Mikhail Andreev, Aleksey Suvorov, Ruslan Ufa, Igor Razzhivin

Tomsk Polytechnic University

doi:10.15199/48.2021.06.27

Relay Protection Settings Determination Using Its Mathematical Models

***Abstract**. The correct functioning of relay protection (RP) largely determines the stability of electric power systems (EPS). The key point, which in turn determines the behavior of protection in various emergency modes, is their setting. The existing methods and means often do not allow to guarantee the adequacy of protection setting to the real operating conditions, which is confirmed by the statistics of accidents in the EPS. The root cause of this problem is the impossibility using the software tools used in practice for relay settings calculation to reliably reproduce the transient processes in the power system. The EPS simulator – Hybrid Real-Time Power System Simulator (HRTSim), developed by the authors, allows to adequately reproduce the entire spectrum of normal and emergency processes for a power system of any dimension, topology and configuration through the use of detailed three-phase models of all EPS elements. Given this possibility, the task of detailed modeling of relay protection, including instrumental current and voltage transformers, becomes promising. The developed protection modeling tools in combination with the capabilities of the HRTSim allow the development of new methods for determining the relay protection settings. This article presents an algorithm for determining the polygonal and circular tripping characteristics of distance protection, and also presents graphic materials demonstrating the operation of this algorithm. This approach allows to adapt the settings to the real conditions of protection application in the power system, while minimizing the likelihood of their incorrect behavior.*

***Streszczenie.** Od prawidłowego działania zabezpieczenia przekaźnikowego (RP) w dużej mierze zależy stabilność układów elektroenergetycznych (EPS). Kluczowym punktem, który z kolei determinuje zachowanie zabezpieczeń w różnych trybach awaryjnych, jest ich ustawienie. Istniejące metody i środki często nie pozwalają na zagwarantowanie adekwatności ustawień zabezpieczeń do rzeczywistych warunków eksploatacji, co potwierdzają statystyki wypadków w SEE. Podstawową przyczyną tego problemu jest niemożność wykorzystania narzędzi programowych stosowanych w praktyce do obliczania ustawień przekaźnika w celu niezawodnego odtworzenia procesów nieustalonych. Opracowany przez autorów symulator EPS - Hybrid Real-Time Power System Simulator (HRTSim) pozwala na adekwatne odwzorowanie całego spektrum procesów normalnych i awaryjnych dla systemu elektroenergetycznego o dowolnym wymiarze, topologii i konfiguracji poprzez zastosowanie szczegółowych trójstopniowych modeli fazowych wszystkich elementów EPS. Biorąc pod uwagę tę możliwość, zadanie szczegółowego modelowania zabezpieczeń przekaźników, w tym przekładników prądowych i napięciowych, staje się obiecujące. Opracowane narzędzia do modelowania zabezpieczeń w połączeniu z możliwościami HRTSim pozwalają na opracowanie nowych metod określania nastaw zabezpieczeń przekaźników. W artykule przedstawiono algorytm wyznaczania wielokątnych i kołowych charakterystyk wyzwalania zabezpieczeń odległościowych, a także przedstawiono materiały graficzne demonstrujące działanie tego algorytmu. (**Określanie ustawień zabezpieczenia przekaźnika za pomocą jego modeli matematycznych**)*

Keywords: relay protection, setting up, mathematical simulation, distance protection.
Słowa kluczowe: zabezpieczenia, przekaźniki, modele matematyczne.

Introduction

The correct functioning of relay protection devices (RP) largely determines the reliable, stable operation of electric power systems (EPS). Meanwhile, despite significant progress in the development of protection systems, it is not possible to ensure their error-free operation, which is confirmed by statistical data [1]. Approximately 25% of severe system accidents occur due to incorrect actions of relay protection and automation, and, in 50-70% of cases, incorrect actions of protections lead to the development of emergency situations in severe system accidents (blackouts), characterized by significant economic and technological damage.

Having analyzed the specific reasons for the RP wrong actions, it is possible to divide them into three main categories in order of importance: 1) hardware failures; 2) errors in schemes and settings; 3) staff errors.

