# Development of Selective Automatic Systems for Prevention and Elimination of Out-of-Step Operation Using PMU

**N.I. VOROPAI, D.N. EFIMOV, D.B. POPOV**
**Energy Systems Institute**
**Russsia**
**K. REHTANZ, U. HAEGER**
**Dortmund University of Technology**
**Germany**
**voropai@isem.sei.irk.ru**

## KEYWORDS

Out-of-step operation, prevention, elimination, selective automatic system, PMU.

## 1. INTRODUCTION

Out-of-step operation in power interconnection is one of the most severe emergency conditions. It is related to the loss of stability in power interconnection, which may cause damage to equipment, interruption of power supply to consumers and unwanted development of emergency processes with severe consequences for the entire interconnection and its parts [1-3 et al]. With the future possibility for the UCTE and IPS/UPS power interconnections to operate jointly by the AC tie lines the occurrence of out-of-step operation of the interface between these power interconnections can be dangerous for both of them and result in undesirable consequences for the systems and consumers. Measures are therefore required to detect, prevent and eliminate out-of-step conditions.

Special automatic out-of-step protection systems (OSPS) have been used in electric power system for reliable, timely and selective detection and elimination of out-of-step conditions [1, 4, 5]. The most effective system is the so called selective OSPS which is based on the angle measurement [5, 7]. Previously the difficulties of measuring angles by the devices for teletransmission of voltage phase made us use indirect angle calculation. Most popular methods of this calculation are based on determination of current amplitude or complex impedance at a connection point of automatic system [5, 8, 9]. In this case the system is represented by a two-machine equivalent with regard to cutset of the ties in which the OSPS is installed. The parameters of the two-machine equivalent are determined on the assumption that the motion of generators in the initial system along both sides of the cutset at issue is coherent [5, 10 et al]. This assumption is based on the fact that kinetic energy of generators' mutual oscillations in the transient process under disturbance, in the case of out-of-step conditions, passes to the kinetic energy of the out-of-step motion of two groups of generators along both sides of the cutset at which the out-of-step conditions occur, while inter-machine oscillations within these two groups of generators decrease essentially.

The easiest to implement indirect method for calculating transmission angle is the use of angle dependence of transmission current. The disadvantage of this method is a wide scatter of operating angle values of the OSPS under the assumed current pickup settings due to various possible compositions and structure of ties in the cutset in different schemes and conditions of power system. Besides, this dependence is nonlinear. The lesser error is obtained by the use of the so called phantom scheme, i.e. by modeling of voltage phasor of a point located at some distance from the site of automatic system placement, for example a receiving end of transmission line. The phantom scheme is used in the OSPS installed in power systems in Russia. Particularly complicated conditions for selective operation of OSPS occur in the multi-frequency out-of-step conditions along several cutsets [5].

Further development of selective OSPS has resulted in creation of a multifunctional device. The device makes it possible not only to eliminate the out-of-step conditions if they have occurred but also to prevent their occurrence. It has two stages of control actions [5]: the control actions of the first stage are intended to prevent the loss of stability and for this purpose generation is disconnected in the surplus part of the system and fast reserve is used (or secondary load is shed) in the deficient part. If these control actions are insufficient and fail to prevent out-of-step operation the control actions of the second stage are triggered and split power interconnection.

The use of synchronized voltage phase measurements obtained from PMU offers principally new capabilities of implementing the selective OSPS and selective out-of-step protection and prevention system (SOSPPS) [11]. Some SOSPPSs have been lately suggested on the basis of PMU. In [12, 13] in order to reveal transient instability the equal-area criterion is used when representing the system by a two-machine equivalent. Its parameters are determined by the complex values of power system state variables. In [14] the measurements of voltage phases and differences of their first derivatives are used to forecast power system stability losses according to the criterion based on energy function. In [15] an integrated criterion is suggested to reveal the center of oscillations with the use of estimates of the voltage magnitude projection at some point of the tie line between two parts of the system and current along this tie line when using the two-machine equivalent of power system on the basis of the generators motion coherence in these two parts of the system which is estimated on the basis of currently measured angles.

The authors of the paper suggest the principles of designing a modified SOSPPS with the use of PMU measurements. Its efficiency is demonstrated on the test power system.

