

EMERGENCY CONTROL IN ELECTRIC POWER SYSTEMS WITHIN SMART GRID CONCEPT*

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ABSTRACT. The objective trends in electric power systems (EPSs) are discussed. New measurement, communication and control tools, information and computer technologies are considered as good possibilities for improving EPS controllability. Current emergency control system in Russia is presented. A modern approach to monitoring, forecasting and control is suggested. Some artificial intelligence applications for development of automatic emergency control in EPS are discussed.

Keywords - Electric Power System (EPS), Emergency Control, Smart Grid Concept, Intelligent Control, Intelligent Coordination.

1. INTRODUCTION

Emergency control, including emergency operation dispatching and automatic emergency control that provides reliability and survivability of the electric power grids plays an important part in controlling the operating conditions of Russia's Unified Energy System (UES). Emergency control is performed by the technological (dispatching and automatic) control systems that include the automatic systems of voltage, frequency and capacity regulation, basic automatic systems of EPS elements, relay protection and automatic line control, system emergency control [12,10].

Many thousands of emergencies and more occur usually in large power systems during a year for different reasons – short circuits, failure of equipment, errors of personnel, etc. Most of these emergencies are eliminated by relay protection devices and automatic emergency control systems. The failures of relay protection and emergency control devices and personnel errors lead to cascading development of emergencies. The automatic emergency control system of higher level localizes and eliminates such cascading emergencies. If this high level control system operates ineffectively or unreliably and additional failures and errors occur we will have unique and catastrophic blackouts like in North America and Europe in 2003 [5], Moscow blackout in 2005 [9], European blackout in 2006 [1] and others.

An important trend in electric power industry is towards integration of electric power systems and formation of regional, state and interstate interconnected electric power grids. Interconnection of EPSs results in system effects owing to maneuvering the energy resources, generation capacities and power flows.

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The integration of EPSs is primarily intended to provide consumers with power and power services of high quality on the whole territory of electric power grid. Thus the electric power industry becomes to a larger extent an infrastructural sector of the economy.

Liberalization of electric power industry leads to a principal change in the EPS organizational structure that does coincide with its technological structure and the structure of control system. The wholesale electricity market participants have principally new character of interrelations that are on the market principles. All this requires that the organization of operating and emergency control of EPS must be revised in the context of a market environment without a damage to the efficiency of the EPS operation.

As for future EPS we have to consider possible new generation and network technologies, new principles and ideas in the development and construction of electric power industry, and so on.

All these factors essentially complicate power system operation, increase its changeability and unpredictability, raise danger of severe emergencies with undesirable development and massive consequences for a system and consumers and, therefore, call for prompter and more adequate response of control systems. This generates the need to improve and develop principles and systems of power system operation control which can be based on [15]:

- new systems for measurement of operating parameters (PMU) and their control (FACTS, energy storage devices, etc.) that significantly improve EPS observability and controllability;
- modern communication systems, new information technologies and artificial intelligence methods, highly efficient computers, which totally change the processes of acquisition, transmission, presentation (visualization) and use of information on power systems;
- efficient mathematical control theory methods in multicriteria non-coincident conditions.

Based on the above circumstances the so called Smart Grid concept was developed [4, 3].

Smart Grid concept relates to energy generation, transmission, distribution and delivery. This concept means the use of:

- Highly intelligent systems for monitoring and control, integration and control of renewable sources, distributed generation and energy storage devices on the basis of the Internet technologies;
- Wide area monitoring of operating conditions and their control with the help of new devices and technologies (FACTS, PMU, artificial intelligence, etc.);
- Distributed microprocessor-based control and protection systems, new information and computer technologies;
- Highly intelligent systems intended for electricity control and metering for consumers, demand-side management and load control in emergency situations.

Emergency control ideology in UES of Russia is a hierarchical approach and is realized by coordinated operation of many control devices, which maintain EPS stability and interrupt the expansion of emergency situation in the case of stability violation and a treat of undesirable cascade emergency development. Coordinated emergency control is realized by joint participation of generators, network and consumers.

The paper deals with the analysis of current emergency control system of UES of Russia and possible ways to develop Smart Grid concept concerning advanced emergency control system by using new technologies and devices.

