Electrical Power and Energy Systems 135 (2022) 107572

Contents lists available at ScienceDirect

International Journal of Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

Novel approach for relays tuning using detailed mathematical model of electric power system

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ARTICLE INFO

Keywords:
Relay protection
Tuning
Simulation
Detailed model
Hybrid approach

ABSTRACT

The correct operation of relay protection (RP) devices largely determines the security of electric power systems (EPS). The key point that in turn determines the behavior of protection in various emergency modes is a determination of their settings. The existing methodologies and tools often do not allow to provide RP settings adequate to the practical conditions of their functioning. This statement is confirmed by the statistics of faults in EPSs. The main reason for this issue is the inability to reliably reproduce transients in EPS via the software programs used in practice to calculate the RP settings. The Hybrid Real-Time Power System Simulator (HRTSim), developed by the authors, allows to reliably reproduce the entire range of normal and emergency modes and processes in EPS of any scale, topology and configuration by using detailed three-phase models of all power system components. Taking into account this possibility and features of the HRTSim, the task of detailed modeling of RP devices, including instrument current and voltage transformers, becomes relevant. The implemented special tools for RP modeling and the HRTSim in general allow to develop a new methodology for RP tuning. At the same time, the typical elements – relays – can be identified for each type of RP that determine their operation algorithm. This paper presents an analysis of the main relays of the most modern microprocessor-based RP devices and proposed principles of their tuning. The developed approach allows to adapt the RP settings to the practical conditions of their functioning in EPSs and to minimize the probability of RP maloperation.

1. Introduction

Security and stability of electric power systems (EPS) is largely determined by the correct operation of relay protection (RP) devices. Meanwhile, despite significant progress in the development of protection systems, it is not possible to ensure their operation without errors, which is confirmed by statistical data. Approximately 25% of severe system faults occur due to maloperation of RP and automation devices. At the same time, in 50…70% of cases, maloperation of protection systems leads to the development of simplest faults into severe system faults (blackouts), characterized by significant economic and technological damage [1–4].

After analyzing the specific reasons of RP maloperation, they can be divided into three main categories in order of importance: (i) hardware failures, (ii) errors during design and settings determination, and (iii) personnel errors. The least progress has been made in solving issues related to the second category. The main reasons for this are the following factors:

1. The use of incomplete and in most cases unreliable information about modes and processes in EPSs during RP settings determination.
2. The excessive overestimation or underestimation of the RP thresholds due to the use of approximate generalized coefficients in the corresponding methodologies and guides for RP tuning to take into account the errors introduced by a specific type of RP and primary transducers.

Mathematical modeling of EPS is the only way to obtain data on the entire range of processes and modes of power equipment, RP and power system as a whole. At the same time, the aggregated mathematical model of even a regional EPS forms a stiff system of high-order differential equations. This system is numerically ill-conditioned for the application of various numerical methods for ordinary differential equations [5–8]. Such situation occurs only in the case of using the most detailed three-phase mathematical models of both main and auxiliary equipment with their control systems, even without taking into account the RP devices. The identified challenge determines the need in

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https://doi.org/10.1016/j.ijepes.2021.107572
Received 6 May 2021; Received in revised form 15 August 2021; Accepted 31 August 2021
Available online 4 September 2021
0142-0615/

decomposition of a single continuous process in an EPS into steady states (normal, emergency and post-emergency) and stages of transients (mainly electromechanical). Steady states are usually calculated using static mathematical models (system of algebraic equations) and the method of symmetrical components. Electromechanical transients are calculated using systems of differential equations for generating sources, static models of network elements, as well as the method of symmetrical components. Such approach to power system modeling does not allow to adequately reproduce the dynamics of transients, within which the relay protection should operate. The protection tripping is determined by the following main factors: (i) type of fault, (ii) location of fault, (iii) presence of transient impedance, (iv) possibility of transition from one type of fault to another, (v) configuration of EPS and its parameters in relation to the location of fault and relay protection, which can change in time both depending on the EPS operating modes and directly during a fault due to closing of individual circuit breakers, etc.

In addition, the possibility of assessing the RP behavior in post-emergency modes, often accompanied by synchronous or asynchronous oscillations in EPSs, is completely excluded. In particular, in [4], a particular case is described when asynchronous swings in EPS after the localization of a short-circuit (SC) have led to maloperation of distance protection and the development of a local fault into a blackout that covered most of the state grid.

The lack of a tool for comprehensive and reliable modeling of a single continuous process in EPSs under all possible normal, emergency and post-emergency modes of their operation made the issue of leveling the second highlighted factor irrelevant. The latter is associated with the inevitable need for a more adequate simulation of the processes emerging in the RP itself, as well as in the instrument current (ICT) and voltage (IVT) transformers.

This circumstance for a long time prevented the solution of the indicated issue of improving the efficiency of RP devices tuning, adequate to the specific operating conditions in EPS. Within the National Research Tomsk Polytechnic University (Tomsk, Russia), a simulation tool has been developed based on a fundamentally alternative approach to power system modeling (in relation to numerical methods) – the Hybrid Real-Time Power System Simulator (HRTSim) [9]. The possibility of implementing the most detailed three-phase mathematical models of the power equipment in EPS of any scale, combined with the possibility of their real-time solving on an unlimited time interval with a guaranteed acceptable accuracy, make it possible to declare the excluding of the first highlighted factor related to the issues of RP settings determination.

The solution of the issue of adequate mathematical modeling of EPS made possible a more detailed mathematical modeling of RP devices, including ICT and IVT, as well as a development of means for implementing these models. A description of the detailed mathematical models of RP developed by the authors, as well as software and hardware systems for RP modeling, is presented in [10]. In contrast to the existing methods and means of RP modeling [11–14], the implemented means allow reproducing a single continuous spectrum of processes in the entire set of elements that determine the structure of RP: auxiliary converters, filters, relays, etc.

Using the new possibilities for modeling EPS and RP, indicated earlier and described partially later in this paper, authors have developed a novel approach to obtain settings for microprocessor-based relay protection devices in conditions as close as possible to real ones. This is achieved through the use of a detailed model of the protected power region or EPS, a reasonable permissible network reduction of neighboring EPSs that are connected with the protected EPS, as well as reproducing the overwhelming majority of the most typical emergency and non-emergency modes for each specific protected object of the selected EPS. In this paper, the authors have presented the main fragments of the obtained results on this topic. The rest of this paper is organized as follows. Section II presents an analysis of the existing approaches to RP tuning, as well as a description of the proposed approach to RP tuning using its mathematical models. Section III describes the principles of forming the settings of relays used in the most modern microprocessor-based RP devices, which determine their operation in general. Section IV shows the main fragments of the obtained results of the formation of the relay settings using the developed approach. In Section V, a summary and conclusion are presented.

2. Methodology for relay protection settings determination using 'power system – protection' mathematical model

2.1. Existing approaches to relay protection tuning

The issue of solving mathematical models of large-scale EPSs by numerical integration methods, which is discussed in detail by the authors in [9], leads to the fact that specialized digital tools for power system modeling based on them are not used for calculating the RP settings. The determination of the RP settings is currently carried out by means of calculating the steady-state values of currents and voltages in emergency modes, e.g., using the Computer-Aided Protection Engineering tools. The shortcoming of such programs is that, in general, the power of sources and loads in the original scheme are not equal to the corresponding power in the equivalent scheme, as well as the use of single-line diagrams and the method of symmetrical components for the calculation of asymmetrical SCs. In this case, synchronous machines are reproduced in the form of a constant electromotive force (EMF) behind the impedance. The EMF of the machine (sub-transient or transient) and the internal angle are considered constant during the entire calculation process and are assumed to be equal to the value in the normal mode. The constancy of the resulting magnetic flux and the corresponding EMF in the air gap at the first moment of SC is determined by the known principle of constancy of flux linkages, according to which the aperiodic component of the stator current and the magnetic flux created by it are neglected. The resulting error depends mainly on the value of the aperiodic component, which is taken into account in the form of a generalized coefficient K calculated by Eq. (1) [15,16]:

$$K = 1.02 + 0.98 \cdot e^{-3/\omega \cdot T_{dc}} \tag{1}$$

where ω is a rotating speed, T_{dc} is a time constant of a decay of aperiodic component of a SC current.