## 2. PRINCIPLES OF DESIGNING A MODIFIED SOSPPS

### 2.1. The scheme of interrelation between states and control actions

Loss of synchronism in power system operation in some cutset can be caused by two main reasons:

- the maximum admissible transfer capability of the cutset is exceeded and, thus, the aperiodic static stability of the system is lost;
- the transient stability is lost as a result of disturbance on one of the ties or near the considered cutset.

In both cases an indicator of synchronism loss and the beginning of out-of-step conditions is the difference in voltage phases on the ends of the most critical tie line of the considered cutset. In other words there is some maximum value of the voltage phase difference $\delta^{as}_{\lim}$, whose excess indicates to the beginning of the out-of-step conditions.

In order to avoid this critical situation it is necessary to maintain the cutset load at the level not exceeding some admissible level corresponding to $\delta_{\lim} < \delta^{as}_{\lim}$. The difference between $\delta_{\lim}$ and $\delta^{as}_{\lim}$ should take into account irregular variations of flows along the tie lines and the need to ensure transient stability of power systems under standard disturbances. In Russia dispatching centers of power systems use the recommended values of transmission loading margins under normal and post emergency states [16]. In the power systems of UCTE there are no similar explicit recommendations. Nevertheless, setting the value $\delta_{\lim} < \delta^{as}_{\lim}$ can be expedient.

Thus, power systems can have four states (Fig. 1): secure, dangerous, emergency (out-of-step conditions) and post-emergency. The secure state of power systems is determined by the condition $|\delta_{ij}| < \delta_{\lim}$. PMU measurements are used to trace the current value of $\delta_{ij}(t)$. The dangerous state of power system occurs at $|\delta_{ij}| > \delta_{\lim}$. For the power system to return to a secure state it is necessary to perform control cutset unloading actions by decreasing loads of units at power plants on the transmitting side and by using fast reserve (or disconnecting secondary consumers) on the receiving side. If these control actions are sufficient power system returns to the normal state. However, if the control actions are insufficient the system passes to the emergency state (out-of-step conditions) which is eliminated by disconnecting the cutset (by dividing the power system). Should the power system be split unsuccessfully the emergency situation can develop and post-emergency state may turn out to be severe and even turn into a blackout. In the event of successful splitting the generation and load in the split subsystems are balanced by generation disconnection in the surplus subsystem and by the action of automatic frequency load shedding in the deficient subsystem. Post-emergency state in this case will be less severe as compared to the previous one.

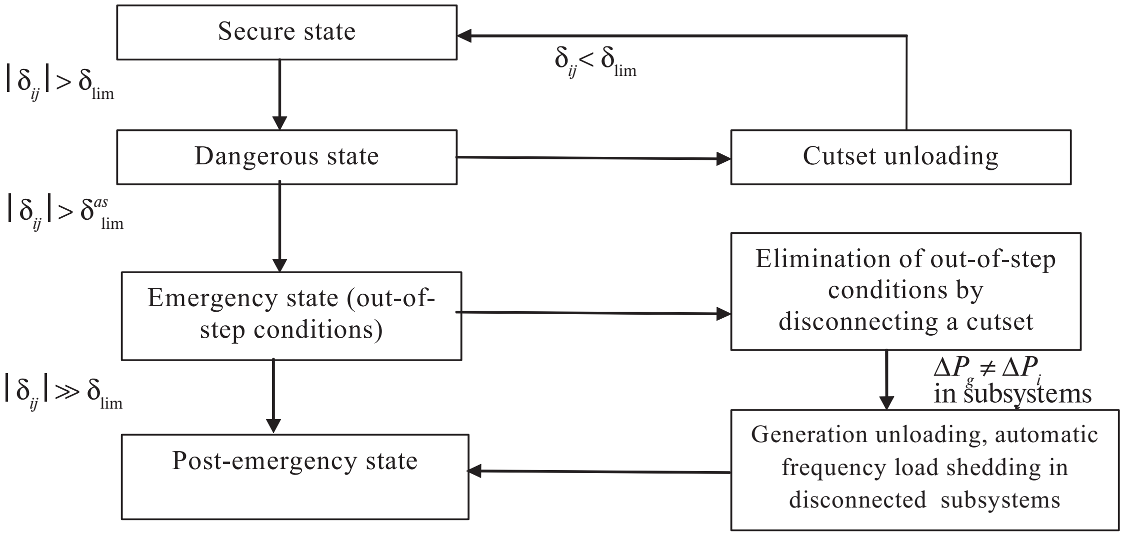


**Fig. 1:** A scheme of interrelation between power system states and control actions in SOSPPS

It should be noted that traditionally in Russia's power system dispatching practice automatic load shedding and OSPS are considered separately due to the fact that the former is adjusted and operates using the power flow values as an indicator of overload while the latter is intended for the transmission angle action, with transmission angle being determined by indirect methods [1]. The use of one and the same indicator which is the difference between PMU-measured voltage phases on both ends of power transmission allows one to consider both types of automatic systems as a single integrated emergency control system.

