Multifunctional electronic devices protected and automatic of modern electricity system

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Abstract. The report reflects the long-term solutions for the modernization of main means of emergency control and protection of integrated power systems in the implementation of adaptive control algorithms.

1. The relevance of research area and the degree of its development.

The existing financial and economic, and as well operational and technical interrelations between the electric power engineering entities are characterized by a reduction in costs for depreciation, ageing of the resource and poorly justified prolongation of the operating lifetime of the main equipment of power plants and substations. In these complicated conditions, ensuring the reliability and stability of the power supply in the integrated power system (IPS) can be partially solved by introducing into the operation practice a new electrical power equipment for regulation and control of the interchange power (FACTS), as well as the by creating of ring circuits of electric networks [1-8]. However, this approach significantly complicates the problem of fast and high-quality supervisory control of transient operation modes of power systems [9-11]. The appearance of new measuring and information systems, monitoring means (WAMS) of transient modes and systems of centralized (system) control allowed to some extent to improve the efficiency of dispatch and emergency control of the integrated power systems modes [12,13]. An important role in this has the information and technical perfection of communication devices.

Many researches and scientific publications have been devoted to the issues of stability and reliability growth of electrical power equipment operation of power systems. By means of these studies, advanced control means of the excitation of synchronous machines have been created [2, 4, 11], [14-17], the technical possibilities and conditions for the transmission of electric power by alternating current in extended power pools have been scientifically justified. Despite significant advances in research on sustainability and the principles of emergency control of the integrated power systems,
there is much concern about the issue of ensuring the speed performance, selectivity, and operating reliability of the protection and automation means. It must be emphasized that practically all (with rare exception) scientific research and publications of authors are based on the use of an idealized mathematical description and linear models of power equipment [1, 2, 4, 14, 16-19], and of a robust description of the filter synthesis problem [15]. And by extension, such an approach is characterized not only by the presence of a method error, but also by errors in practical and quantitative assessments of the limit conditions and, as a consequence, in the choice of parameters of technical protection means and other means of emergency control that do not satisfy basic regulatory requirements.

The elimination of this substantial defect is possible only with the development of the theory of nonlinear filtration [3, 20-23], the application of numerical methods and rigorous mathematical models in the study of quasi-stationary asynchronous and oscillatory synchronous modes of the integrated power systems. Such approach becomes possible now due to growth of computing capacities and functional capabilities of industrial microcontrollers, and as well due to the increase in the automation level of modern power facilities. Obviously, the validity of the new obtained research results should be confirmed based on carrying out and improving physical, full-scale experiments and experimental-industrial trials.

All these current problems, the issues of qualitative and reliable control of modern integrated power systems, predetermined the subject of complex research, reflected in this report on the author's research.

2. New generalized stability criteria and the fundamentals of adaptive highly sensitive means of emergency instability prevention automation (APNU) of intersystem (interstate) power transmission lines of extended power pools

The modern development of energy systems is characterized by the inclusion of maneuverable and powerful blocks for parallel operation with the previously introduced aggregates of power plants and large power pools [1-4, 7, 8]. Within the integrated power systems, individual plants and even parts of the power systems can be located at a considerable "electrical" removal from each other. In systems of a simple structure, asynchronous regimes as a rule are caused by loss of the synchronism of one of the generators. Though, due to the fact of the creation of integrated power systems with an advanced electrical network circuit, the conditions for resynchronization after the appearance of an asynchronous regime turned out to be rather complicated and negative. Moreover, with asynchronous modes in complex systems, phenomena and processes that are unusual to simple structure systems have been revealed. Their main feature is the possibility of an asynchronous mode occurrence of many generated sources, due to additional loss of stability. To reveal the area boundary of oscillatory stability, the author proposes an algorithm for controlling the generalized stability criteria (Jacobian) [1, 3, 8], whose coefficients are calculated by differentiating the expressions for the active and reactive components of the nodal and exchange power.