During calculation of this coefficient in complex schemes, an equivalent time constant T_{dc} is used, for determining of which several methods are used based on the equivalent resistance and reactance of the scheme [17]. However, its determination in a practical EPS is an extremely difficult task, the solution of which does not provide a significant increase in the reliability of the calculations of a peak SC current. Therefore, in practice, the equivalent time constant is not determined, but a generalized value is taken for it with a corresponding peak current factor, depending on the SC location [18].

The above-mentioned specificity of accounting the impact of transients in EPS excludes the need for reliable accounting of the errors of both ICTs and IVTs, as well as of the RP hardware part during RP tuning – in the currently used methods, these errors are also taken into account by generalized constant coefficients [19–22].

The indicated simplifications in power system modeling determine that, in accordance with existing approaches, the sensitivity assessment is carried out in case of SCs, which are considered to be the least severe, and, therefore, are accompanied by the emerging of the lowest SC currents in comparison with other emergency modes. The selectivity analysis is not performed, since this requires the use of detailed mathematical models of RP devices with their algorithms, but this is not provided in the tools used for RP tuning. The behavior of protection in specific modes, e.g., in the case of the magnetizing current inrush (MCI) for the protection of power transformers (autotransformers), is not also carried out, which does not allow to exclude maloperation in non-emergency modes of operation of the protected object and EPS as a whole.

The existing approach, due to the indicated assumptions, often leads to an erroneous selecting of protection thresholds and, in some cases, their maloperation, as evidenced by the statistics. One of the methods that involves a radical change in the approach to RP tuning is the setting-less method [23]. This method requires an excessively large number of measured parameters, as well as a validation by a variety of physical laws. This complicates the actual scheme of connecting the protection system to the object in a practical EPS. In addition, it is not clear how this model takes into account the errors of instrument transformers, especially their nonlinear change due to saturation, as well as the internal elements of the RP: auxiliary converters and filters. Moreover, it should be noted that there is no practical experience with setting-less protection in power systems, consequently, it is difficult to assess its reliability. The existing algorithms have proven their efficiency and high reliability. Moreover, the implementation of such scheme will require a radical change in the principles of RP configuration, since it is not applicable on the existing devices.

Therefore, the authors have proposed an approach to improve the efficiency of RP tuning, which does not require a radical change in the element base or functional algorithms. The developed methodology is presented below. However, before discussion of the methodology, it is necessary to consider the issue of detailing of EPS equipment mathematical models. The level of detail of any model determines the amount of required initial information, requirements for implementation tools, solution methods, solution time, etc. Therefore, depending on the tasks to be solved, as a rule, acceptable mathematical models and means of their implementation are determined. Further, this issue is considered in relation to the task of RP tuning.

2.2. Power system simulation

In this subsection, the features of mathematical modeling of the main EPS elements are discussed.

Synchronous and asynchronous electrical machines. The universal mathematical model of synchronous and asynchronous electrical machines includes a complete system of Park equations of increased accuracy, equations for the formation of a three-phase *abc* system and mutual transformation of variables from *dq* system ($dq \leftrightarrow abc$). The high accuracy is achieved by increasing the number of simulated damper circuits and taking into account the frequency dependence of their parameters. Taking into account three damper circuits along *d* axis and four damper circuits along *q* axis provides in almost all cases the necessary reliability of modeling of the real range of processes in an electrical machine.

In addition, the formed system of equations is supplemented by differential equations describing the processes in excitation systems and automatic voltage regulators, as well as by differential equations that reproduce the processes in prime movers (e.g., steam or hydraulic turbine) and corresponding governors. Moreover, the model of an electrical machine takes into account the nonlinearity of magnetization of the rotor armature, as well as the dependence of the resistance of the rotor circuits on the frequency.

The processes in the prime mover are rather slow, which in turn is due to the high inertia of the equipment of a mechanical part of a power unit, as well as the inertia of the generator rotor itself (inertia constant is usually in the range of 2…6 MWs/MVA). Powerful electrical motors are also quite inertial due to the massiveness of the rotor itself and the presence, as a rule, of a massive load on the shaft. As a result, this part of electrical machine does not significantly affect the dynamics of the electromagnetic transients and value of the total SC current, which takes the highest value at the very beginning of the fault. The foregoing makes it possible to actually simplify this equation and to consider the shaft rotation frequency constant at the initial stage of the fault occurrence. However, for some protections of the 'non-damaged' part of EPS, e.g., distance and phase-comparison protections, the post-fault process may be relevant: even in the case of timely localization of fault in EPS, prolonged synchronous or asynchronous oscillations may occur, leading to the distortion of parameters monitored by the RP and its maloperation. Consequently, the mechanical swing equations of the rotor, as well as the model of governor cannot be excluded or simplified in the aggregate model of electrical machine, otherwise the dynamics of the post-fault mode in EPS will be significantly distorted.

In addition, it is necessary to discuss the model of excitation system. The most modern are thyristor excitation systems, which use controlled thyristor rectifiers, provide a high rate (four or more) of excitation field and have a low time constant (about 10…20 ms). For automatic voltage regulation, digital and digital-analog voltage regulators are currently widely used. The response rate of the regulator and the value of the control signal determine the number of channels, their implementation and settings (mainly their time constants). Based on this, response time of voltage control system would be in the range of 20…100 ms. Taking this into account, the impact of the excitation system and voltage regulator will manifest themselves both at the stage of transient process and in the post-fault mode. Accordingly, the simplification of the excitation control system will lead to a decrease in the reliability of processes modeling that determine the RP operation.

Power transformers and autotransformers. The mathematical model of transformers combines the systems of equations for three phases of a multi-winding transformer, each of which includes the equation of the winding circuits magnetically coupled by the flux of a given phase as in Eq. (2).

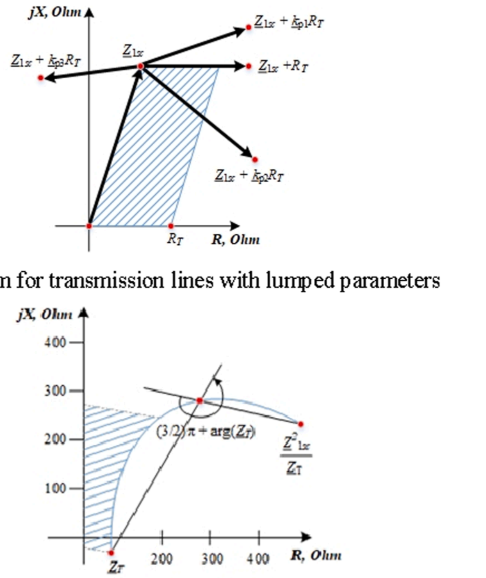
$$W_{\xi n}\frac{d\Phi_{\xi}}{dt} \pm L_{\xi n}\frac{di_{\xi n}}{dt} + r_{\xi n}i_{\xi n} - u_{\xi n} = 0 \qquad (2)$$

where $W_{\xi n}$ is a number of turns for winding of the phase ξ, Φ_{ξ} is a value of the main magnetic flux of the phase ξ, $L_{\xi n}$ is a leakage inductance of *n* winding of the phase ξ, $i_{\xi n}$ is a current value in *n* winding of the phase ξ, $R_{\xi n}$ is a resistance of *n* winding of the phase ξ, $u_{\xi n}$ is a voltage value of *n* winding of the phase ξ.

One of the key issues in the transformers simulation is the model of magnetization, especially hysteresis. In this paper, the authors used a model based on the classical Preisach theory [24], which most reliably reproduces the process of magnetization.