## 2.2. Criteria for actions of SOSPPS's stages

As was noted in 2.1 the conditions for transition from normal (safe) state to the emergency one is formulated as $|\delta_{ij}| > \delta_{\lim}$. Hence the criterion for action of the cutset unloading stage of SOSPPS will look as

$$C^{ul}_{act} - (|\delta_{ij}(t)| > \delta_{\lim}). \tag{1}$$

In the event that the action of the cutset unloading stage is insufficient or inefficient the difference in the voltage phases along the critical tie line of the cutset at its overload continues to increase and reaches the value $\delta^{as}_{\lim}$. This point to the loss of aperiodic static stability of power system along the considered cutsets and the need to split the system. The criterion for action of the SOSPPS's division stage will have the form

$$C^{as}_{act} = (|\delta_{ij}(t)| > \delta^{as}_{\lim}. \tag{2}$$

To formulate the criterion for action of SOSPPS's division stage according to the conditions of transient instability of power system under large disturbances it is necessary to use the second derivative of the difference between the voltage phases of a critical tie line in the cutset. Decrease in the second derivative of voltage phase difference indicates conservation of transient stability of EPS. System transition to an emergency state (out-of-step condition) is revealed provided that at least for three cycles of measurements by using PMU, the second derivative value of voltage phase difference for the critical tie line at the cutset does not go down below some small value $d\delta_{\min}$. In this case each cycle may account for several scores of milliseconds. Theoretically, $d\delta_{\min} = 0$, however practically this value is not equal to zero because of errors and noise in measurements and also inaccurate determination of the second derivative due to discrete measurements. Determination of the acceptable value $d\delta_{\min}$ is an independent problem.

Hence, for the direct power flow by the cutset from node i to node j the criterion for action of SOSPPS's division stage subject to transient stability will have the form

$$C_+ = (\Delta\delta_{ij}(t) > 0) \wedge (\frac{d^2\delta_{ij}(t)}{dt^2} \geq d\delta_{\min}) \wedge \ldots \wedge (\frac{d^2\delta_{ij}(t) - 2T_s}{dt_2} \geq d\delta_{\min}), \tag{3}$$

where $T_s$ – cycle length between the PMU measurements.

The corresponding criterion $C\_$ for the reverse power flow by the cutset (from node j to node i) is determined in a similar way.

The general criterion of transition to an emergency state (out-of-step condition) and the action of SOSPPS's division stage is written in the following way:

$$C_{as} = (C^{as}_{act} \wedge (C_+ \vee C\_)) \tag{4}$$

As a result EPS is split into two isolated subsystems.

## 2.3. Related problems

The formulated approach to SOSPPS improvement based on PMU measurements includes only its basic principles illustrated by the test example later in Chapter 3. Actually consideration should also be given to the related problems to be solved in the course of approach application. Below are the main problems.

As indicated above, it is reasonable to measure voltage phases on the basis of PMU on the ends of the critical tie line at the cutset. The problem is that the increase of transmitted power along the cutset results in different loading of individual tie lines at the cutset. Such a situation is caused by the parameters of tie lines and also the structure and parameters of adjacent electric networks. This inhomogeneity of an electric network is revealed in the fact that the sensitivity of nodes and tie lines at the loaded cutset proves to be unlike [17]. Hence, conditions for transition to the out-of-step operation are formed first of all in the most sensitive tie line. The tie line turns out to be critical at the cutset and it is expedient to place PMUs on its ends.

It should be noted that significance of a critical tie line at the cutset requires additional studies. It is explained by the fact that with the start of out-of-step condition change in the voltage angles will be observed in all tie lines of the cutset. It is important to establish the extent to which the change in tie line loading at the beginning of out-of-step condition is significant in terms of the efficiency of SOSPPS operation.