Research of the stability is made to structural diagrams, and chain ring of power (figures 1, 2) when the variation of stiffness and the installed capacity equivalent power systems [1, 3, 19]. The figures show the maximum conditions of convergence modes, the parameters of the elements of the circuit and ring structures are specified for each voltage class in the reduced units with respect to the base power $S_{bas} = 10000$ MVA. The value and direction of the exchange power were set by reducing the volume of generation in the receiving part of the power system with a balanced load of intermediate power systems.

Synthesis of the measuring body of emergency automation to prevent violations of the stability of intersystem transmission lines is feasible on the example of the design scheme figure 1. In this case we assume that the interconnection 500 kV double circuit is made by overhead lines. Taking into account stated earlier, means of emergency automation in this scheme are placed on substations of 500 kV (buses of knots 501, 502 and 503, figure 1) of intersystem transit 503-501.
Figure 1. The simplified scheme is equivalent scheme of the power pools chain structure.

Thus, the assessment of stability of intersystem transit of 500 kV of the three-machine settlement scheme of power connection (figure 1) is made as a result of calculation of the Jacobian (determinant) of the matrix of coefficients formed according to (1).
where $P_{501}, Q_{501}$ - respectively, the active and reactive components of the analytical signal power node 501, measured in [W] and [var]; $U_{m501}, \gamma_{u501}$ - respectively, the instantaneous amplitude and the instantaneous angle of the voltage controlled on the buses of the node 501, measured in [V] and [degree]; $P_{501/502}, Q_{501/502}$ - active and reactive components of the analytical power exchange signal in section 501-502, controlled by node 501 and measured in [W] and [var].

Explanations for the values of the system of equations (1) are given for one of the combinations (501 and 502) of the indices of the nodes of the calculation scheme in figure 1. The physical meaning of the other node and the exchange capacity is completely analogous.

\[
J = \begin{bmatrix}
\frac{\partial P_{501}}{\partial U_{m501}} & \frac{\partial P_{501}}{\partial \gamma_{u501}} & \frac{\partial P_{501/502}}{\partial U_{m502}} & \frac{\partial P_{501/502}}{\partial \gamma_{u502}} & 0 & 0 \\
\frac{\partial Q_{501}}{\partial U_{m501}} & \frac{\partial Q_{501}}{\partial \gamma_{u501}} & \frac{\partial Q_{501/502}}{\partial U_{m502}} & \frac{\partial Q_{501/502}}{\partial \gamma_{u502}} & 0 & 0 \\
\frac{\partial P_{502/501}}{\partial U_{m501}} & \frac{\partial P_{502/501}}{\partial \gamma_{u501}} & \frac{\partial P_{502}}{\partial U_{m502}} & \frac{\partial P_{502}}{\partial \gamma_{u502}} & \frac{\partial P_{502/503}}{\partial U_{m503}} & \frac{\partial P_{502/503}}{\partial \gamma_{u503}} \\
\frac{\partial Q_{502/501}}{\partial U_{m501}} & \frac{\partial Q_{502/501}}{\partial \gamma_{u501}} & \frac{\partial Q_{502}}{\partial U_{m502}} & \frac{\partial Q_{502}}{\partial \gamma_{u502}} & \frac{\partial Q_{502/503}}{\partial U_{m503}} & \frac{\partial Q_{502/503}}{\partial \gamma_{u503}} \\
0 & 0 & \frac{\partial P_{503}}{\partial U_{m502}} & \frac{\partial P_{503}}{\partial \gamma_{u502}} & \frac{\partial P_{503}}{\partial U_{m503}} & \frac{\partial P_{503}}{\partial \gamma_{u503}} \\
0 & 0 & \frac{\partial Q_{503}}{\partial U_{m502}} & \frac{\partial Q_{503}}{\partial \gamma_{u502}} & \frac{\partial Q_{503}}{\partial U_{m503}} & \frac{\partial Q_{503}}{\partial \gamma_{u503}}
\end{bmatrix}
\]

(1)

Figure 3. Changing the criteria $J$ (dashed line) and active capacities $P_{501/502}$ (solid line), $P_{502/503}$ (dashed line) in intersystem sections 501-502, 502-503