The smallest progress is observed in solving problems belonging 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 the modes and processes in the EPS when calculating the relay settings.
2. Excessive overestimation or underestimation of the settings due to taking into account errors introduced by specific relay protection and primary transducers as approximate generalized coefficients.

For a long time, the first factor was an obstacle to the elimination of the second – the lack of a tool for detailed reliable modeling of a single continuous process in the EPS under all kinds of normal, emergency and post-emergency modes of its operation made it senseless to take into account the processes taking place in the relay protection themselves, as well as in the instrumental current (ICT) and voltage (IVT) transformers.

Mathematical modeling of EPS is the only way to obtain data on the entire spectrum of processes and modes of power equipment, relay protection and the power system as a whole. In this case, the total mathematical model of even a regional EPS, in the case of using the most complete three-phase mathematical models of all main and auxiliary equipment, even without taking into account the RP, forms a stiff system of differential equations of an extremely high order, badly solved by methods of numerical integration of ordinary differential equations. The designated problems determine the need to decompose a single continuous process in an EPS into steady-state normal, emergency and post-emergency modes, calculated using static (a system of algebraic equations) mathematical models and the method of symmetric components, as well as the stage of transient processes, mainly electromechanical, calculated using systems of differential equations generating sources, static models of power grid equipment. In accordance with this, mainly software calculation tools are developed and used. In practice, for relay protection settings determination, highly specialized software systems are used using extremely simplified static mathematical models of all EPS equipment, which make it possible to determine only the periodic component of the short-circuit current. The errors of the ICT and IVT, as well as the hardware of the relay protection, during RP' setting up, are taken into account by the generalized fixed coefficients.

For a long time, this circumstance hindered the solution of the indicated problem of increasing the efficiency of the settings calculation and its adequacy to the specific conditions of utilization in the EPS. At Tomsk Polytechnic

University, a tool has been developed based on a fundamentally alternative (in relation to numerical methods) approach to EPS modeling – Hybrid Real-Time Power System Simulator (HRTSim) [2]. The possibility of implementing the most complete three-phase mathematical models of EPS equipment of any dimension, combined with the possibility of solving them on an unlimited interval with a guaranteed acceptable accuracy, makes it possible to declare the elimination of the first factor that determines the presence of the problem of determining the relay settings.

The solution to the problem of adequate mathematical modeling of EPS has opened up opportunities for more detailed mathematical modeling of RP, including ICT and IVT, and the development of tools for implementing these models. The description of the hardware and software systems for the RP simulation developed by the authors is presented in [3]. In contrast to the existing methods and tools for modeling relay protection [4-10], the created systems make it possible to reproduce a single continuous spectrum of processes in the entire set of elements that determine the structure of relay protection: auxiliary converters, filters, relays, etc.

New possibilities for modeling EPS and RP made it even more urgent to solve the problem of increasing the efficiency of setting up protection in conditions as close as possible to real ones. In this article, the authors present fragments of the available research results on this topic.

Materials and methods

The proposed approach is generally described by the diagram in Fig. 1. The RP settings are determined in the process of modeling the modes in the EPS-RP aggregate model. After last mode simulation, the settings for the protection device are formed. If, as a result, the relay becomes insensitive to internal damage, the simulation results in certain modes can be excluded when forming the relay settings, provided that the protection action is blocked in this modes. Such approach to settings determination have the following advantages:

- eliminates the need for checks, including repetitive checks, in case of settings adjustments in some individual mode;
- eliminates the need for a theoretical search (which is not always unambiguous, due to the huge number of determining factors) for limiting conditions in which it is necessary to determine the settings and evaluate the RP sensitivity;
- protection operation in non-emergency modes, potentially capable of provoking its incorrect action, is taken into account.

This approach makes it possible to determine the settings of the relay protection, taking into account both the influence of the EPS equipment and the elements of the measuring protection circuits. At the same time, it is flexible in terms of adapting to changes in the EPS – by adding new models of renewable energy sources, FACTS and HVDC systems, etc. to the EPS model, one can analyze their impact on the functioning of a specific RP and take this influence into account in its settings in a natural way.