2. EMERGENCY CONTROL SYSTEM IN RUSSIA

The electric power object called “Unified Energy System of Russia” is a power interconnection, where seven Interconnected Power Systems (IPSs) are combined by weak ties. Under the emergency conditions the UES of Russia as a power interconnection is able to disintegrate into autonomously operating self-balanced IPSs without grave consequences. At the same time disintegration of any of the mentioned seven IPSs is far from smooth. Because of large power flows in the ties, practically any disintegration creates parts with power lack and power surplus. As a result, load and generator disconnections are quite possible and can acquire a cascade character, i.e. turn into system crash fault. For this reason at the IPS level the generator and load disconnections by special system emergency devices (in order to unload cutsets and to maintain admissible values of operation parameters) are of course more preferable than cascade disconnection by protection devices (after these parameters go beyond the fixed limits). Just this principle is basic for arranging the emergency control in Russian EPSs [12,10,5,6].

The emergency control system in Russia’s IPSs includes the following components:

A) Dispatching emergency control: to provide admissible loading of the electric network ties according to the Guidelines on power system stability [7].

B) Automatic emergency control:

▷ *In pre-emergency conditions* - to maintain necessary transfer capabilities of ties by efficiently controlling them through the use of PSS; control systems of reactive power sources, DC links, etc.

▷ *In emergency conditions* -

- The above automatic controllers and control systems – to maintain the voltage levels and damp the oscillations in EPS;
- Automatic stability control of EPS;
- Automatic frequency load shedding; automatic voltage deviation limiting, automatic isolation of power plants with maintaining the auxiliary power supply, etc.

C) Restoration of EPS after large emergencies.

The main principles of emergency control system operation in Russia’s IPS are:

- Observation of standard transfer capabilities margins in electric ties in pre-emergency and post-emergency operating conditions;
- Echelonized system of automatic emergency control whose actions are coordinated in order, depending on type, time and severity of emergency; the system is aimed at interrupting the emergency process development at its earliest stage;
- Prevention of development and interruption of severe system emergency is an exclusive prerogative of the automatic emergency control system due to a fast development of the process and, therefore, impossibility for dispatcher to act adequately; after a large emergency EPS is mainly restored by dispatching personnel through the use of some automatic systems.

It is important to draw the attention on hierarchical two level automatic centralized emergency control system which realizes effective stability control of EPS. This system collect and process information regarding current state and disturbances in a large EPS region or in the entire power system. The remedial actions are supported by analytical tools and may include a variety of geographically dispersed measures triggered by sophisticated algorithms. The algorithms perform the following functions:

- identifying the danger of instability and decision making whether remedial control actions are necessary;

- selecting the most effective control actions to prevent instability from the arsenal of available remedial actions;
- determining the size of the corrective remedial control actions.

Above mentioned main principles and components of emergency control system of Russia's UES show that this control system has just now the elements of Smart Grid ideology. Such elements include:

- ▷ *adaptability by* coordination of control actions in order, depending on type, time and severity of emergency; echelonized control system is tried to interrupt the cascading emergency process the sooner the better;
- ▷ *optimality* in the control actions especially by hierarchical two level automatic centralized emergency control system which includes the top coordinating subsystem with fast algorithms for optimal choosing of control actions for control devices on the bottom level;
- ▷ *intellectuality* of decision making process with the learning and optimal control actions in the hierarchical two level automatic centralized emergency control system; such a system has the properties of multi-agent systems.

3. THE SYSTEM OF MONITORING, FORECASTING AND CONTROL OF EPS

Advanced smart devices and technologies, such as PMU, artificial intelligence and so on give new possibilities for solving complex and comprehensive problem of emergency control using monitoring, forecasting and control of EPS operating conditions. Time sequence of individual stages of monitoring, forecasting and control of operating conditions is shown in Fig. 1.

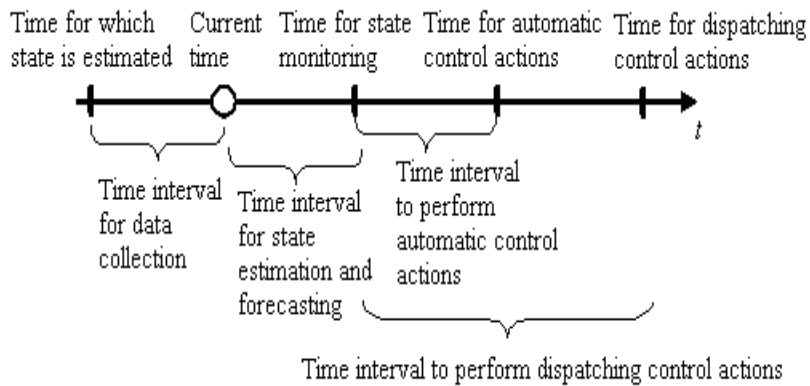


Figure 1. Time diagram of events in the system for monitoring, forecasting and control in EPS.