Another problem is the necessity for verification of criterion (3). It has two components. The first is associated with available errors and noise in the measurements by using PMU, delays in information transmission, measurement frequency, etc. These technical properties should be studied thoroughly and individually. And the results of studies will determine specific features of the designs of automatic systems.

The other component of the problem is the accurate determination of the second derivatives of variation of voltage phase differences. It depends on the monotone change of phase differences and the length of intervals between measurements, as well as on measurement errors. The problem is that the second derivatives must be calculated by numerical differentiation of measured parameters. This question also requires thorough additional studies.

The results of studies on both components determine efficiency of using criterion (3) and in particular, certainty in setting the value $d\delta_{\min}$.

The issue about selectivity of action of the modified SOSPPS at the multi-frequency out-of-step condition for the case of stability loss at several cutsets remains to some extent open. It seems that selectivity of work of automatic systems should be sufficiently high and acceptable, since the change of voltage phases on the ends of tie lines at the cutset is a quite definite indicator of the beginning out-of-step condition. Here the value $\delta_{\lim}$ is uniquely determined by the state variables of the critical tie line of the cutset and the required margins of its transfer capability.

# 3. TEST STUDIES

Let the test electric power system (Fig. 2) operates in post-emergency conditions when the tie 8-5 is loaded at 90% of its maximal transmission capability, and voltage mutual angles equal $\delta_{8-5} = 36{,}6^\circ$ and $\delta_{202-100} = 50{,}5^\circ$.

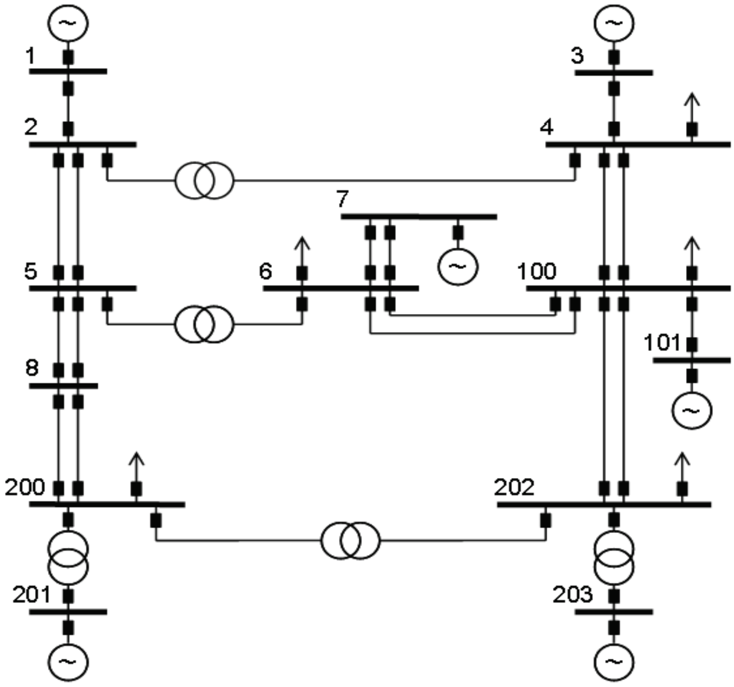
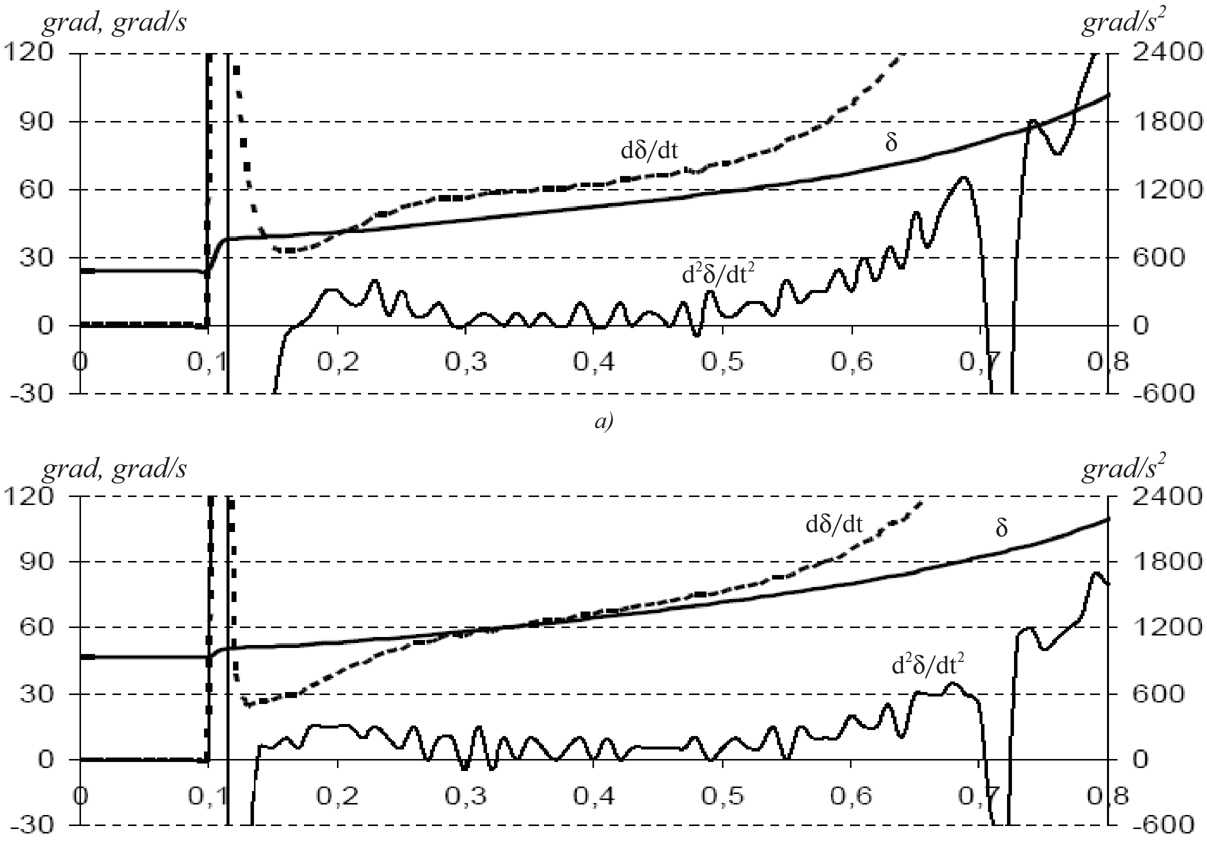


