Problems of fast frequency variation control in interconnected power systems

V. Chuvychin, A. Sauhats, R. Petrichenko, G. Bochkarjova

Abstract—This paper describes problem of fast frequency variation control in large interconnected power system. Interconnection of the large power system with different philosophy of frequency control can cause ineffective and sometimes nonselective behavior of frequency automation. Paper presets results of analysis of frequency control using spinning reserve. Optimal distribution of the primary reserve can be based on cooperative game theory method. Severe system disturbances can result in fast frequency drop, which makes fast governor and boiler response impossible. If the governor action cannot activate spinning reserve quickly enough to restore the system to its normal operating frequency, underfrequency load shedding (UFLS) serves as a last-resort tool to prevent the system from collapse. Application of smart metering and communication can improve efficiency of emergency automation during underfrequency condition. A new load shedding method is suggested. Simulation of frequency behavior was conducted for existing load shedding system and a new one.

Keywords—Interconnected power systems, smart metering system, cooperative game theory, load shedding.

I. INTRODUCTION

DURING the last years many international projects were devoted to the problem of interconnection of the large transmission networks in Europe [1], [2]. There are many problems that complicate such interconnection:

1) Initial period of interconnected operation of power systems usually is characterized by relatively weak intersystem ties. There will be problem of control the intersystem ties.
2) Different philosophy of frequency and active power control can cause oscillations of power transmitted through the intersystem tie line.
3) Methods of frequency control for normal and emergency operational conditions in different systems are different.

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Compatibility problem of operation during normal and emergency conditions of interconnected power systems is aroused.

During emergency situation in the power system caused by generating power deficiency frequency decline takes place. Dynamics of frequency behavior can have very different character. It depends on the value of disturbance, response of emergency automation, governor system and reasons of emergency situation. If governor action cannot activate spinning reserve fast enough to restore the system to its normal operating frequency, frequency actuated automatic load shedding serves as a last-resort tool to prevent the system from the collapse [3], [4]. Interconnection of large power systems with different underfrequency automation and systems' parameters can cause ineffective behavior of frequency in the interconnection.

For small frequency deviation primary and secondary frequency control form a resource to improve efficiency of power system. Many papers are dedicated to the quality improvement of frequency control. The introduction of market conditions in the task of the power system operation changes formulation and solving of energy cost minimization problem in the transient conditions.

For fast and deep frequency decline load shedding automation systems will be applied to restore a normal frequency. Smart metering and communication systems should be used for creation of new solution.

Paper describes possible approach to use smart technology for control fast frequency variation in the interconnected power system.

II. POSSIBLE APPROACH FOR FREQUENCY CONTROL USING SPINNING RESERVE

This chapter illustrates example of frequency control using spinning reserve operation. For integrated power system distribution of spinning reserves is important problem. The operation of several power companies (players), which simplified scheme is presented in Fig.1, is observed. Let us suppose that each company contains several power plants, which are operating in market conditions. At the same time the cooperation between power plants is possible and the support of generated and consumed energy balance at the nominal frequency and costs minimization are the general targets of this cooperation.
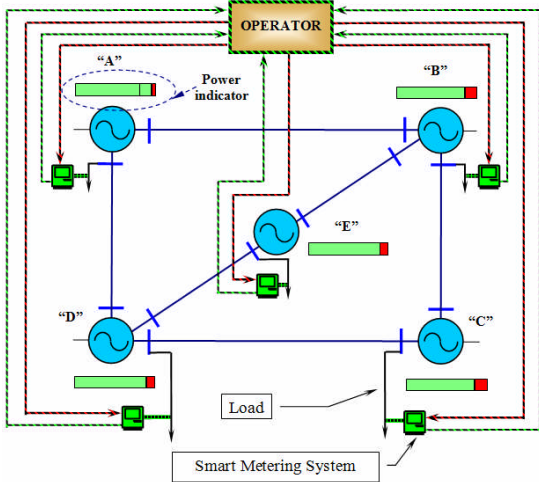
Fig.1 simplified diagram of interconnected power plants involved in primary frequency control

Each power plant is equipped with smart metering system information from which is supplied to the central processing block "Operator".