In essence this combination of stages represents a comprehensive system providing stability, reliability and controllability of modern power systems. At the same time from the viewpoint of efficiency of this system it is essential to increase the adaptability of control and improve coordination of the control stages, means and systems. The blocks of monitoring and forecasting of the EPS normal, pre-emergency and post-emergency operating conditions include the following problems:

- System state estimation.
- Forecasting the parameters of expected operating conditions. Forecasting is necessary because during the state estimation procedure current state is estimated with some delay, while monitoring and control problems require some advance estimation of system state

(“to control is to foresee”); let us note that for these two blocks of problems the advance time can vary.

- Detection of weak points in the system in the expected operating conditions.
- Determination of margins for transfer capabilities of ties in the expected conditions; this is necessary for efficient use of the margins in operating conditions and for automatic control through appropriate control actions.
- Visualization of expected conditions. Determination of indices and criteria for transition from normal to pre-emergency conditions and, vice versa, from post-emergency to normal conditions.
- Effective organization of the system of EPS operating condition monitoring and control is possible by an extensive involvement of new tools for the analysis and calculations of operating conditions and control actions, primarily technologies of artificial intelligence.

4. ARTIFICIAL INTELLIGENCE APPLICATION

Let us consider some specific possibilities of artificial intelligence application to development of principles and tools of automatic emergency control in EPS.

A. Adaptation of a fuzzy logic-based AVR of generators

A fuzzy regulator is automatically adapted over the whole region of values of operating conditions, variants of networks (normal, maintenance, post-emergency) and studied disturbances at the set time interval (day, week, month, etc.). The problem is solved at two stages [14].

At the first stage the fuzzy regulator parameters are tuned off-line for the finite set of studied situations – combinations of network variants, operating conditions and studied disturbances. The fuzzy regulator parameters are optimized for each studied situation by using the genetic algorithm. The initial set of studied situations and the obtained optimal parameters of the fuzzy regulator are a learning sample for the artificial neural network learning.

At the second stage the learned artificial neural network chooses on-line tuning parameters of the fuzzy regulator that are optimal for the current situation.

Figure 2 illustrates efficiency of damping generator rotor oscillations for the test EPS by the suggested adaptive fuzzy regulator at system disturbance.

It is important to note, that in this and following subsections rather extreme emergency scenarios were used to better demonstrate the efficiency of the suggested techniques.

B. Coordinated emergency control of load and FACTS devices

Special automatic load shedding systems (SALS) are an effective means of emergency control to interrupt cascading emergency processes and prevent EPS instability. However, nowadays the earlier applied forced principles of SALS arrangement do not suit consumers more and more, since they contradict the ideology of market relations. Hence, the question arises, whether it is possible to transfer, though partially, the SALS functions to other feasible devices, for example FACTS [12].

The method has been devised for coordination of emergency control of loads and FACTS devices, when it is needed to unload transmission lines to prevent emergency development. Application of FACTS devices on the unloaded lines enhances efficiency of using these lines and hence, decreases the volume of load tripped because of emergency situations. This fact makes it possible to minimize the total damage due to load shedding in emergency situations, preserving efficiency of emergency control of EPS as a whole.

Figure 3 illustrates efficiency of the suggested coordinated emergency control at emergency disconnection of one transmission line in the test EPS.

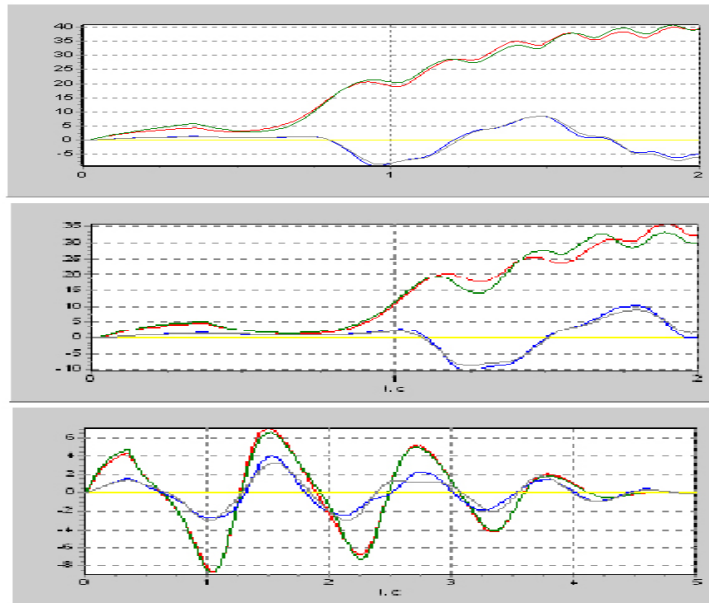


Figure 2. Variations of the angular velocity of generator rotors at emergency disconnection of line: *a*-for traditional AVR; *b*-for fuzzy AVR with expert tuning; *c*-for fuzzy AVR with optimal tuning.