**Fig. 2:** Case study network



a)

b)

**Fig. 3:** Time behavior of δ, dδ/dt and d$^2$δ/dt$^2$ in the absence of control actions:
a*)* for the tie 8–5, *b)* for the tie 202–100

Let us consider as a disturbance the unscheduled disconnecting the one of two lines of the tie 8–5. The behaviors of voltage mutual angles and their time-derivatives without any control actions are shown in Fig. 3.

Suppose the system is equipped with SOSPPS, and a starting value for action of the cutset unloading stage (see criterion (1)) is set as $\delta_{\lim(8-5)} = 52{,}2°$. At the time of t = 0,4 s the control actions will be realized as partial disconnections (of generation in power surplus part of the system and of load in its deficient part). The values of disconnected power are shown in Fig. 4. Suppose the larger disconnections are to be highly undesirable through technical and/or economical limitations.

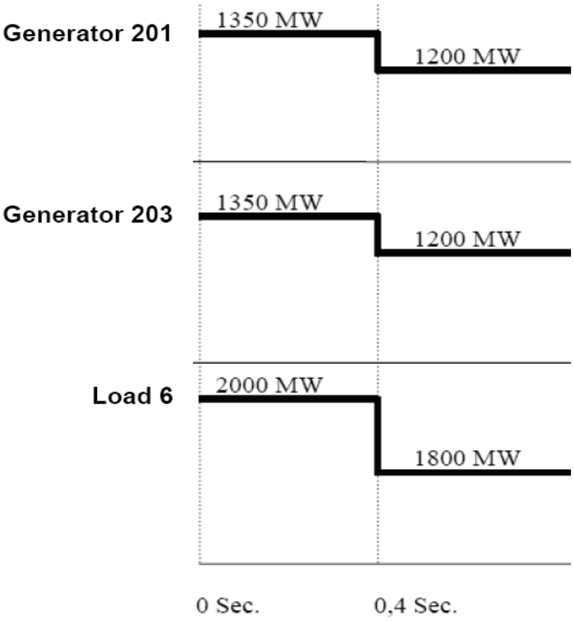


**Fig. 4:** Generation and load tripping for the cutset unloading

The behaviors of voltage mutual angles and their time-derivatives with above mentioned control actions are shown in Fig. 5.