Let us consider two possible approaches for spinning reserve distribution:

1 - Five plants operate independently, supporting specified part (reserve) of the planned power (classical approach);

2 – All five plants strive to most profitable operation and costs minimization.

Let's suppose, that five power plants are operating – A, B, C, D, E (Fig.1). The power capacities of each plant are - P_1, P_2, P_3, P_4, P_5. Production cost values - C_1, C_2, C_3, C_4, C_5 (EUR/MWh). Each plant provides a reserve - p_1, p_2, p_3, p_4, p_5, with production costs c_1, c_2, c_3, c_4, c_5 (EUR/MWh).

The resulting costs RC_j for each Δt_j (where j =1, ...N) are

$$RC_j = \sum_{i=1}^{5} (P_i \cdot C_i + p_i \cdot c_i) \cdot \Delta t , \qquad (1)$$

Assume, that generators must provide a planned power P_Σ of interconnected power system, as well as possible random deviations of power p_Σ for all i of $C_i < C_i +1$ and $c_i < c_i +1$. Suppose that density of power deviations $f_{ij}(p_{ij})$ is known for each time interval Δt.

The goal is to provide balance of powers:

$$\sum_{i=1}^{5} (P_i + p_i) = P_\Sigma + p_\Sigma , \qquad (2)$$

with minimal RC_j in the interval Δt.

Selecting generators' powers P_i and reserves p_i it is necessary to take into account many technical limitations, which depend on: thermal and electrical loads of consumers, operational condition of thermal and electrical network, water levels in reservoir of hydro power plants.

To provide these limitations the fulfillment of conditions (3) is required:

$$\{P_{ij}, p_{ij}\} \ni A, \qquad (3)$$

where A is the domain of the allowed states of the power system. The task for selection of spinning reserve can be formulated as:

$$\{P_{ij}^*, p_{ij}^*\} = argmin \sum_{j=1}^{N} \sum_{i=1}^{n} (P_{ij} \cdot C_{ij} + E_{ij}(c_R)) \cdot \Delta t_j, \qquad (4)$$

with (2) and (3) conditions fulfillment in equation (4) $E_{ij}(RC_{ij})$ is mathematical expectation of the spinning reserve expenses i-th power plant at j-th time interval of Δt.

$$E_{ij}(RC_{ij}) = \int_{0}^{p_{ij\,max}} p_{ij} \cdot c_{ij} \cdot f_{ij}(p_{ij})dp_{ij} , \qquad (5)$$

P_{ij}^* and p_{ij}^* - optimal capacity of considered plants (providing the minimum cost).

Redistribution of network primary power reserve must be done by information and control center "operator". Taking into account complexity of processes, "operator" has to be realized by IT technologies. Let's describe steps of information and control center's algorithm:

a) algorithm ranks all players (power districts) by value of profitability, from the least to the most profitable (as example see Table 1, 2nd column);

b) algorithm solves all possible combinations of the primary reserve allocation among the players and calculates the most profitable variant. During analysis of variants the initial data for creation coalition of players can be received.

c) algorithm calculates the sharing of benefit among the players;

d) "operator" generates control signals to change the settings of the primary reserve control equipment for each players.

III. BENEFIT SHARING APPROACH

The mentioned above algorithm's point c) is most interesting, because benefit sharing is one of the main power market issues. In the case of the coalition formed by two players, profit sharing is equally distributed between the players (50%/50%).

However, in the case of three, four or five players' coalition, the problem of equitable profit sharing appears. So, if the optimal variant is a coalition of more than two players, profit sharing is done by using the Shapley vector [5].

Let's suppose that the i-th player gets benefit equal to the average value of this player contributions to all coalitions [5]:

$$\phi_i(v) = \sum_{S \subset N} \frac{(|S|-1)!(n-|S|)!}{n!}(v(S) - v(S \setminus \{i\})) \quad (9)$$

The number $v(S)-v(S \setminus \{i\})$ is the contribution of i player when he is joining the coalition $S \setminus \{i\}$, but the weight factor

$$\frac{(|S|-1)!(n-|S|)!}{n!} ,$$

can be interpreted as the probability of the coalition $S \setminus \{i\}$ forming.

