Защита работы генерирующих установок при отклонении параметров режима, используя секционирование как средство предотвращения системных аварий.

Анализ системных аварий показал, что обычно авария является результатом перегрузки опасных сечений, что вызывает каскадные отключения элементов энергосистемы. Это неизбежно приводит к отключению электростанций ещё до потери устойчивости, в результате полный или частичный развал системы. Единственная возможность остановить развитие начавшейся аварии является разгрузка опасных сечений. Учитывая, что перегрузки могут достигать большие значения, авторы предлагают использовать превентивное оптимальное кратковременное секционирование, которое позволяет разгрузить перегруженную сеть, сохранив в работе линии электропередач с допустимой нагрузкой. В результате чего предотвращается развал системы, а нормальный режим самовостанавливается в короткое время без участия персонала. В статье рассмотрено влияние отклонений режима на генерирующие источники в переходном процессе, которые могут вызвать отключения электростанций. Задача противоаварийной автоматики – защита генерирующих источников с целью сохранить их в работе, что является основой успешного самовосстановления.