Power transmission lines. For transmission lines less than 300 km long, a mathematical model is acceptable in the form of a three-phase system of differential equations with lumped parameters. According to many years and numerous studies on long transmission lines (the length of transmission lines is more than 300 km), the wave nature of the transportation of electromagnetic energy is manifested. For such transmission lines, a wave model should be used that takes into account the distribution of these parameters. The theoretical basis of the mathematical model of long transmission lines, instead of a model based on a T-shaped equivalent circuit, is determined by the general solution of partial differential equations interpreted for three-phase transmission lines in the system $\xi = \alpha, \beta, 0$, which allows to reduce the scale of the aggregate model. Reproduction of corona effect in this type of model is carried out in the same way as in the model of three-phase transmission lines with lumped parameters. The use of a model of power transmission lines with lumped parameters instead of a model with distributed ones will lead to obtaining inaccurate information about the primary processes and the operation of power transmission lines (Fig. 1) and, as a consequence, incorrect tuning of the relay protection.

Shunt reactors, capacitor banks and static loads. Mathematical models of static loads, capacitor banks and shunt reactors can be represented in the form of *RLC* circuit. The expediency of latter is due to the identity of equivalent circuits and the corresponding mathematical models. The saturation is also taken into account for shunt reactor model.



(a) diagram for transmission lines with lumped parameters

(b) diagram for power transmission lines with distributed parameters

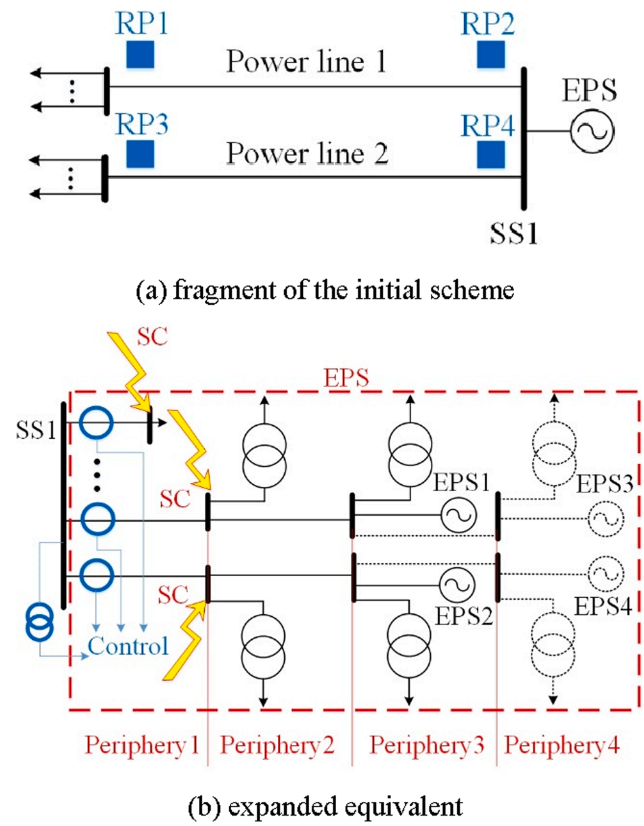
Fig. 1. Impedance dynamic in case of a SC through the transition resistance (impedance): R_T ($\underline{Z}_T$) is a transition resistance (impedance) at the SC location, k_{p1} , k_{p2} , k_{p3} are complex coefficients of current distribution, taking into account the difference in currents at the point of SC and at the location of protection installation.

2.3. Determination of protected power system scale

Requirements for the scale of the simulated power system scheme are not indicated in any standard or guide for RP tuning. Excessive equivalence can lead to obtaining simulation results that do not reliably reflect the real processes in a practical EPS. This conclusion is supported by research published in [25,26]. On the other hand, the expansion of the scheme, e.g., to the level of the state grid, even without taking into account interstate connections, seems to be infeasible in practice. In practical calculations, EPS model is usually limited to a regional power system within the regulated area of responsibility of the system operator, replacing all other connections with equivalent sources or loads. This approach is acceptable for calculating the RP settings located in the ‘depth’ of the considered EPS scheme. For protections installed near interconnections, using of equivalents will not allow to reliably take into account the impact of the adjacent power system. In this case, if it is not possible to expand the considered scheme by detailing the equivalent, it is possible to shift it in order to cover part of the main and adjacent power systems.

The key question is how much the scheme of the calculated EPS should be expanded. The principle described below is summarized in Fig. 2. It is obvious that the impact of an individual EPS or its separate area is especially manifested in case of faults near the connection point. Within the framework of the developed concept, it is proposed to simulate the most severe fault in such locations – a SC, having previously expanded the equivalent. The following types of SCs are considered: phase-to-ground (phase A), phase-to-phase (phases A and B), two phase-to-ground (phases A and B) and three phase-to-ground. To assess the impact on various types of relay protection, the following parameters should be monitored during calculation of SCs:

- phasors of phase currents (I_A, I_B, I_C),
- phasors of positive-sequence, negative-sequence and zero-sequence currents (I_1, I_2, $3I_0$),
- phasors of positive-sequence, negative-sequence and zero-sequence voltages (U_1, U_2, $3U_0$),
- phasor of impedance of *B*-*C* loop in case of phase-to-phase SC (Z_{BC}).



(a) fragment of the initial scheme

(b) expanded equivalent

Fig. 2. Principle of equivalent expansion.

Initially, it is proposed to expand the zone on two peripheries (up to the border ‘Periphery 2′ in Fig. 2), which allow to cover the maximum protection zone with a margin. Simulation of the SC at the ends of the adjacent boundary substation (SS1 in Fig. 2) of connections is performed, since this is actually the limiting border of the protection zone RP1–RP4. The necessary parameters are measured at the beginning of the expanded zone, because this is the protection installation location, with which the coordination of protections RP1–RP4 may potentially be required. Further, the equivalent expands to one more periphery (up to the border ‘Periphery 3′ in Fig. 2) – SCs are simulated, necessary parameters are measured.

If the measured parameters differ slightly (the boundary values are indicated below), then it is considered that the coverage to the border ‘Periphery 2′ was sufficient, if not, then the equivalent expands to the border ‘Periphery 4′ and the experiments are repeated again. The expansion of the equivalent continues until the deviations of the parameters at the measuring point satisfy the set of boundary conditions. It is important to note that the point of fault appearance and measurement do not change as the boundaries of the equivalent change.

The following conditions are accepted as criteria by which the absence of impact of the added periphery is determined:

- for each type of SC, the maximum difference over the entire simulation time between the modules of the phasors of phase currents, positive-sequence, negative-sequence and zero-sequence currents for the initial and next periphery of the equivalent does not exceed 5%,
- for each type of SC, the maximum difference over the entire simulation time between the modules of the phasors of positive-sequence, negative-sequence and zero-sequence voltages for the initial and next periphery of equivalent does not exceed 5%,
- the maximum difference over the entire simulation time between the modules of phasors of impedances of *B*-*C* loop for the initial and next periphery of the equivalent does not exceed 5%,

- for each type of SC, the maximum difference of the angles of the phasors of phase currents, positive-sequence, negative-sequence, zero-sequence currents and voltages for the initial and next periphery of the equivalent does not exceed 5 degrees.

2.4. General description of developed methodology

The proposed approach is generally described by the diagram in Fig. 3. The RP settings are determined in the process of modes modeling in the aggregated model 'EPS – RP'. For each protection of each EPS object, a list of modes should be formed, which consists of two parts: (1) modes for settings determination, (2) test modes. The first group includes all modes in which protection should not trip. The second group includes modes of internal faults, which protection must reliably detect and isolate – they are used to assess both the sensitivity of relay protection and its selectivity. The number and nature of studied modes in the general case depend on the covered zone, the need for coordination with other relay protection, the operating features of protected equipment and other factors that determine the dynamics of changes in the signals monitored by the protection. The main factors that are common to all protections are presented below. If some modes can be used for several protections at the same time, then they are not duplicated. The modes of the second group are reproduced only after settings obtained for all protections in EPS. As a result, it becomes possible to assess the selectivity of all RPs of the protected region or EPS.

