Mikhail ANDREEV, Alexander GUSEV, Aleksey SUVOROV, Nikolay RUBAN, Ruslan UFA

Tomsk Polytechnic University, Russia

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Study of mutual influence of measuring part elements of transformer differential protection and its impact on the primary signal processing

Abstract. *Calculation of relay protection (RP) settings ensuring its adequate functioning under specific operating conditions is extremely difficult task. The main prerequisite for solving this problem is availability of a detailed analysis of functioning of key elements of RPs schemes in the specific conditions of its operation. That is possible to do with adequate RPs mathematical models and modern EPS simulators. Based on developed by authors approach for detailed RPs simulation the models of the whole circuit of measuring part (MP) of numerical transformer differential protection were developed for different types of auxiliary transformers and low-pass filters. A comparative numerical analysis of its impact on the primary signal processing is carried out, including taking into account the magnetization current transformers. Summarizing, the theoretical and practical studies presented in the article allows formulating requirements for RPs' detailed mathematical models, which will be used in the further research.*

Streszczenie. *W artykule analizoano warunki prawidłowej pracy cyfrowego zabezpieczenia pracy transformatora. W tym celu opracowano model matematyczny układu zabezpieczającego ze szczególnym uwzględnieniem pracy filtru. Przeprowadzono symulacje dla różnych typów zewnętrznego transformatora i filtru dolnoprzepustowego.* ***Analiza wpływu części pomiarowej różnicowego cyfrowego zabezpieczenia transformatora uwzględniająca przetwarzanie sygnału pierwotnego***

Keyword: mathematical simulation, flow graph, settings, relay protection.
Słowa kluczowe: cyfrowe różnicowe zabezpieczenie transformatora, model matematyczny.

Introduction

The well-known fact is the rapid growth of energy consumption in the world. Over the past 15 years, the increase was approximately 35-40% [1] and there are no prerequisites for reducing these numbers. Thus, the build-up of generated capacities will also continue. As a result, the modern electric power system (EPS), which already is a complex, dynamic and nonlinear system, will become even more complicated. The situation is aggravated by increasing the share of distributed generation and penetration of renewable energy sources [2]. In accordance with [1], the total generated power of wind and solar energy sources has increased by more than 30% over the past 15 years. Protection of EPS due to these changes becomes extremely difficult and urgent task.

According to the statistics [3], one of the main causes of severe accidents in the world is incorrect actions of relay protection (RP) and automation. As for the specific reasons, approximately 20% of the incorrect actions are associated with errors in the schemes and settings, which are connected with discrepancy of protection settings and real operating conditions. This problem and factors determining it are considered by the authors in [4].

An obvious condition for solving the problem is possibility of a detailed analysis of operation of RP devices key elements in its specific regimes [5, 6]. This will allow to reliably estimate the processes in the protected objects, to evaluate the processing error of instrument transformers (IT) – current transformers (CT) and potential transformers (PT), as well as RP elements, and also to determine the parameters of adequate RP settings. The RPs detailed mathematical models reproducing the entire set of elements, including CTs and PTs, ensure this possibility.

The main demotivator for creating such models for a long time was the lack of tools for complete and reliable EPS simulation. That is determined by the adequacy of the applied mathematical models of the primary and auxiliary equipment, including RPs and ITs, as well as the ability of their implementation tools to solve the whole model of a large-scale EPS with guaranteed acceptable accuracy. The mathematical description of EPS power equipment is already known. The main problem connected with its solution and determined by the problematics of the applied numerical methods used for integration of ordinary differential equations describing processes in equipment and EPS as a whole [7, 8]. An alternative to the indicated methods is a complex approach, the practical implementation of which is a multiprocessor software and hardware system – Hybrid Real-Time Power System Simulation (HRTSim) [9].

Application of HRTSim in combination with detailed RPs mathematical models opens the possibility for in-depth studying processes in RP circuits and developing novel techniques for its setting up. The numerical transformer differential protection (NTDP) was chosen as an object of research. The NTDP is one of the main protections and it is of considerable interest in terms of studying.

Development of detailed mathematical models of relay protection

The authors formulated and justified the approach for development of detailed RPs mathematical models, which reproduce the processes in specific implementations and ITs. The positions of this approach are presented, for example, in [4]. Therefore, this publication only briefly outlines the main points:

1) Equivalent circuit is basis for the RP mathematical description. The equivalent scheme is compiled on the basis of RP principle scheme. At the same time, RP and IT (CT and PT) are modeled together as a whole.

2) The RPs mathematical descriptions, including ITs, as transfer functions (TF) are developed on the basis of the equivalent circuits. The TFs allow analyzing the elements of the simulated protection in frequency and time domains. One of the most effective methods for obtaining the TFs is the method of flow graphs [10]. There are two possible approaches for the TFs compilation: a) full equivalent circuit: simulation of the RP scheme, including ITs, as a whole; b) divided equivalent circuit: separation of the principle scheme and the equivalent circuit into functional fragments, and then sequentially mathematically describing each such fragment accounting all interconnections. The first option is hardly applied for modeling large schemes, because of complexity of mathematical model. The second option allows creating a flexible model for any scheme.

However, the chance of an error is increased in scheme reduction.

