Adaptive correction of current longitudinal differential protection of power equipment

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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. The substantiation of new structures and algorithms for the formation of corrective signals using non-stationary filters of the displacement current of overhead power lines is performed. Calculated, using the bias currents of the phases are used for dynamic correction of the working and brake signals of the longitudinal differential protection. 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. A mathematical description of the optimization problem of determining the response parameters of sensitive longitudinal current differential protection with adaptive correction of operating and braking signals is performed.

Key Words: power equipment, power pools, adaptive means, current differential protection, measuring elements, sensitivity enhancement, dynamic correction, Hilbert transform.

1. Introduction.

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.

2. Methods and relevance of research area.
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 \cite{2, 4, 11, 14, 15}, 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 \cite{1, 2, 4, 14, 16, 17}, and of a robust description of the filter synthesis problem \cite{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 \cite{3, 18-21}, 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.

3. Results of researches of adaptive protection and emergency control of electrical power equipment of extended power pools.

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 \cite{1, 3, 22}. 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.

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 1). 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.
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 1). 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.

In the block diagram of Figure 2, the phase voltage is numerically differentiated. This method is most effective for increasing the sensitivity and selectivity of the line protection in the modes of its inclusion at idle.

An alternative is the use of nonlinear capacitive current filters of the line, implemented according to the scheme of Figure 3.

In this scheme, to obtain the imaginary part of the $u_{A,\text{im}}(t)$ analytical phase signal (the figure shows the example of phase A) voltage filter is used Hilbert [23, 24], which is not physically feasible. However, its application in the practice of digital signal processing is widely known [25]. At the output of

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**Figure 1.** Generalized diagram of correction signals formation

**Figure 2.** The filter circuit of the phase charging current line with the control of the derivative of the phase voltage

**Figure 3.** The filter circuit of the bias current of transmission line orthogonal control additions by Hilbert for the phase (shown only for phase A) voltage
the phase-reversal link (block 2, figure 3), an orthogonal complement $u_{Aim}(t)$ of the phase A voltage is formed with a shift of the instantaneous spectral density $S(\omega)$ by ninety degrees. Instantaneous frequency measurement (block 1, figure 3) is also performed using the Hilbert transform [23-25].

![Figure 4. Change of the phase C protection tripping current in the power line idle mode from the opposite side of the substation in the absence of (1, solid line) and the presence (2, dash-dotted line and 3, dashed line) of correction signals.](image)

The calculated characteristics of the change in the protection response current (dashed and dashed lines characteristics 2, 3), as well as the differential signal (solid line, characteristic 1) are shown in figures 4, 5. Due to the limitations on the volume of illustrative material, these figures reflect the change in only one, the most characteristic phase current of the protection operation. Since the C phase current has the largest of the three phases of the value for the mode of switching on the idle transmission line, its calculated dependences are shown in figures 2, 3. Accordingly, to assess the selectivity and sensitivity in the mode of interphase (AB) short circuit, the most characteristic are the calculated oscillograms of the differential current of phase B (figure 5) smaller in comparison with phase A values current.

The change in the current of protection operation during the control of the derived voltage corresponds to the characteristics 3 (dashed line, figures 4, 5). The practical implementation of this scheme (figure 2) introduces significant difficulties associated with the need to increase the sampling rate over time (ADC survey), as well as to ensure the selectivity of the protection operation in case of internal short circuits. As follows from the characteristics 3 presented in figure 5, the application of the considered method of correction can lead to a deep (more than one and a half), non-selective overstrain in case of short circuits.

The only measures that allow to justify the admissibility of this method of forming correction signals are the introduction of blocking, after the successful inclusion of the line at idle or the introduction of a limit of its operating time in the test cycle. Taking into account the uncertainty of the criteria for the successful inclusion of the line, as well as the difficulties of implementing the logic of the blocking body, this issue is not considered in the publication and can be the subject of future, promising research.
Figure 5. Change of the phase B protection tripping current in the internal two-phase (AB) short circuit mode near opposite side substation buses in the one-way power supply circuit in the absence of (1, solid line) and the presence of (2, dash-dotted line and 3, dashed line) corrections

Analysis of the change in the current of protection operation in the correction of its dynamic properties with the use of bias current filters (figures 3) showed that the proposed method can be effective in a variety of modes of operation of intersystem power lines with proper and reasonable selection of the parameters of operation of differential protection. The choice of the parameters of operation of the protections meeting the requirements of standard sensitivity is made according to the below methodical instructions.