1. The presence of an arc and/or transition resistance at the SC location. Bold SCs (also called metallic SCs) which do not take into account the transition resistance, are unlikely in practical EPSs. Most often, SC occurs through the resistance of the arc or other element that prevents the current flow, reduces the total level of SC current and, depending on the nature of the transient resistance, shifts current phase relative to voltage. According to standard of Federal Grid Company of Russia, the transition resistance for ground faults is in the range of 5…20 Ohm, in special cases (with a small number of groundings in the network and stony ground) it can reach hundreds of Ohms.

2. The presence of reactive power compensation devices on the protected object or its nearest periphery. The latter in the general case affects the level of SC currents and their phase shift relative to voltage. With regard to series compensating devices (SCD) there may be phenomena called 'current inversion' and 'voltage inversion'. Voltage inversion is a phenomenon that occurs in case of a SC near the location of SCD installation and when SCD protection is not operate (without shunting of the SCD during a SC). The voltage phasor at the location of installation of the protection shifting by an amount greater than 90 degrees along clockwise with respect to the voltage phasor of the previous mode. In the case of voltage inversion, the inductive nature of the SC current in relation to the voltage remains. During current inversion, the inductive nature of the current is changing on the capacitive nature in relation to the voltage at the location where the protection is installed.

3. Neutral grounding mode. There are four main modes of neutral grounding: (i) insulated (ungrounded), (ii) solid grounded (directly connected to the grounding loop), (iii) grounded through an arc suppression reactor and (iv) grounded through an impedance (low resistance or high resistance). In case of a SC in networks with a solid or low-impedance neutral grounding, a very significant current flows through the protected object. In other grounding options, the current to the ground is much less. In the case of an insulated neutral connection, a phase-to-ground fault is not critical and does not require instant switch off due to a small increase in current relative to the operating one.

4. Pre-fault mode. The operating mode of EPS and protected object largely determines the dynamics of the transient process at the moment of a SC. A fault at a protected object can occur both in the EPS steady-state mode, characterized by minimal deviations of electrical parameters from normal values, and, e.g., as a result of overloading by currents flowing to the SC point outside the protection zone during MCI mode, motor starting, unsuccessful autoreclosing, etc. An important factor is the phase of the current: it passes through zero or is at its peak. As a rule, in such experiments the main indicator is a voltage: if the voltage phase is zero, then the phase current is at its peak and, accordingly, in case of SC, it will reach the maximum value possible under these conditions, in another case, if the voltage phase is equal to 90 degrees, the current passes through zero.

5. Loading of the protected object. For most EPS facilities, two extreme modes can be highlighted – under minimum and maximum load, e.g., with parallel power transmission line or transformer switching on and off, respectively. In the process of RP settings determination, it is necessary to carry out studies in each of the indicated modes, if it is possible to provide in the existing topology without EPS instability.

For each mode, a script is prepared that reproduces, e.g., a SC or a consequence of events leading to an asynchronous operation, taking into

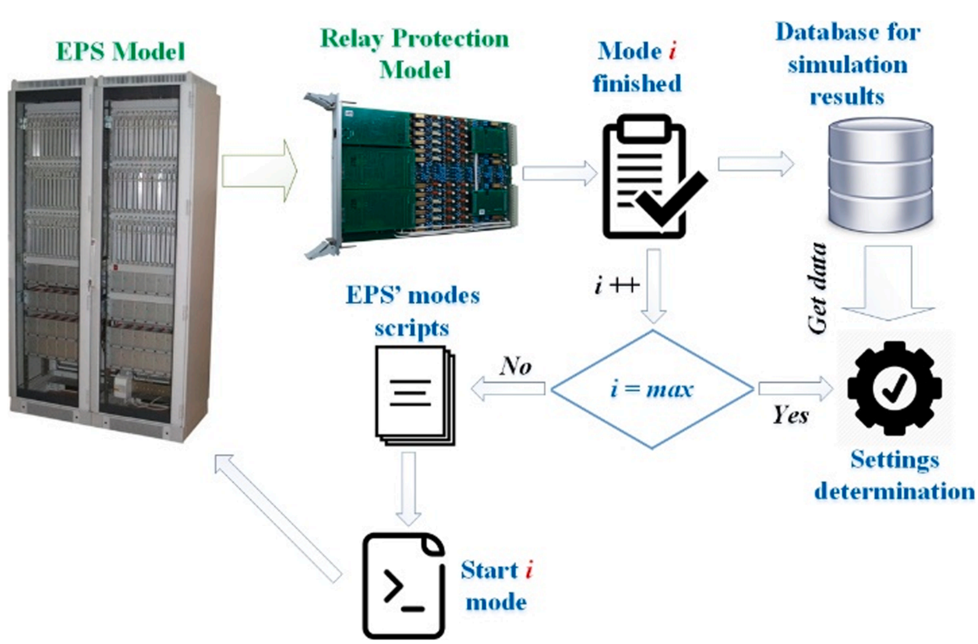


Fig. 3. Generalized structure of the proposed approach.

account the factors listed above. These scripts are reproduced one by one in the 'EPS Model' block (Fig. 3). The monitored signals from the simulated EPS equipment enter the 'Relay Protection Model' block, which is a specialized analog–digital system – specialized processor. The detailed structure and principles of development for specialized processors of the HRTSim are presented in [9]. The features of the developed specialized processor for RP simulation are presented in [10]. Upon completion of the scenario of EPS mode ('Mode *i* finished'), the generated fault characteristic and/or the trajectories of the controlled signals change are saved from the 'Relay Protection Model' block to the 'Database for simulation results'. Next, it is checked if the completed script was the last one. If not, then the start of the next script 'Start *i* mode' from the base of prepared scripts 'EPS modes scripts' is initiated. Then the process is repeated in the order described above. If the script was the last one and there are no more modes for simulation, then all trajectories and characteristics accumulated in the 'Database for simulation results' are loaded into the 'Settings determination' block, in which the tripping curves and/or thresholds is formed for each relay as part of microprocessor-based relay protection (see Section 3).

With this method of forming the RP settings, the following is carried out:

- the need for testing of settings, including repeated one in the case of adjustments, in each individual mode is excluded,
- the need for a theoretical search of critical modes (which is not always unambiguous, due to the significant number of determining factors), in which it is necessary to determine the corresponding thresholds and assess the sensitivity, is excluded,
- the operation of protection systems in non-emergency modes, which can potentially provoke its maloperation, is taken into account.

This approach allows to determine the RP settings, taking into account the impact of both the power system main equipment and the elements of the RP measuring part. At the same time, the proposed approach is flexible in terms of adapting to significant changes in EPS structure – by adding new models of renewable energy sources, FACTS and HVDC systems into the EPS model. It is possible to analyze their impact on the operation of a particular RP device and consider this impact during its tuning without any simplifications or limitations.

The possibility and prospects of using detailed mathematical models for RP tuning are mentioned in number of research [11–14], the analysis of which is described in more detail by the authors in [10]. The object of research of the vast majority of works is a microprocessor-based RP (MRP).

A distinctive feature of the mathematical models developed by the authors is a more detailed representation of the MRP internal structure: measuring, converting and logical parts of the protection. At the same time, the elements of the measuring part (instrument transformers, auxiliary converters, analog low-pass filters), in which the highest error during the conversion of the controlled signal is formed, are reproduced as a single continuous part, which allows to adequately take into account their mutual impact.

Considering the variety of the indicated elements of measuring part of the RP devices with different hardware implementation, the most optimal option is a 'flexible' combination of their mathematical descriptions – transfer functions [27]. At the same time, in order to correctly take into account the mutual interaction of the RP elements, the burden of the elements is set by a universal transfer function, the coefficients of which are determined based on the structure of the RP input circuits.