Fig. 5 demonstrates the inefficiency of undertaken control actions for providing the system stability. The non-periodic growth of mutual angles in the cutset, which appeared virtually straight after the disturbance, lasts also after these actions (although not so fast as without them). If we suppose (only with a view to exemplify the study) the inadmissibility of further mutual asynchronous motion for the power system, then the starting value for action of the cutset division stage (see criterion (2)) in accordance with Fig. 5 is to be set as $\delta^{as}_{\lim(8-5)} = 57{,}3°$. At that case the system is being divided at the time of t = 0,5 s (when the first derivative of the angle reaches its maximum $\frac{d\delta_{8-5}}{dt} = 44$ deg/s).

After splitting the system into two separate subsystems (one of them with the surplus and other with the lack of active power) each subsystem faces the challenge of bringing the frequency to admissible level. The solution is in the further reducing the power (of the generation and load respectively). This reducing may ensue less than that would be required under saving the parallel operation with unified frequency. In general the system splitting involves the more beneficial effect the higher power of the subsystem which separates with the power lack.

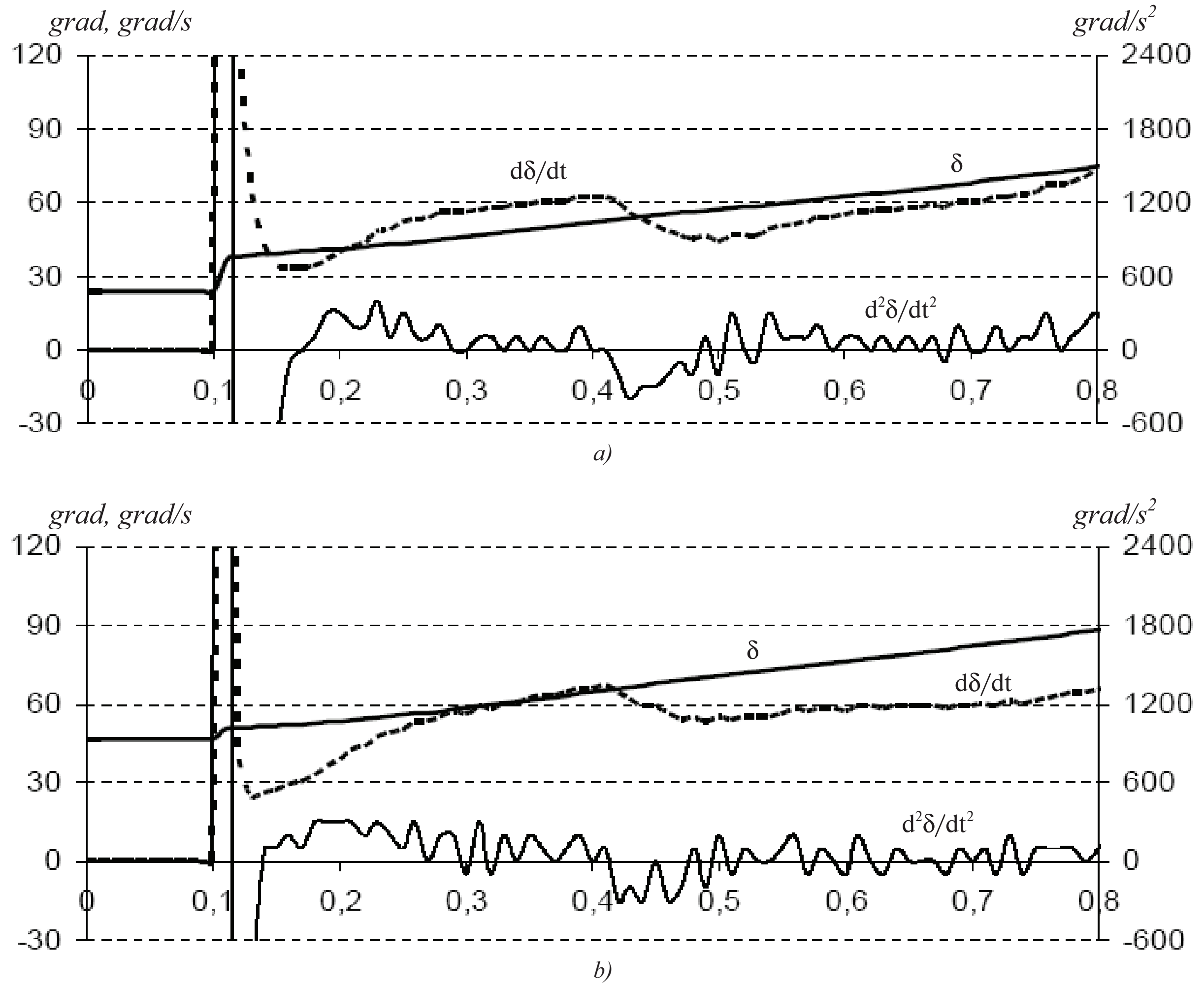


**Fig. 5:** Time behavior of δ, dδ/dt and $d^2\delta/dt^2$ when maximum permissible unloading the cutset: *a)* for the tie 8–5, *b)* for the tie 202–100

## REFERENCES

[1] Sovalov S.A., Semenov V.A. Emergency control in power systems. Moscow, Energoatomizdat, 1988, 416 p. (in Russian).

[2] Pourbeik P., Kundur P.S., Taylor C.W. The anatomy of a power grid blackout. IEEE Power and Energy Magazine, 2006, Vol. 4, No. 5, p. 22-29.

[3] Makarov Yu.V., Reshetov V.I., Strojev V.A., Voropai N.I. Blackout prevention in the United States, Europe and Russia. Proccedings of the IEEE, 2005, Vol. 93, No. 11, p. 1942-1955.

[4] Barzam A.B. System automatic devices. Moscow, Energiya, 1964, 356 p. (In Russian).