Shapley's value of cooperative game is a vector [5]:

$$\phi(v) = (\phi_1(v), \ldots, \phi_n(v))^T \quad (10)$$

IV. CASE STUDY

Let's consider operation of proposed automation using a specific example. Suppose that initial capacities of power plants are known, as well as prices, reserves, etc. Frequency control reserve is stated by system operator equal to 4% of maximal generated power P_{Max}. The initial parameters required for calculations are shown in the Table 1.

The power system operates in normal condition, when the generated and consumed active powers are equal (initial situation): $P_{Generated} = P_{Load} = 6.2$ (p. u.).

Table 1 Parameters of Players Before Optimization

Player	$C_{Cost Price}$ (p. u.)	P_{Max} (p. u.)	P_{Min} (p. u.)	P_{Res} (%)	$P_{Pot. Res.}$ (%)	$P_{Generation}$ (%)
"A"	0.9	1.500	1.410	4.00	0.67	94.66
"B"	0.8	1.400	1.334	4.00	0.43	95.57
"C"	0.7	1.300	1.238	4.00	0.15	95.38
"D"	0.6	1.200	1.132	4.00	1.67	96.00
"E"	0.5	1.100	1.046	4.00	0.36	95.45
Σ		6.5		4.00		95.38
Initial situation						

$C_{cost price}$ – production cost value of produced power (p. u.).

Let's assume that the selling price of electricity is equal to 1.1 (p. u.). Algorithm calculates profitability of all possible combinations of players. In our case, using the basic parameters listed in Table 1 and using equations (9) and (10), the algorithm calculates (Fig.2 situation 1) that the best variant would be a coalition of all players ("A+B+C+D+E") with a total additional profit equal to 0.0076 (p. u.).

As a result of proposed optimization, the primary reserve control function is redistributed from more effective power station to a less one (with a higher production cost). The total value of the primary reserve isn't changed.

The maximum additional profit arises in case when the primary reserve was not activated in specific time interval. Using equations (9) and (10), it is possible to calculate the sharing of profit among the players. The results of the sharing are presented in Table. 2
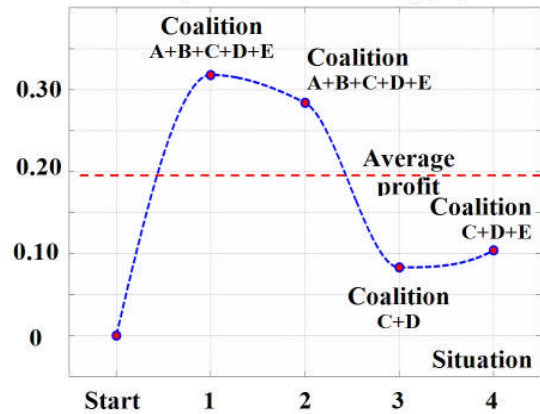

Fig.2 players' profitability in different situations

Table 2 Players' Profitability in Different Situations and Results of Profit's sharing

Number of situation	1	2	3	4
Additional profit of coalition (p. u.) Benefit of player (%)	0.0076	0.0068	0.0020	0.0025
"A"	35.74	31.37	0.00	0.00
"B"	10.61	12.60	0.00	0.00
"C"	5.26	18.63	50.00	46.66
"D"	18.86	23.28	50.00	36.66
"E"	29.52	14.12	0.00	16.66

A. Example of Possible Annual Profit Calculation

The visual demonstration of advantage to use suggested method is practical calculation of additional profit using denominated quantities of power system parameters.

When average value of additional profit is equal (see Fig.2) to 0.2% for power system with average capacity equal to 1000 MW and average price of energy is 50EUR/MWh. Additional profit is 876000 EUR.

Such additional benefit will cover the cost of creation the appropriate control system.