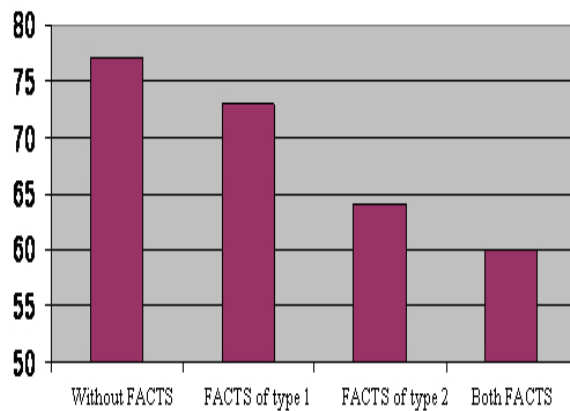


Figure 3. Efficiency of coordinated emergency control of load and FACTS devices.

C. Dynamic control of FACTS using PMU

As a rule the automatic control systems of EPS, in particular automatic regulators installed at FACTS devices, use local information on the system state. This measure is not always effective for prevention of emergency situations especially at intersystem oscillations to occur in bulk extended EPSs [2].

The studies have been performed on the possible use of signals received from WAMS on the basis of PMU measurements as initial information for FACTS regulators. The static thyristor-controlled series compensator is considered as a FACTS device.

Stage 1 of studies deals with the application of local signals to control static thyristor-controlled series compensators. Their regulators were optimized for maximum damping of rotor oscillations during disturbances. The results show that joint application of the static

thyristor-controlled series compensators and PSSs prevents from EPS instability in such considered situations, when the system stability is lost without these compensators with optimized tuning.

However, during heavy disturbances the static compensator control based on local operating parameters may happen not to cope with its function and the EPS stability can be lost. Figure 4,*a* presents a similar situation for the test EPS. The use of information from WAMS allows the successful solution to the problem of system stability conservation (Figure 4,*b*). Adaptation of tuning of static compensator control system that is similar to the described one for the fuzzy voltage regulator enhances control efficiency all the more.

D. Development of out-of-step protection using PMU

Out-of-step operation in EPS is the one the most severe emergencies. It is related to the loss of stability in EPS which may cause damage to equipment, interruption of power supply to consumers and unwanted development of emergency processes with severe consequences for EPS and consumers. Special automatic out-of-step protection systems (OSPS) have been used in EPS for reliable, timely and selective detection and elimination of out-of-step conditions [10].

Further development of selective OSPS has resulted in creation 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 stage of control actions: 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 EPS.

The use of synchronized voltage phase measurements obtained from PMU offers principally new capabilities of implementing the selective the selective out-of-step prevention and protection system (SOSPSS) [11].

Loss of synchronism in EPS operation in some cutest can be caused by two main reasons:

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

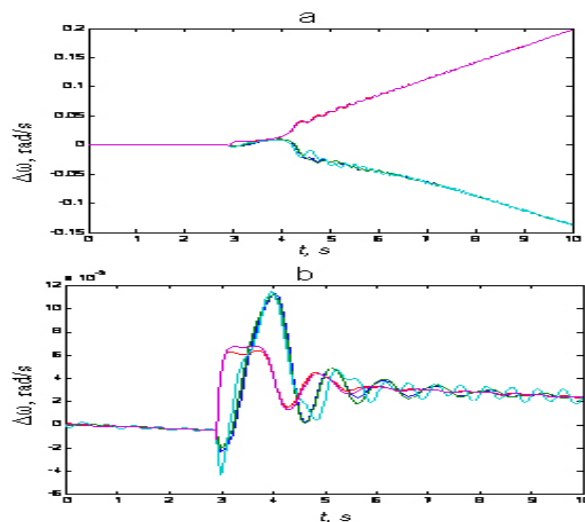


Figure 4. Deviation of the angular velocity of generator rotors during disturbances.