2.5. Distance protection test modes

This subsection provides a description of the selected modes for distance protection (DP) tuning. As a rule, DP has several zones (and the same number of relays), each of which has its own purpose and coverage area and, as a result, its own setting modes, the peculiarity of which is mainly determined by the SC location. In accordance with the requirements of regulatory documents in Russia, three zones for DP are required, although, in fact, their number can reach six (for a microprocessor-based relay): zones 4, 5 and 6 are used as additional, in particular, they can be directed 'backward'. Before proceeding to the description of the modes for each zone, it is necessary to explain some of the features specific to all zones of the DP.

1. The presence of a transition resistance at the point of fault necessitates an expansion of the tripping curve (TC) covered area. In case of phase-to-phase SCs, the transition resistance is determined by the resistance of the electrical arc between the phases. In case of phase-to-ground SCs, the transition resistance is determined by the following factors: the ratio of the SC currents flowing through the fault location from the opposite end of the line, the ratio of active resistances of ground and line, the permissible grounding resistance of the line tower, the grounding conditions of the lightning protection, the spreading resistance of zero-sequence currents in the ground.

2. The TC must be configured in such a manner to avoid false tripping of DP zones when impedance phasor swinging in case of load changing.

3. It should be ensured that the DP does not trip in the swinging and asynchronous modes, taking into account the possible trajectories of the input impedance phasor.

4. The DP should not trip in case of SCs 'behind the back', if the protection zone is not originally designed to work in the reverse direction.

5. The DP should reliably trip in case of SCs close to the installation location.

6. The operation of autoreclosing can lead to the fact that in the ICT due to the accumulated residual induction when a SC was previously disconnected, the new minor hysteresis loop is shifted relative to the original one, which leads to distortion of the secondary current shape [24].

7. After unsuccessful autoreclosing, the magnetization starts from a certain value equal to the residual magnetic induction and there are two possible scenarios: the most unfavorable situation, when magnetization occurs in the same direction as the residual magnetic flux of the core and the ICT quickly passes into the saturation region, otherwise the residual magnetic induction is added to the negative magnetic induction that occurs, which slows down the transition of the ICT to saturation region [24].

8. Transitions of one SC to another also lead to a shift of the minor hysteresis loop relative to the original one, which affects the shape of the secondary current.

9. The presence of parallel protected transmission lines reduces the SC current recorded by the DP, and, consequently, decreases impedance in case of fault. Therefore, parallel transmission lines should be disconnected in the DP setting modes (Pre-fault → 'Maximal load'), and connected in the sensitivity assessment modes (Pre-fault → 'Normal load').

The following is a description of SC locations (see Fig. 4):

- SC1 – point at the end of the protected transmission line, shifted inside by 5% (by 25% for the first zone) of its length relative to the opposite substation,
- SC2 – point at the beginning of the protected transmission line, shifted inside by 5% of its length relative to the RP installation location,
- SC3 – point 'behind the back' of the considered DP, shifted inside the following line by 5% of its length relative to the RP installation location,
- SC4, SC9, SC15 – points on substation buses,
- SC5, SC7, SC10, SC12, SC16, SC18 – points on the low voltage side of transformer,
- SC6, SC8, SC11, SC13, SC17, SC19 – points on the medium voltage side of transformer,

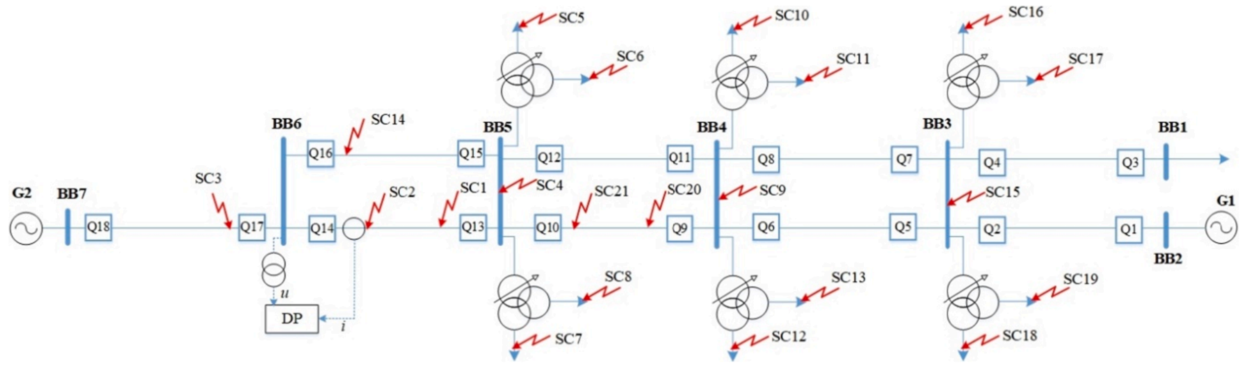


Fig. 4. Diagram of DP testing modes: BB – busbar, G – generator.

- SC14 – point on a parallel power transmission line, shifted inside by 5% of its length relative to the RP installation location,
- SC20 – point at the end of the previous (adjacent) power transmission line, shifted inside by 5% (by 25% for the first zone) from its length relative to the opposite substation,
- SC21 – point at the beginning of the previous (adjacent) power transmission line, shifted inside by 5% of its length relative to the RP installation location.

Below is a description of the modes in which the DP is tuned taking into account different zones and their areas of tripping.

Zone I. The DP' zone I covers the zone of the line, determined by necessity to avoid tripping in case of SCs on the low and medium voltage sides of transformers, as well as on the substation buses of the opposite end of the line. The following is a typical script of modeling modes for DP tuning:

1. Setting the initial mode.
2. Simulation of SC.
3. Setting the voltage phase of the damaged phase in pre-fault mode.
4. Setting the transient resistance.
5. Simulation of SC clearing after time t_{SC}.
6. Simulation of automatic reclosing after time t_{AR}.
7. Simulation of SC (if unsuccessful autoreclosing is assumed).
8. Simulation of SC clearing (if unsuccessful autoreclosing is assumed) after time t_{SC}.

Zone II. The DP' zone II covers the area determined by the condition of no-tripping in SC on the low and medium voltages sides of transformers connected to the buses of the substation on the opposite side of the line and all its connections, as well as the condition of coordination with the zone I of the line (lines) of the previous adjacent section of the network.

Considering the above, the list of modes for tuning and assessing the sensitivity of DP' zone II includes modes for the zone I. In addition, taking into account the conditions of coordination, the list of modes should be supplemented with SC modes of the same types as for zone I at the points SC9, SC10, SC11, SC12 and SC13.

Zone III. The DP' zone III covers the area determined by the following conditions:

- zone III is a backup for DP of the previous adjacent line (lines),
- zone III should detect SCs on the low and medium voltages sides of transformers connected to the substation buses on the opposite side of the line and all its branches,
- zone III should operate in coordination with the DP' zone II of the previous adjacent line (lines) (if it is not dead-end line).

Modes are similar to zone I, but SCs should be simulated at the points SC9, SC10, SC11, SC12 and SC13. The same modes are used to coordinate the DP' zone III with the zone II of the previous DP. The simulation is provided at the points SC15, SC16, SC17, SC18, SC19.

The sensitivity of zones II and III is assessed according to the covered area in the same way as for the DP' zone I. For all zones of DP, no-tripping must be ensured in the maximum load modes, taking into account the self-starting of the electrical motors. In accordance with the standard of the Federal Grid Company of Russia, DP must detect swing modes with a frequency up to 3 Hz inclusively and, accordingly, do not trip in such modes. It is necessary to simulate such a mode to make sure that this requirement is satisfied. Non-fault modes are common for all stages of the DP and are determined based on specific operating conditions of considered EPS scheme.

3. Tuning principles for relays of microprocessor-based protection system

In any microprocessor-based protection systems, the following relays are presented in different combinations:

- maximal relays, which detect the controlled parameter became higher than threshold,
- minimal relays, which detect the controlled parameter became lower than threshold,
- speed relays, which detect increasing of the rate of change of the controlled parameter,
- power direction relays, which indirectly determine the direction of current flow: from bus or into bus,
- distance relays, controlling the magnitude and phase of the impedance phasor,
- differential relays, controlling the value of the difference in currents at the sides of the protected object,
- phase comparison relays, controlling the phase difference of currents at the sides of the protected object.