[5] Gonik Ya.E., Iglitsky E.S. Automatic elimination of out-of-step condition. Moscow, Energoatomizdat, 1988, 112 p. (in Russian).

[6] Brinkis K.A., Semenov V.A. Selective partitioning protection at out-of step conditions. Elektricheskiye stantsii, 1975, No. 2, p. 66-68 (in Russian).

[7] Ohura Y. e.a. A predictive out-of-step protection system based on observation of the phase difference between substations. IEEE Trans. Power Delivery, 1990, Vol. 5, No. 4, p. 661-667.

[8] Quintana V.H., Mueller H. Partitioning of power networks and application to security control. IEE Proc.: Generation, Transmission and Distribution, 1991, Vol. 138, No. 6, p. 535-545.

[9] Wang X.M., Vittal V. System islanding using minimal cut sets with minimum net flow. IEEE PES General Meeting, Denver, USA, June 6-10, 2004, 6 p.
[10] Narovlyansky V.G., Nalevin A.A. A method for determination of equivalent parameters of power system network during out-of-step condition. Elektrichestvo, 2005, No. 8, p. 15-21 (in Russian).
[11] Phadke A.G., Thorp J.S. Synchronized phasor measurements and their applications. Berlin: Springer, 2008, 288 p.
[12] Centeno V. e.a. An adaptive out-of-step relay. IEEE Trans. Power Delivery, 1997, Vol. 12, No. 1, p. 131-138.
[13] Bozchalui M.C., Sanaye-Pasand M. Out-of-step relaying using phasor measurement unit and equal area criterion. IEEE Power India Conference, April 10-12, 2006, 6 p.
[14] Padiyar K.R., Krishna S. Online detection of loss of synchronism using energy function criterion. IEEE Trans. Power Delivery, 2006, Vol. 21, No. 1, p. 163-171.
[15] Li Li, Liu Yutian, Mu Hong, Yu Zhanxun. Out-of-step splitting scheme based on PMUs. DRPT'2008 Int. Conf. Nanjing, China, April 6-9, 2008, 6 p.
[16] Methodological guidelines on power system stability. Moscow, NTs "ENAS", 2004, 16 p. (in Russian).
[17] Voitov O.N., Voropai N.I., Gamm A.Z., Golub I.I., Efimov D.N. Analysis of inhomogeneities of electric power systems. Novosibirsk: Nauka, 1999, 256 p. (in Russian).