Figure 6 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 6,a). The selective operation of the measuring elements of undamaged phases (phase C, figure 6,b) is characterized by opposite conditions for the arrangement of surfaces.

![Diagram](image_url)

a) protection tripping current of phase A  
b) protection tripping current of phase C

Figure 6. Protection tripping currents of phases A (a) and C (b) in the space of parameters $K_T$ and $K_C$ when the line is switched to idle (shaded surface) and in short-circuit mode of phases A and B (white surface)

Taking into account the complexity of the perception of new principles for calculating the triggering parameters of current differential protections, the author, in the concluding part, presents a mathematical description of the method for selecting the operating values ($I_{prot\,min}$, $K_T$, $K_C$) of advanced current lengthway differential protections with dynamic correction of their operating and brake signals.
Then, the vector functions of the selectivity of protection in idle mode \( W_{\text{prot select idle}} \) and short circuit mode \( W_{\text{prot select fault}} \) (figure 7) are described by expressions (with explanations only for phase A):

\[
W_{\text{prot select idle}} = I_{\text{prot max}} - \max \left( I_{\text{prot max}}^A \left( K_c \right), I_{\text{prot max}}^B \left( K_c \right), I_{\text{prot max}}^C \left( K_c \right) \right) \geq 0, \tag{1}
\]

\[
W_{\text{prot select fault}} = \min \left[ I_{\text{prot max}}^A \left( K_T^* K_c \right) - I_{\text{prot max}}^A \left( K_c \right), I_{\text{prot max}}^B \left( K_T^* K_c \right) - I_{\text{prot max}}^B \left( K_c \right), I_{\text{prot max}}^C \left( K_T^* K_c \right) - I_{\text{prot max}}^C \left( K_c \right) \right] \geq 0, \tag{2}
\]

where \( I_{\text{prot max}}^A, I_{\text{prot min}}^A \) - 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:

\[
W_{\text{prot sense fault}} = I_{\text{prot max}}^{\text{set}} \left( K_T^* K_c \right) - I_{\text{prot max}}^{\text{set}} \leq 0, \tag{3}
\]

\[\text{Figure 7.}\] 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 (\( K_T \)) and correction (\( K_c \)).

Absolute selectivity of the protection, characterized by zero value of the minimum operating current (\( I_{\text{prot min}} = 0 \)), is achieved with 100-120% correction of operating signals (figure 7, small area \( K_T = 0-0.2 \) p.u.). From the analysis of figure 7 it follows that the normative sensitivity is achieved with the braking coefficient \( K_T \leq 0.2 \) p.u. and the correction coefficient \( K_c \), equal to 0.70-1.25 p.u. The increase
of the braking coefficient more than \( K_T = 0.35-0.40 \) p.u. leads to a narrowing of the selectivity area (figure 7).

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 author has developed and justified new structures and algorithms for the formation of correction signals using non-stationary filters of the bias current of overhead power lines. Phase bias currents calculated with their help are used for dynamic correction of operating and braking signals of longitudinal differential protection.

As a result of the comparative analysis of digital filters of bias current it is established that the best indicators in terms of ease of implementation, sensitivity and speed have filters, which are based on the Hilbert transform. All further evaluation of the effectiveness of the correction of the dynamic properties of protection obtained in its application.

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 \( I_{\text{prot,min}} = 0 \), is achieved only by correction of operating signals in the volume of 100-120%.

3. A mathematical description of the optimization problem of determining the response parameters \( I_{\text{prot}, \min}, K_T \) and \( K_C \) of sensitive longitudinal current differential protection with adaptive correction of operating and braking signals is performed.

As a result of testing of this technique, it is shown that the absolute selectivity of the protection, characterized by a zero value of the minimum operating current \( I_{\text{prot}, \min} = 0 \), is achieved at the level of correction signals of 100-120% or more \( (K_C \geq 1.2 \text{ p.u.}) \).

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