In accordance with the above ideology (Fig. 3), the settings are determined based on the simulation results of all selected modes. The following is a more detailed description of the formation of settings for differential and distance relays, which are used as primary protections for different power system equipment. If the protection has several stages (or zones), then the settings in accordance with the approach indicated below are determined for the relays of each stage (zone).

3.1. Distance relays

For distance relays, based on the simulation results, it is required to form a TC, which can have a different geometric shape, depending on the specific implementation. The area inside the figure is the tripping area. Simulation of various operation modes, including critical modes for this relays, characterized by swings of current and voltage, of the protected object and EPS as a whole will allow to estimate the trajectory and speed of the impedance phasor on the *R-X* plane, defining the desired position and parameters of the applied TC.

Either the directionality property is provided by displacement of the TC to the area of the desired direction, or by dividing it according to the direction characteristic. The most widely used are the directional circular or polygonal characteristics for distance relays. Non-directional relay is only used in case of unidirectional power flow (e.g., for generators). Considering the above, this paper considers two types of characteristics: circular and polygonal TC, excluding overload modes area.

For non-directional elements, the simplest option to avoid false tripping in overload modes, which is also used in existing techniques, is to take into account the impedance of protected object and then to check RP operation in case of SC at the border of the protection zone. For other TCs, their position and size, based on existing capabilities, will be determined as a result of modeling SC modes and specific modes, accompanied by swings in EPS. In general, the formation of a polygonal characteristic is determined by the parameters, which are grouped in Table 1.

The swing mode is identified by distance relay, as a rule, by two possible features: (1) the rate of change of current, (2) the rate of change of impedance. When a SC occurs, the impedance phasor 'jumps' from the load area to the tripping area. When synchronous oscillations occur, the impedance phasor appears in the tripping area and leaves it. Swing is detected when it passing along a monotonous trajectory. If the impedance phasor passes through the tripping area, covered by the swing area, then the parts of EPS began to work asynchronously. At the stage of settings determination, the study of EPS modes accompanied by synchronous and asynchronous swings, and analysis of the trajectory of dependence $Im = f(Re)$ will allow to form a TC ensuring reliable appearance of $Im = f(Re)$ in the controlling zone of the rate of change of impedance. For Russian protection systems, the following values are recommended: $\Delta X = \Delta R = 5$ Ohm for ICTs with a secondary rated current equal to 1 A, $\Delta X = \Delta R = 1$ Ohm – for ICTs with 5 A. Thus, the protection monitors the time spent by the phasor in the controlling zone.

During the process of a TC forming, it is necessary to analyze the oscillations of the impedance phasor when the load in EPS changes. If $Im = f(Re)$ enter the tripping area, the load zone is 'cut out' from the TC by setting the corresponding parameters that determine it: R_{LOAD} and φ_{LOAD}. The algorithm for forming a polygonal TC is presented below.

1. Determination of the TC boundaries. R_{SET} and X_{SET} are fixed after a time T_{BL}, equal to the operating time of the blocking element of the distance protection (e.g., the blocking element response time for distance protection is not more than 25 ms) after the moment of SC occurrence. Among all the options, the largest *Re* and *Im* values corresponding to R_{SET} and X_{SET} are selected. Parameters R_{SET} and X_{SET} must be the first point of entry of the fault characteristic $Im = f(Re)$ into the tripping zone.

2. The angle φ_1 is taken as the average value for the simulated EPS and it is called as the maximum sensitivity angle φ_{MS}: according to the standard of the Federal Grid Company of Russia, the φ_{MS} is recommended to be taken in the range of 60…70 degrees for 110 and 220 kV networks. Taking into account the practical experience that served as the basis for the choice of the specified range of angles, as well as the focus on the existing capabilities of the protection devices, the proposed methodology retains the existing principle of determining the angle φ_1.

Table 1
Parameters for setting the tripping curve of the distance relay.

Parameter	Description
R_{set}	Threshold for resistance
X_{set}	Threshold for reactance
φ_1	Angle of slope for right part of TC
φ_2	Angle of slope for bottom part of TC
φ_3	Angle of slope for left part of TC
φ_4	Angle of slope for top part of TC

3. Using R_{SET}, X_{SET} and φ_1, a parallelogram can be formed, which determines the primary tripping zone of the relay, as well as a parallelogram. Parameter Δ is a margin added due to the assumptions of the means of mathematical simulation of EPS and RP in general. Studies carried out and partially presented in [9] have proved that the deviation between the results obtained via the HRTSim and recorded field data does not exceed 10%. Moreover, if the error of the disturbance recorders is taken into account, the information from which was taken as a benchmark, then the deviation could be limited within 5%. If detailed information is available on the real parameters of the equipment installed in EPS, the difference in results could be limited within 1%. Understanding the fact that the latter is difficult to implement in practice, the error of EPS simulation tool is assumed to be 5% in this paper. Regarding the MRP modeling tools, the estimation of the error is complicated due to the impossibility of comparing the processes in the measuring circuits of the model and the real device. Taking into account that, despite the specific features, each manufacturer of MRP mostly adheres to the basic algorithms and structure described, e.g., in [28–30], it can be assumed that the error in RP modeling as a whole, according to the authors' assessment, is within 10% [31]. Thus, in the developed methodology, the resulting value of Δ is equal to 15%. It is necessary to underline, that the parameter Δ does not replace the coefficients that were different for each protection and were used to raise or lower thresholds in existing methods. The parameter Δ is the error of mathematical simulation of processes in the power system and measuring circuits of RP, estimated by the authors. Therefore, it is the same for all relays of microprocessor-based relay protection.

4. The angle φ_2 is selected in such a way as to cover all fault characteristics $Im = f(Re)$ of internal SCs in the tripping area of the protection. To do this, initially it is necessary to determine the lowest point located in the tripping zone – the point $Im_{\varphi 2}$ according to Eq. (5).

$$Im_{\varphi 2} = min\begin{pmatrix} if\ Im_1^k < X_{SET}\ AND\ \ Im_1^k > -X_{SET} \Rightarrow min\left(Im_1^k\right); \\ if\ Im_2^k < X_{SET} AND\ \ Im_2^k > -X_{SET} \Rightarrow min\left(Im_2^k\right); \\ \ldots \\ if\ Im_n^k < X_{SET} AND\ \ Im_n^k > -X_{SET} \Rightarrow min\left(Im_n^k\right) \end{pmatrix} \quad (5)$$

Using $Im_{\varphi 2}$ it is possible to determine corresponding $Re_{\varphi 2}$. Then φ_2 with margin Δ can be calculated by Eq. (6):

$$\varphi_2 = \mathrm{atan}\left(\frac{Im_{\varphi 2}}{Re_{\varphi 2}}\right) + \Delta \quad (6)$$

5. The angle φ_3 is selected in such a way as to avoid appearance of fault characteristics $Im = f(Re)$ of external SCs inside the tripping zone. To determine it, the point closest to the vertical axis is initially determined, which is within the parallelogram. The selected value of $Re_{\varphi 3}$ by Eq. (7) determines the corresponding value of $Im_{\varphi 3}$.

$$Re_{\varphi 3} = max\begin{pmatrix} \text{if}\left(Re_1^k < 0 AND\, Re_1^k > -R_{SET}\right) AND\left(Im_1^k < X_{SET}\right) \Rightarrow max\left(Re_1^k\right) \\ \text{if}\left(Re_2^k < 0 AND\, Re_2^k > -R_{SET}\right) AND\left(Im_2^k < X_{SET}\right) \Rightarrow max\left(Re_2^k\right) \\ \ldots \\ \text{if}\left(Re_n^k < 0 AND\, Re_n^k > -R_{SET}\right) AND\left(Im_n^k < X_{SET}\right) \Rightarrow max\left(Re_n^k\right) \end{pmatrix} \quad (7)$$

Using $Re_{\varphi 3}$ it is possible to determine corresponding $Im_{\varphi 3}$. Then φ_3 with margin Δ can be calculated by Eq. (8).

$$\varphi_3 = \mathrm{atan}\left(\frac{Re_{\varphi 3}}{Im_{\varphi 3}}\right) + \frac{\pi}{2} + \Delta \quad (8)$$

6. The angle of slope of the top part of the TC φ_4 within the framework of this methodology is not determined and, accordingly, is taken equal to zero.