In all existing types of relay protection, some of the following triggering elements are present in different combinations:

- maximal element, which detect the fact that the controlled parameter exceeds the threshold;
- minimal element, which detect the fact of decrease of the monitored parameter below the threshold;
- speed element, which detect the fact of increasing the rate of change of the controlled parameter;
- directional element, which determine the direction of current flow from the buses or into the buses;
- distance element, controlling the magnitude and phase of the impedance vector;
- differential element, detecting the value of the difference in currents at the ends of the protected object;
- phase-comparison element, element the phase difference of currents at the ends of the protected object.

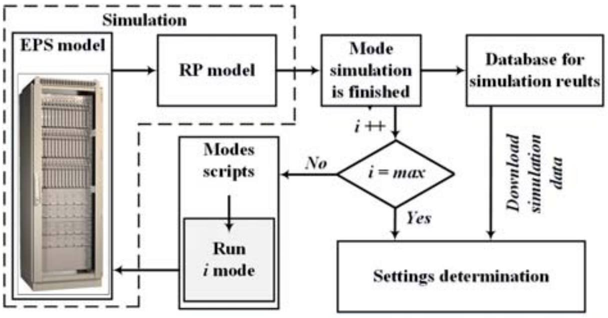

Fig.1. Generalized structure of the proposed approach

In accordance with the above ideology (Fig. 1), the settings are determined based on the results of modeling all planned modes. Settings determination algorithm for distance triggering elements are disrobed below.

For distance triggering elements based on the simulation results, it is required to form a tripping characteristic (TC), which, depending on the implementation, can have a different geometric shape. The area inside the figure is the tripping zone. Modeling various modes of operation, including critical modes for this protection, characterized by strong fluctuations in current and voltage, the protected object and the EPS as a whole will allow to estimate the trajectory and speed of movement of the impedance vector in the R-X plane and determine the desired position and parameters of the applied TC.

Depending on the element base, one or another TC is specified in the form of a set of parameters that determine it. The directional property is provided either by shifting the response TC to the area of the desired direction, or by dividing it according to a direction characteristic similar to the directional triggering element. The most widely used are circular or polygonal characteristics for distance protection. Non-directional impedance control operate selectively only network with one-way supply.

Considering the above, this article 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 check for a short-circuit 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 the short-circuit modes on the protected object and specific modes characterized by swings in the EPS. In general, the formation of a polygonal characteristic is determined by the parameters grouped in Table 1.

The swing mode is identified by distance protection, as a rule, by two possible features: 1) rate of current change; 2) the rate of impedance change. When a short-circuit occurs, the impedance vector “jumps” from the load area to the tripping area. When synchronous oscillations occur, the impedance vector appears in the tripping area and leaves it. Swing is detected when passing along a monotonous trajectory. If the impedance vector passes through the tripping area, covered by the swing area, then the network parts began to work asynchronously. At the stage of settings determination, the study of EPS modes, accompanied by synchronous and asynchronous oscillations, and analysis of the trajectory Im = f(Re) will allow to form a TC in such a way as to ensure reliable appearance Im = f(Re) into the zone of controlling the rate of impedance change (ΔX = ΔR = 5 Ohm at a secondary rated current of the ICT 1 A, ΔX = ΔR = 1 Ohm – at 5 A) – the protection monitors the time spent by the vectors in the control zone.

Table 1. Distance elements parameters determining TC

Parameter	Description
R_{set}	Thershold for resistance
X_{set}	Thershold 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

In the process of TC forming, it is necessary to analyze the oscillations of the impedance vector when the load in the EPS changes. If Im = f(Re) appear int 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}.

Research results and discussion

The principle of TC forming for distance triggering elements is shown in Figs. 2-4.

The polygonal TC forming algoritm is described below.

1 The TC boundaries determination. R_{set} and X_{set} should be fixed after a time T_b, equal to the operating time of the blocking element of the distance protection (for example, the blocking element response time for distance protection in ShE 2607 021 (Russian protection system) is not more than 0.025 s), begining from the moment of short-circuit occurrence. Among all the results, the largest Re and Im corresponding to R_{set} and X_{set} are selected (Fig. 4). Parameters R_{set} and X_{set} must be the first point of entry of the fault characteristic Im = f(Re) into the tripping area.