Figures 3 and 4 (using the example of a chain circuit with controlled system interconnections 501-502 and 502-503) show the results of studies of dynamic regimes of IPS and the revealed regular patterns of the change in the generalized criteria - the dynamic determinant $J(t)$. As a result of research it was established that the boundary of the oscillatory stability area of extended power pools corresponds to the minimum of the dynamic determinant $J(t)$, which is always in the range of the angles of conditional stability (Figure 4, dashed line).
The maximum of the generalized criterion characteristic $J(t)$ (Figure 3, dashed line) is located in the range of angles $\gamma = 270-280^\circ$ and corresponds to the limiting negative active power in the controlled intersystem section 501-502. The dependences of the criteria $J$ and the angular characteristics of the controlled section power for the volume variation ($k_p = \text{var}$) of its emergency shutdown are shown in Figures 4, 5.

Taking into account the generalized criteria for the violation of stability, the equality to zero of the determinant ($dJ(t) = 0$), the thesis is proposed and, as a result of analytical and numerical studies, the law of emergency control of the exchange capacity ($dP$) of power systems with the control of the change in the generalized stability criterion $J(t)$:
\[ dP = \frac{J}{1 + pT_S} \left( k_p + \frac{k_{\text{int}} \cdot p}{pT_{\text{int}} + 1 + pT_{\text{diff}}} \right) \]  
(2)

where \( T_S \) - time constant, taking into account the complete delay of the introduction of emergency response, sec; \( k_p, k_{\text{int}} \) - respectively, the coefficients of proportional and integral channels of emergency power control, p.u.; \( T_{\text{int}} \) - is the integration time constant taken as 0.2 c; \( T_{\text{diff}} \) - is the time constant of the differential link equal to 5 msec.

As a result of the equation roots research (2), it is shown that in the absence of changing the sign of the criterion characteristic (\( J \)), the emergency control system will be stable for positive values of the coefficients \( k_p, k_{\text{int}} \) of the amplification of the proportional and integral component of the control signal:

\[
C_{1,2} = \text{sign}(J) \cdot \frac{-\left(\frac{1}{T_{\text{diff}}} + \frac{1}{T_S}\right) \pm \sqrt{\left(\frac{1}{T_{\text{diff}}} + \frac{1}{T_S}\right)^2 - 4 \cdot \left(1 + \frac{k_{\text{int}}}{k_p \cdot T_{\text{int}}} \right) \cdot \frac{1}{T_{\text{diff}} \cdot T_S}}}{2}
\]  
(3)

Dropping of delay (\( T_S = 0 \)) in the structure of the emergency control does not introduce qualitative changes into the stability assessment of the proposed law of emergency control of extended power pools.

The development and implementation of the above-described APNU devices of extended power pools will allow to manage the congestion of intersystem power transmission lines (with reserves of up to 2-5%) effectively and safely, while ensuring their stability.

### 3. Fundamentals of adaptive self-adjusting means of protection and emergency control of electrical power equipment of electrical systems.

According to modern estimates, the degree of reactive power compensation in backbone networks is on average no more than 50% for 500-1500 kV lines [1, 3, 25-29]. The acuteness of this problem has increased even more recently due to a certain decrease in power consumption and, as a result, a decrease in active power flows with a significant undercompensation of the reactive power of extended electrical networks. Due to this situation, most of the large integrated power systems (IPS) have a very difficult situation with reliability and sensitivity of the main (differential) protections of electrical power equipment of the backbone network of 500-1500 kV - the minimum operating current is about 0.7-1.0 p.u. In addition, the problem of reliability of modern microprocessor differential protection systems is exacerbated by the large nomenclature and variety of used devices (half-sets), as well as the insufficient experience (lifetime) in operation of digital protections and the absence of a scientifically grounded approach to the selection (calculation) of their response parameters.

In connection with the abovementioned negative factors, cases of non-selective protection operation, accompanied by overloading of the lower voltage class lines entering the controlled sections, have become more frequent, which, eventually can cause a breakdown in the stability of the parallel operation of power pools.