7. The speed control area is adopted according to the manufacturer's recommendations, e.g., for distance protection $\Delta X = \Delta R = 5$ Ohm or 1

Ohm.

8. Determination of the load area. The value of R_{LOAD} is determined based on the analysis of trajectories of $Im = f(Re)$ in various non-emergency modes, accompanied by load changes in studied EPS by Eq. (9). R_{LOAD} is the 'depth' of the entry of $Im = f(Re)$ into the tripping zone, or, in other words, R_{LOAD} is the closest point to the ordinate within the tripping zone. The angle φ_{LOAD} is determined by Eq. (10) via the coordinates of the intersection point of the TC and $Im = f(Re)$ of the loading mode: R_{LOAD_SLOPE} and X_{LOAD_SLOPE}.

$$R_{LOAD} = min\begin{pmatrix} \text{if } \left(Re_1^k > 0 AND\, Re_1^k < R_{SET}\right) AND \left(Im_1^k < X_{SET}\right) \Rightarrow min\left(Re_1^k\right) \\ \text{if } \left(Re_2^k > 0 AND\, Re_2^k < R_{SET}\right) AND \left(Im_2^k < X_{SET}\right) \Rightarrow min\left(Re_2^k\right) \\ \dots \\ \text{if } \left(Re_n^k > 0 AND\, Re_n^k < R_{SET}\right) AND \left(Im_n^k < X_{SET}\right) \Rightarrow min\left(Re_n^k\right) \end{pmatrix} + \Delta \quad (9)$$

$$\varphi_{LOAD} = \text{atan}\left(\frac{X_{LOAD\ SLOPE}}{R_{LOAD\ SLOPE}}\right) + \Delta \quad (10)$$

The algorithm for forming a circular TC is presented below.

1. The values R_{SET} and X_{SET} are determined in the same way as for the polygonal TC. These values in turn determine the length of the phasor Z_{SET}, which is the diameter of the circle of the tripping zone.

$$Z_{SET} = \sqrt{R_{SET}^2 + X_{SET}^2} \quad (11)$$

2. The slope angle φ_1 determine in the same way as for polygonal TC.

3. The total tripping zone is determined by the length of the phasor Z_{SET} with margin Δ rotated by the angle φ_1.

4. The area of the speed control zone is adopted in accordance with the manufacturer's recommendations.

5. The principle of constructing the load area is completely identical to that described earlier for polygonal TC.

3.2. Differential relays

As a result of differential relay tuning the TC should be determined based on the results of mathematical simulation of various external SCs, as well as in specific EPS modes (e.g., modes accompanied by MCI, overvoltage modes), in which the incorrect behavior of relay is potentially possible. The differential relay of MRP must reliably operate at any internal SC, in connection with which it is also necessary to carry out studies of the relay model in these modes. In the general case, the TC of a differential relay is determined by a set of parameters presented in Table 2.

The algorithm for the TC parameters (Table 2) determination is as follows.

1. The pickup value of differential current $I_{diff>}$ determines the first sector of the TC, on which the protection operates without restraining, i.e. with zero slope. Theoretical and experimental data indicate that only with internal SCs, the fault characteristic $I_d = f(I_s)$ (relation between differential I_d and restraining I_s currents) crosses the TC in this sector, since the differential and restraining currents change in equal proportions. The $I_{diff>}$ according to the recommendations of the manufacturers and the standard of Federal Grid Company of Russia is regulated in the range of 0.2…0.4 pu. A lower level is undesirable, since it may be less than the unbalance current that occurs due to conversion errors by the instrument transformers, as well as the protection system itself. A higher level will lead to a decrease in sensitivity to internal SCs and a slower operation. Based on this, within the framework of the proposed methodology, $I_{diff>}$ is set according to the recommendations of the protection manufacturer in the range of 0.2…0.4 pu.

Table 2
Parameters for setting the tripping curve of the differential relay.

Parameter	Description
$I_{diff>}$	Pickup value of differential current
$I_{diff\gg}$	Pickup value of high set trip
I_{base1}	Base point for second sector of tripping curve
slope$_1$	Slope of second sector of tripping curve
I_{base2}	Base point for third sector of tripping curve
slope$_2$	Slope of third sector of tripping curve

2. The second sector of the TC is defined by two parameters: I_{base1} and slope$_1$. The slope of the TC makes it possible to exclude incorrect tripping of the relay in case of external SCs, accompanied by saturation of the ICT. I_{base1} is determined from the minimum value of the restraining current of the fault characteristic $I_d = f(I_s)$ in case of external SCs according to Eq. (12):

$$I_{base1} = \min\begin{pmatrix} \min\left(I_{s1}^1, I_{s1}^2 \dots I_{s1}^k\right) \\ \min\left(I_{s2}^1, I_{s2}^2 \dots I_{s2}^k\right) \\ \dots \\ \min\left(I_{sn}^1, I_{sn}^2 \dots I_{sn}^k\right) \end{pmatrix} \quad (12)$$

To determine the slope of the TC second sector slope$_1$, the coordinates of the point p_1 are determined by Eq. (13) – the point of the fault characteristics of the external SC modes closest to the ordinate axis, provided that it is above the pickup value of differential current $I_{diff>}$.

$$X_{p_1} = \min\begin{pmatrix} I_{s1}^k, \text{ if } I_{d1}^k > I_{diff} \\ I_{s2}^k, \text{ if } I_{d2}^k > I_{diff} \\ \dots \\ I_{sn}^k, \text{ if } I_{dn}^k > I_{diff} \end{pmatrix} \quad (13)$$

Using the X coordinate, which is equal to a certain value of the restraining current, the corresponding differential current I_d is selected, which forms the Y coordinate of the point p_1. Than slope$_1$ could be calculated by Eq. (14).

$$\text{slope}_1 = \frac{Y_{p_1}}{X_{p_1} - I_{base1}} \quad (14)$$

3. The third sector of the TC should have a significantly greater slope than the second in order to exclude the incorrect behavior of the protection in modes accompanied by deep saturation of the ICT and significant distortion of secondary currents. In accordance with the standards of Federal Grid Company of Russia, the slope$_2$ is recommended to be twice more than slope$_1$. Within the proposed methodology, slope$_2$ is defined by Eq. (15):

$$\text{slope}_2 = 2 \cdot \text{slope}_1 \quad (15)$$

4. Another parameter that determines the third sector of the TC is I_{base2}, which is determined using the slope of the third sector slope$_2$ and the coordinates of the point p_2 according to Eq. (16) – the 'highest' point of the fault characteristics of those modes, in which the protection should not operate, providing that the X coordinate of this point (actually braking current) is greater than I_{base1}.

$$Y_{p_2} = \max\begin{pmatrix} I_{d1}^k, \text{ if } I_{s1}^k > I_{base1} \\ I_{d2}^k, \text{ if } I_{s2}^k > I_{base1} \\ \dots \\ I_{dn}^k, \text{ if } I_{sn}^k > I_{base1} \end{pmatrix} \quad (16)$$

Using the Y coordinate, which is equal to a certain value of the restraining current, the corresponding braking current I_s is selected, which forms the X coordinate of the point p_2. The base point for the third sector of tripping curve is determined by Eq. (17).

$$I_{base2} = X_{p_2} - \left(\frac{Y_{p_2}}{\text{slope}_2}\right) \quad (17)$$

5. The fourth sector is determined by the pickup value of high set trip $I_{diff}\gg$. If the fault current value is exceeded this threshold, then the relay is tripped, regardless of the magnitude of the restraining current or other conditions. The $I_{diff}\gg$ is determined from the maximum through-current in case of external SCs or the maximum inrush current (for the case of a transformer (autotransformer) switching-on mode under voltage at no-load conditions).

$$I_{diff>>} = \max\begin{pmatrix} I_{d1}^{k} \\ I_{d2}^{k} \\ \ldots \\ I_{dn}^{k} \end{pmatrix} + \Delta \tag{18}$$

4. Tuning results for relays of microprocessor-based protection system

The following are the results of MRP relays tuning in accordance with the developed approach.