2 The angle φ_1 is taken as the average value of the calculated network and is conventionally called the angle of maximum sensitivity φ_{ms}: by the standard of the Federal Grid Company of Russia, the recommended values are φ_{ms} = (60 ÷ 70) ° – for a 110 kV network; φ_{ms} = (60 ÷ 70)° – for 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 terminals, the proposed methodology retains the existing principle of determining the angle φ_1.

3 Using R_{set}, X_{set} and φ_1, a parallelogram can be constructed, which determines the primary tripping zone of the triggering element, as well as a parallelogram, taking into account the reserve Δ = 15%. The value of Δ is chosen based on the analysis of studies, published in [3].

4 The angle φ_2 selecting in such way to cover all fault characteristics Im = f(Re) of internal short-circuits 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 Imφ_2 (1).

(1)
$$\mathrm{Im}_{\varphi 2}=\min\left(\begin{array}{l} if\ \mathrm{Im}_1^k < X_{\text{уст}}\ AND\ \ \mathrm{Im}_1^k > -X_{set} \Rightarrow \min\left(\mathrm{Im}_1^k\right);\\ if\ \mathrm{Im}_2^k < X_{\text{уст}} AND\ \ \mathrm{Im}_2^k > -X_{set} \Rightarrow \min\left(\mathrm{Im}_2^k\right);\\ \ldots\\ if\ \mathrm{Im}_n^k < X_{\text{уст}} AND\ \ \mathrm{Im}_n^k > -X_{set} \Rightarrow \min\left(\mathrm{Im}_n^k\right). \end{array}\right)$$

Using Imφ_2 it is possible to determine corresponding Re$_{\varphi 2}$. Then φ_2 with reserve Δ can be calculated (2):

(2)
$$\varphi_2=\operatorname{atan}\left(\frac{\mathrm{Im}_{\varphi 2}}{\mathrm{Re}_{\varphi 2}}\right)+\Delta$$

5 The angle φ_3 selecting in such way to avoid appearance of fault characteristics Im = f(Re) of external short-circuits modes inside the tripping area. To determine it, the point closest to the vertical axis is initially determined, which is within the parallelogram. The selected value of Re$_{\varphi 3}$ (3)determines the corresponding value of Im$_{\varphi 3}$.

(3)
$$\mathrm{Re}_{\varphi 3}=\max\left(\begin{array}{l} if\ \left(\mathrm{Re}_1^k<0\,AND\ \ \mathrm{Re}_1^k>-R_{set}\right)\ AND\\ \left(\mathrm{Im}_1^k<X_{set}\right)\Rightarrow \max\left(\mathrm{Re}_1^k\right);\\ if\ \left(\mathrm{Re}_2^k<0\,AND\ \ \mathrm{Re}_2^k>-R_{set}\right)AND\\ \left(\mathrm{Im}_2^k<X_{set}\right)\Rightarrow \max\left(\mathrm{Re}_2^k\right);\\ \ldots\\ if\ \left(\mathrm{Re}_n^k<0\,AND\ \ \mathrm{Re}_n^k>-R_{set}\right)AND\\ \left(\mathrm{Im}_n^k<X_{set}\right)\Rightarrow \max\left(\mathrm{Re}_n^k\right). \end{array}\right)$$

Next, the value of φ_3 (4) with reserve Δ is calculated in the same way as φ_2.

(4)
$$\varphi_3=\operatorname{atan}\left(\frac{\mathrm{Re}_{\varphi 3}}{\mathrm{Im}_{\varphi 3}}\right)+\frac{\pi}{2}+\Delta$$

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. For distance protection ShE2607 021, for example, ΔX = ΔR = 5 Ohm or 1 Ohm.

8 The load area is set. R_{load} (5) is determined based on the analysis of trajectories Im = f(Re) in various non-emergency modes, accompanied by load changes in the EPS. 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} (6) is determined by the coordinates of the intersection point of the TC and the trajectory Im = f(Re) of the loading mode: R_{load_slope} and X_{load_slope}.