V. APPLICATION OF SMART LOAD SHEDDING SYSTEM

Severe system disturbances can result in fast frequency drop, which makes fast governor and boiler response impossible. If the governor action cannot activate spinning reserve quickly enough to restore the system to its normal operating frequency, underfrequency load shedding (UFLS) serves as a last-resort tool to prevent the system from collapse.

In most power systems up-to-date automatic load shedding systems practically foresee disconnection of the load at underfrequency without time delay or with small delay [6]-[8]. The numbers of load shedding steps and the value of load to be shed vary for different power systems. Some power systems use rate-of-change of frequency as additional factor to shed a load [9]. Fig. 3 presents an example of a frequency variation during operation of the frequency actuated load shedding system. The point $f < f_{nom}$ corresponds to the moment of active power deficiency appearance in the power system. From this moment the frequency drop starts. When the power system frequency reaches the level of a first load shedding setting f_{set1}, the first part of the load is disconnected. The next part of the

load will be disconnected when frequency reaches second load shedding setting f_{set2}.

With each next load shedding step rate-of-change of frequency decline is cut down and after a certain moment the increase of frequency takes place. Such logics of the load shedding operation apply to most of the power system utilities [9].
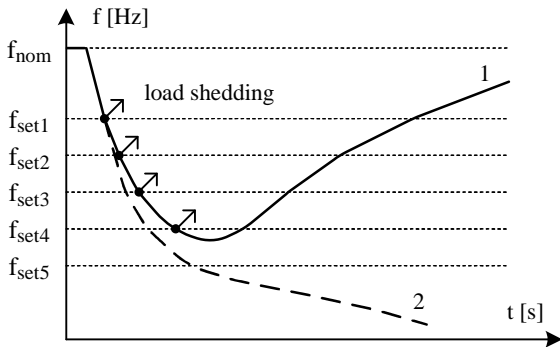

Fig.3 power system frequency variations during the UFLS operation

UFLS schemes can be categorized into three groups [3]:
   1. the traditional UFLS schemes;
   2. the semi-adaptive UFLS schemes;
   3. the adaptive UFLS schemes.

Existing UFLS automation has drawbacks, which limit the adaptability of emergency situation control to a change of underfrequency situation in a power system. UFLS tripping frequency settings are selected for some specific emergency situation, which is considered as more probable for a specific power system. It is not possible to foresee all situations that can occur in the power system. UFLS operation will be secure effective only for the pre-calculated emergency cases. Problems related to the value of a load to be shed are very topical. Redundantly tripped load can create overfrequency situations, which sometimes is more dangerous than underfrequency. Mentioned situation is presented in Fig.4.

The overfrequency situation after UFLS operation happens because the total disconnected load of the steps of UFLS is two times as large as the deficiency of active power in the network [9].

A. Analysis of Frequency Behavior for Different Algorithms of UFLS

Authors investigated frequency behavior during sever disturbances in united ENTSO-E power system and IPS/UPS power system of Russia. Appropriate model was developed with the real settings of load shedding automation. Different variants of frequency behavior were investigated [9].
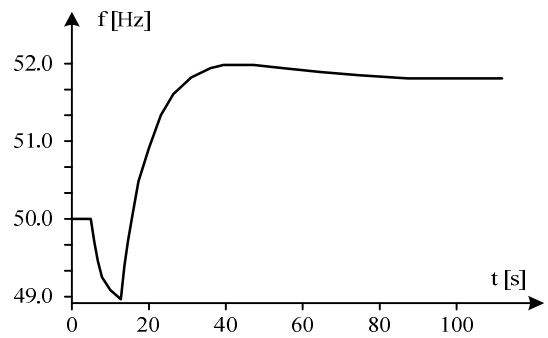