![Figure 6. Generalized diagram of correction signals formation.](image-url)
To ensure the selectivity, increase the speed performance and sensitivity of the improved current lengthway differential protection of power equipment inter-system (interstate) power transmission lines, the adaptive correction of the response characteristic must be performed (Figure 6). Approbation and evaluation of the efficiency of correction of the response characteristic of the current lengthway differential protection is performed using a database of digital oscillograms of full-scale experiments on the study of non-stationary modes of electrical power equipment of extended power pools.

Figure 7 shows the conditions of normative sensitivity and selectivity, which corresponds to the space of the protection operation parameters for which the white surface (the vector function of the protection operation parameters) prevails over the shaded for the damaged phases (phase A, figure 7, a). The selective operation of the measuring elements of undamaged phases (phase C, figure 7, b) is characterized by opposite conditions for the arrangement of surfaces.

\[ W_{I_{\text{prot select idle}}} = I_{\text{prot min}} - \max \begin{bmatrix} I_{\text{prot idle max}}^A(K_C) \\ I_{\text{prot idle max}}^B(K_C) \end{bmatrix} \geq 0, \]  
\[ W_{I_{\text{prot select fault}}} = \min \begin{bmatrix} I_{\text{prot fault min}}^A(K_T,K_C) - I_{\text{prot idle max}}^A(K_C) \\ I_{\text{prot fault min}}^B(K_T,K_C) - I_{\text{prot idle max}}^B(K_C) \\ I_{\text{prot fault min}}^C(K_T,K_C) - I_{\text{prot idle max}}^C(K_C) \end{bmatrix} \geq 0, \]

where \( I_{\text{prot idle max}}^A, I_{\text{prot fault min}}^A \) - the maximum and minimum values of the operating current of phase A protection in the idle and short circuit modes, p.u., respectively.

The requirements for protection according to the conditions of a given sensitivity (\( K_{\text{sense set}} \)) relative to the target set point (\( I_{\text{prot min}} \)) are described by a vector function:

\[ W_{I_{\text{prot sense}}} = \frac{I_{\text{prot fault min}}^A(K_T,K_C)}{I_{\text{prot min}}} - K_{\text{sense set}} \leq 0, \]
Figure 8. The selectivity area (dot-dash line), the sensitivity area (dashed line) and the characteristic (solid line) of the maximum selectivity and sensitivity of protection in the space of the braking parameters (KT) and correction (KC).

Absolute selectivity of the protection, characterized by zero value of the minimum operating current (Iprot min = 0), is achieved with 100-120% correction of operating signals (Figure 8, small area KT = 0-0.2 p.u.). From the analysis of figure 8 it follows that the normative sensitivity is achieved with the braking coefficient KT ≤ 0.2 p.u. and the correction coefficient KC, equal to 0.70-1.25 p.u. The increase of the braking coefficient more than KT = 0.35-0.40 p.u. leads to a narrowing of the selectivity area (Figure 8).

4. Conclusion
The research and development carried are aimed at improving the basic technical high-response means of emergency control of power systems that ensure the continuity of their operation, the quality of electrical energy, economy, technical, information security and automation of its production.

1. The development and implementation of the above-described APNU devices of extended power pools will effectively and safely manage the congestion (with reserves of up to 2-5%) of intersystem power transmission lines, while ensuring their stability. The developed means of APNU should be classified as adaptive, since the measuring element is synthesized on the basis of the control of the generalized stability criteria, which reflects the dynamic properties of the power pools of a free structure.

2. The basis of adaptive means of differential protection of power equipment of power systems is developed. They are based on the use of adaptive correction of operating and brake protection signals. Self-tuning of protection means is achieved as a result of applying gradient parametric numerical methods for identifying the parameters of power equipment that affect the value of the minimum operating protection current. Absolute selectivity of protection, characterized by zero value of the minimum operating current (IC3 min = 0), is achieved only by correction of operating signals in the volume of 100-120%.

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