4.1. Distance relays

Initially, the boundaries of TC R_{SET} and X_{SET} are determined (Fig. 5). They are fixed after a time t_{BL}, equal to the operating time of the blocking element of the distance protection (e.g., the blocking element response time for distance protection is not more than 25 ms) after the moment of SC occurrence. Among all the options, the largest *Re* and *Im* values corresponding to R_{SET} and X_{SET} are selected. These parameters should be the first point of entry of the characteristic $Im = f(Re)$ into the trip area (see Figs. 6 and 7). The results of the formation of TCs based on the previously described algorithm are presented below: for polygonal TC (Fig. 6) and for circular TC (Fig. 7).

4.2. Differential relays

Differential relays, as well as distance relays, operate in accordance with the tripping curve: according to the monitored currents, a fault characteristic is formed (the dependence of the differential I_d on the restraining I_s current) and its location is monitored relative to the TC – appearance of fault characteristic $I_d = f(I_s)$ in the zone above the TC results in tripping. The TC should be formed in such a way as to avoid false tripping in case of external SCs, as well as during MCI, accompanied by significant differential currents due to saturation of ICTs. The results of the TC formation for differential relay as a part of the microprocessor-based differential protection of the power transformer are shown in Fig. 8.

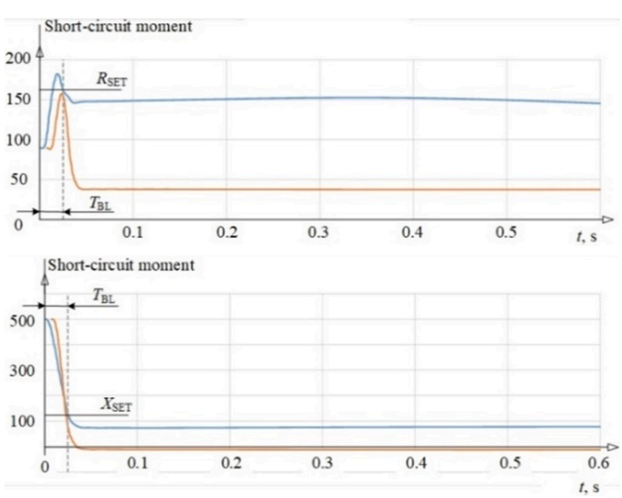


Fig. 5. Diagrams of changes of the resistance and reactance in the modes of internal SCs.

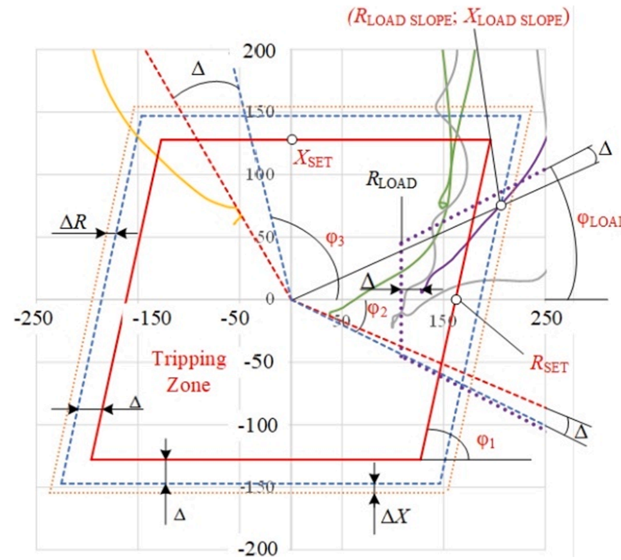


Fig. 6. Formation of the polygonal tripping curve of distance relay.

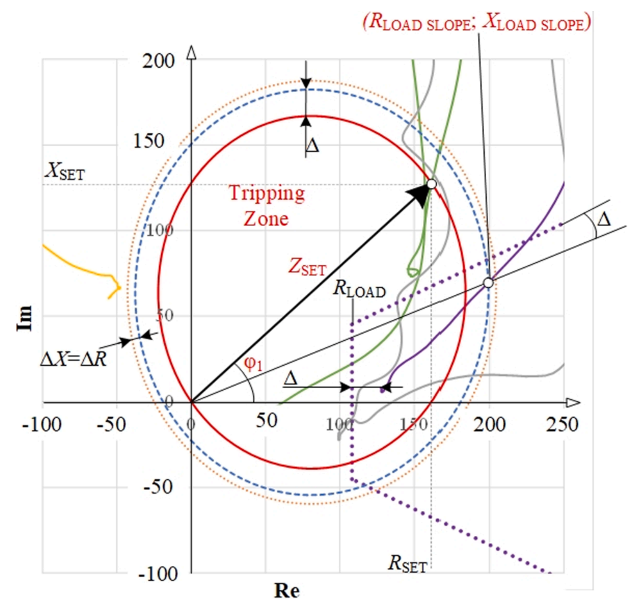


Fig. 7. Formation of the circular tripping curve of distance relay.

5. Conclusion

The novel approach for RP devices tuning is presented in this paper. This approach is flexible by adding new positions considering the prospects of modern power systems. The implementation of such approach allows to determine the settings of RP in specific conditions of its operation and to exclude the unnecessary overestimation or underestimation of RP thresholds. Taken together, this provides a reliable and comprehensive RP operation and reduces the number of possible blackouts. In the future, the process of RP tuning will be automated through the development of appropriate software that will operate off-line or in combination with the HRTSim. It is also planned to develop a system of a remote on-line real-time tuning process of RP devices.

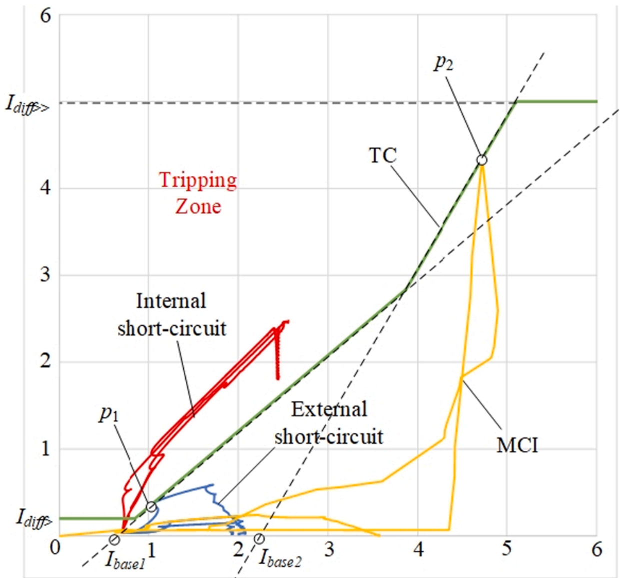


Fig. 8. Formation of the tripping curve of differential relay.

CRediT authorship contribution statement

Mikhail Andreev: Conceptualization, Methodology, Investigation, Resources, Writing – original draft, Writing – review & editing. **Alexey Suvorov:** Investigation, Formal analysis, Writing – original draft. **Alisher Askarov:** Conceptualization, Validation, Software, Writing – review & editing. **Vladimir Rudnik:** Methodology, Validation, Visualization. **Bhavesh R. Bhalja:** Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgment

This research was supported by Tomsk Polytechnic University development program.

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