Fig.4 frequency behavior for 10.8% of active power deficiency

As an example frequency behavior at a load deficiency of 20% and an iterative deficiency of the active power of 6.7% is shown in Fig.5. During cascaded event the stabilization of frequency can occur at a dangerously low level without being noticed by UFLS. It can happen if the active power disconnected by UFLS is not sufficient to return frequency back to permissible range. In the considered case the frequency stays at 48.9 Hz. The reason for that is different load shedding philosophy of two interconnected power systems.
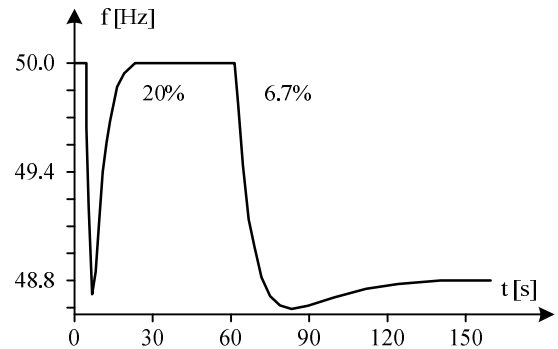

Fig.5 frequency behavior for 26.7% of active power deficiency

B. Application of Smart Technology Approach to the Load Shedding System

Let us return to example of Fig.1 and explain behavior of load shedding automation.

Each district is equipped with an interactive power measuring device (a smart meter) [10]-[14].

The information center "Operator" receives full information about the current condition of the consumption of active power in each power district, about the location and value of the power deficiency that has arisen. In that way, an interactive information system between the districts' load and emergency automation is set up.

Using described metering system the automation operating process (let us call it smart underfrequency load shedding system — SUFLS) can be presented by few calculation cycles:

1. Determination of the value of the deficiency. Transformed rotor swing equation can be used for calculation of this deficiency [6], [7]:

$$\Delta P = T_J \cdot \frac{df}{dt} + \frac{\Delta f}{k_{gov}} + \Delta f \cdot k_{load} \ , \qquad (11)$$

where T_J – rotor's inertia constant; k_{gov} – governor speed droop; k_{Load} – load-damping constant; f – frequency.

2. Memorization of the value of deficiency and its location;

3. Calculation of the number of substations to compensate the deficiency;

4. Calculation the optimum variant for load disconnection.

To compare the results of the operation of UFLS and SUFLS automation, a mathematical model has been constructed by using Matlab/Simulink software. Fig.6 illustrates frequency behavior in the case of emergency situation for existing UFLS and smart SUFLS automation.
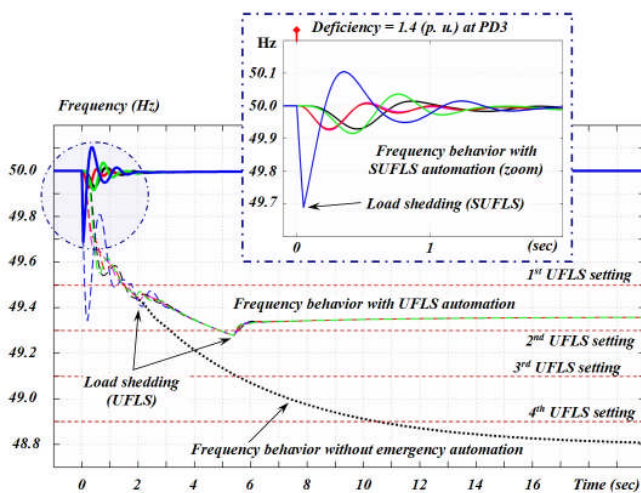

Fig.6 frequency behavior in the case of emergency situation

The more effective operation of SUFLS automation is obvious. The more effective approach is to activate load shedding automation in districts, where power deficiency takes place.

VI. CONCLUSION

Smart metering systems can be used for both – small frequency variations and deep frequency decline operation.

Optimal distribution of the primary reserve can be based on cooperative game theory method.

Proposed algorithm, which takes into account technical limitations and economic aspects of the primary frequency control participants, has to be used.

Results of practical calculation of additional profit prove feasibility of application of game theory method for optimal distribution of frequency control reserves.

The mathematical model of the power system with proposed calculation algorithm can be performed using computer program Matlab Simulink.

Integration of large power systems with different philosophy of underfrequency load shedding systems can cause ineffective and sometimes not selective frequency control.

A new load shedding method is suggested. Simulation of frequency behavior was conducted for existing load shedding system and a new one.

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