(5)
$$R_{load}=\min\left(\begin{array}{l} if\ \left(\mathrm{Re}_1^k>0\,AND\ \ \mathrm{Re}_1^k<R_{set}\right)\ AND\\ \left(\mathrm{Im}_1^k<X_{set}\right)\Rightarrow \min\left(\mathrm{Re}_1^k\right);\\ if\ \left(\mathrm{Re}_2^k>0\,AND\ \ \mathrm{Re}_2^k<R_{set}\right)\ AND\\ \left(\mathrm{Im}_2^k<X_{set}\right)\Rightarrow \min\left(\mathrm{Re}_2^k\right);\\ \ldots\\ if\ \left(\mathrm{Re}_n^k>0\,AND\ \ \mathrm{Re}_n^k<R_{set}\right)\ AND\\ \left(\mathrm{Im}_n^k<X_{set}\right)\Rightarrow \min\left(\mathrm{Re}_n^k\right). \end{array}\right)+\Delta$$

(6)
$$\varphi_{load}=\operatorname{atan}\left(\frac{X_{load\_slope}}{R_{load\_slope}}\right)+\Delta$$

The circulaer TC forming algoritm is described below.

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

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 vector Z_{set} with reserve 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 load area is set. R_{load} is determined based on the analysis of trajectories Im = f(Re) in various non-emergency modes, accompanied by load changes in the

EPS. The principle of constructing this area is completely identical to that described earlier for polygonal TC.

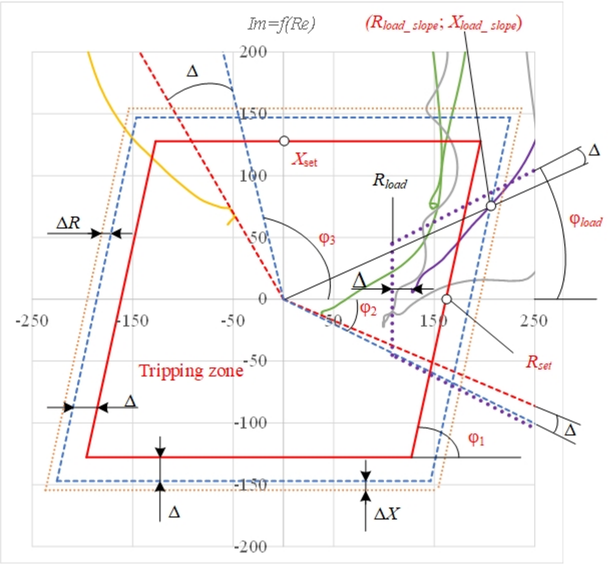

Fig.2. Polygonal TC forming principles

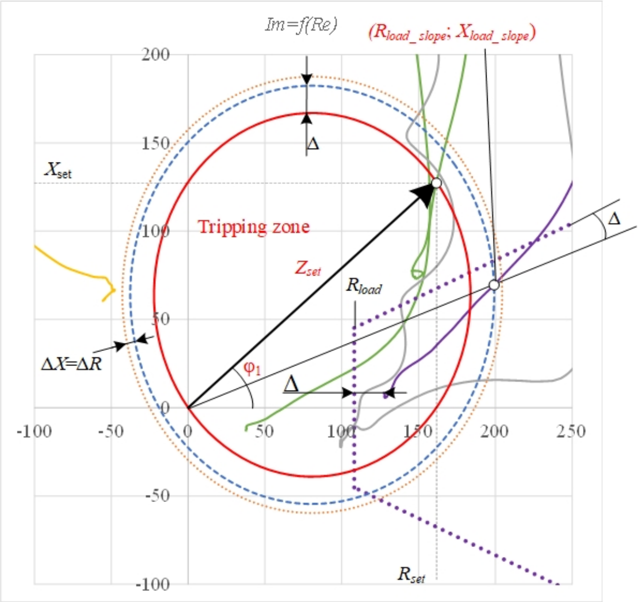

Fig.3. Circular TC forming principles

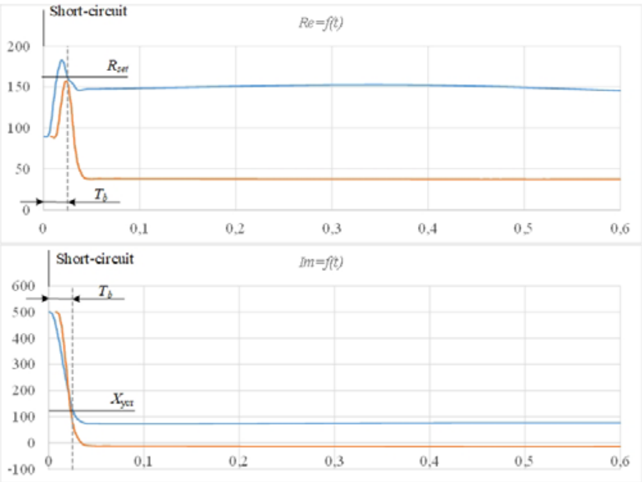

Fig.4. Diagrams of changes of the resistance and reactance in the modes of internal short-circuits