Figure 5 shows the interrelations between EPS states and control actions in SOSPPS. The secure state of EPS is determined by the condition $|\delta_{ij}|$. PMU measurements are used to trace the current value of $\delta_{ij}(t) = \delta_i(t)$, where and are voltage phases on the ends of the most critical tie of the considered cutest. The dangerous state of EPS occurs at $|\delta_{ij}|$, emergency state occurs at $|\delta_{ij}|$, where $|\delta_{ij}|$. Difference between and considers the margin of transfer capability of cutest.

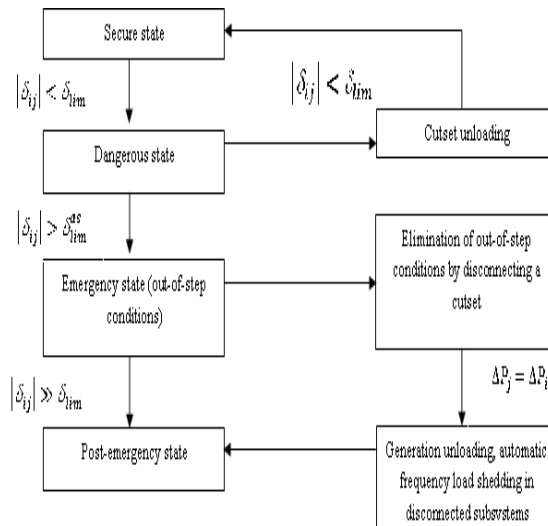


Figure 5. A scheme of interrelation between power system states and control actions in SOSPPS.

E. Multi-agent coordination of emergency control devices

Analysis of the recent blackouts shows, that the most severe contingencies which lead to voltage collapse occur in highly loaded EPS without effective coordination of emergency control devices operation.

The proposed in [8] multi-agent control system provides reactive power control by coordinating the operation of different discrete and continuous control devices in a post-disturbance period in order to prevent voltage collapse of the whole EPS. The model of the test system was simulated by Matlab/PSAT software. Multi-agent control system (MACS) has been implemented in JAVA language using JADE package. The efficiency of proposed technique has been proved by numerical simulations. The proposed MACS allows the use of complex Matlab/PSAT routines as well as the modeling of complex behavior of the agents.

To test the proposed MACS the following sequence of disturbances is examined for test EPS:

- 2 seconds after the simulation start – loss of one generator;
- 40 seconds after the simulation start – loss of one line.

Conventional control system includes Automatic Voltage Regulators (AVR) and Over Excitation Limiters (OXL) for generators, Under Voltage Load Shedding (UVLS) for loads, Under Load Tap Changes (ULTC) of transformers, which operate without coordination. Proposed MACS coordinates the operation of these devices. Figures 6 and 7 show the voltage transients in test EPS without and with MACS, respectively.

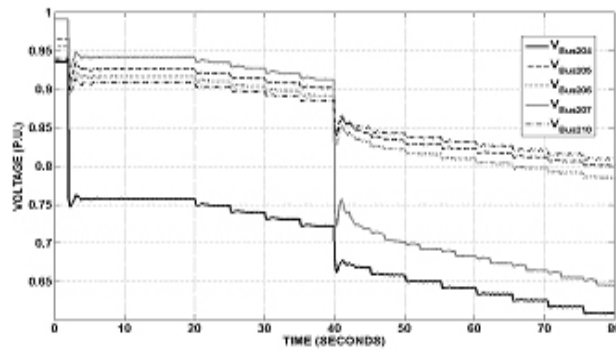


Figure 6. Changes in HV substation voltage level without coordination.

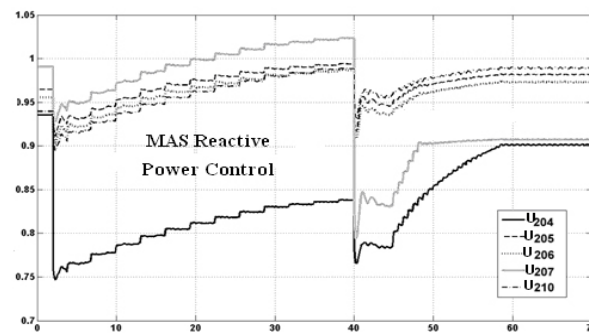


Figure 7. Changes in HV substation voltage level with coordination.

5. CONCLUSIONS

Integration of EPSs, liberalization and modernization of electric power industry increase changeability and unpredictability of EPS operation and generate the need to improve and develop principles and systems of operation and emergency control. Current emergency control system in Russia is rather developed and already now has the elements of Smart Grid ideology. New conditions call for development of a comprehensive system for monitoring, forecasting and control of EPS. Artificial intelligence application is an advanced way to carry out smart emergency control in EPS.

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