Conclusion

The results presented in the article demonstrate that the proposed approach makes it possible to more effectively determine the protection settings that will ensure its correct functioning in an EPS of any configuration.

Acknowledgment

This work was supported by the Ministry of Science and Higher Education of Russian Federation under the governmental grant "Science" № FSWW-2020-0017.

***Authors**: Associate professor of Division for Power and Electrical Engineering, Mikhail Andreev, Tomsk Polytechnic University, 30, Lenin Avenue, Tomsk, Russia, E-mail: andreevmv@tpu.ru; Associate professor of Division for Power and Electrical Engineering, Aleksey Suvorov, Tomsk Polytechnic University, 30, Lenin Avenue, Tomsk, Russia, E-mail: suvorovaa@tpu.ru; Associate professor of Division for Power and Electrical Engineering, Ruslan Ufa, Tomsk Polytechnic University, 30, Lenin Avenue, Tomsk, Russia, E-mail: hecn@tpu.ru; Senior lecturer of Department of Electric Power Systems, Igor Razzhivin, Tomsk Polytechnic University, 30, Lenin Avenue, Tomsk, Russia, E-mail: lionrash@tpu.ru.*

REFERENCES

[1] Sykes, J., Madani, V., Burger, J., Adamiak, M., Premerlani, W. (2010). Reliabilty of protection systems (what are the real concerns). *Proceedings of Int. Conf. Protective Relay Engineer*, College Station, TX, USA, 1-16.

[2] Prokhorov, A., Borovikov, Yu., Gusev A. (2012). Real time hybrid simulation of electrical power systems: concept, tools, field experience and smart grid challenges. *Int. J. Smart Grid Clean Energy*, 1(1), 67-68.

[3] Andreev, M., Suvorov, A., Askarov, A., Kievets, A., Rudnik, V. (2020). Identification of digital relay protection measuring part elements using time of its tripping. *Przeglad Elektrotechniczny, 96*(10), 71-75.

[4] Peng, Z., Li, M., Wu, C., Cheng, T., Ning, T. (1985). A Dynamic State Space Model of a MHO Distance Relay. *IEEE Transactions on Power Apparatus and Systems*. 104(12), 3558-3564.

[5] Romaniuk, F., Rumiantsev, V., Novash, I., Rumiantsev, Y., & Boiko, O. (2016). Comparative assessment of digital filters for microprocessor-based relay protection. *Przeglad Elektrotechniczny, 92*(7), 128-131.

[6] Bejmert, D., Rebizant, W. (2010). Application of fuzzy logic for stabilization of transformer differential protection. *Przegląd Elektrotechniczny*, 86 (8), 11-15.

[7] Novozhilov, A., Yussupova, A., Assainov, G., Novozhilov, T., & Manukovsky, A. (2018). Sources of independent power supply for protection relay. *Przeglad Elektrotechniczny, 94*(5), 23-26.

[8] Mahadevan, N., Dubey, A., Chhokra, A., Guo, H., Karsai, G. (2016). Using temporal causal models to isolate failures in power system protection device." *IEEE Instrumentation & Measurement Magazine*, 18 (4), 28-39.

[9] Hsieh, S., Chen, C., Tsai, C., Hsu, C., Lin, C. (2014). Adaptive Relay Setting for Distribution Systems Considering Operation Scenarios of Wind Generators. *IEEE Transaction on Industrial Application*, 50 (2), 1356-1363.

[10] Kezunovic, M., Chen, Q. (1997). A novel approach for interactive protection system simulation. *IEEE Transactions on Power Delivery*, 12(2), 668-674.