In the framework of previous studies [4], authors selected the second option. The choice was related to modeling electromechanical and electronic protections along with numerical RPs (NRP). The flow graphs of such RPs are very sophisticated with a lot of unconnected contours. Synthesis of TFs on its basis is an extremely difficult task. Since it is hard to automate the contours enumeration according to the Mason formula [10], the chance of error is increase. In addition, the numerical calculation of such TFs led to a "hang" of the calculation programs. As a result, the same direction was chosen for all RP element bases.

Nevertheless, the first approach is preferable. As the second one, it is possible to determine the voltage and current at any node and branch of the equivalent circuit, but it eliminates the need to constantly take care about adequate accounting interconnections of a particular functional element. All connections are taken into account in a natural way when modeling the entire scheme. This approach the authors used for the researches presented in the article.

At present, the integration of NRPs in power systems throughout the world is actively continuing. Therefore, the attention of researchers has shifted toward them. This article also focused on the simulation of NRP, in particular – NTDP.

Any NRP, regardless to the type, has the same structure, containing three serially connected parts [11]:

1) Measuring part (MP), as was mentioned before, includes CT (PT), auxiliary transformers (AT) and anti-aliasing frequency filters, as a rule, low-pass filters (LPF).

2) Converting part (CP) includes analog-to-digital converter (ADC) and commutator, used for sampling analog signals.

3) Logical part (LP) includes microprocessor, which is implements a variety of functions: digital filtering, vector conversion, RP algorithm implementation, etc., as well as digital-to-analog converters (DAC) and output dry-contact relays.

Obviously, CP errors are determined by the hardware characteristics (mainly capacity) of the ADC and can be assessed accurately and accounted in NRP aggregate model. The methods for determining these errors are known and described in the books, for example in [12].

The microprocessor in the LP because of the high quality of its production can be considered as ideal, i.e. hardware errors can be ignored. As for the DAC, the situation here is analogous to the ADC. Speaking about output relays, today there are quite detailed mathematical descriptions of electromechanical relays that can be applied for its simulation. On the other hand, the function of these relays is formation of a discrete signal ('1' is tripping or '0' is not tripping of RP) and there is no need for its detailed accounting. It is sufficient to know relays tripping time (manufacturer data) and set up appropriate response delay at the NRP model output.

The main emphasis in NRP simulation should be made on the MP detailed modeling. This conclusion is supported by other studies, for example [13-16]. The question arises: what and how should be taken into account in the MP model?

In the article [14], author writes that ATs does not affect at the accuracy of the RP simulation results as a whole. In some other projects, for example in [16], analogous simplifications are used. As for anti-aliasing LPFs, there is an uncertainty in their choice, since there is no detailed information in the NRP manufacturer's guidelines. According to open information sources, there are several types of analog filters that can potentially be used in NRP: 1) Butterworth 3rd-order LPF [15]; 2) 4th-order Butterworth LPF; 3) Chebyshev's LPF, Bessel's LPF, elliptical LPF [15]. In [13], the 2nd-order filter was used.

However, there are no publications containing specific data confirming non-influence of these elements on NRP operation as a whole. For this reason, it was decided to carry out research and answer the question posed in relation to the NTDP.

Study of mathematical models

Preliminary conclusion about the influence of one or another LPF and ACT on the MP' input signal processing was made on the basis of its frequency and phase responses (Figs. 1 and 2) analysis. The TFs are synthesized for entire MP circuit. The following abbreviations are used: BWor3 – Butterworth 3rd-order LPF, BWor1 – Butterworth 1st-order LPF, Cheb3 – Chebyshev 3rd-order LPF, Bes3 – Bessel 3rd-order LPF, ATAL – active ACT, PTAL – passive ACT.

It is well known that the CT magnetizing process significantly affect at the transformation of MP input signal and NTDP operation as a whole. In the CT equivalent circuit magnetizing losses are taken into account by the corresponding impedance Z_μ. To obtain the above responses, this impedance value was fixed at 1000 Ohm. However, to analyze the impact of magnetizing circuit nonlinearity, three-dimensional relationship is drawn (Fig.3). It represent the distributions of the TF (module of TF $|W(j\omega)|$ – Z axe) depending on the CT magnetizing impedance (Z_μ – X axe) and the input signal frequency (f – Y axe).

The main conclusion resulting from the analysis of the curves in Figs.1 and 2 is a tangible difference both in amplitude (Fig.1) and in phase (Fig.2) of the "CT-ACT-LPF" output voltage for different filters and ATs. This is observed in the pass band, as well as in the stop band of LPFs. The cutoff frequency for all LPFs is assumed to be 250 Hz. The abrupt change in the TF "CT-ACT-LPF" phase response (Fig.2) is explained by achievement by the LPF of resonance frequency. For cases of using active ACT, it happens later (at a frequency > 10 kHz – not shown in the figure) in compare with the passive ACT (at a frequency of < 1 kHz). This phenomenon is due to the presence of an operational amplifier with negative feedback at the active ACT output.

According to obtained results, it is necessary to have detailed information about a specific implementation of ACT and LPF. In addition, with a more adequate consideration of the magnetizing circuit effect the discrepancies in responses will be much larger. The Fig. 3, in fact, reflect the MP output signal changes when the input signal frequency increasing and CT magnetizing impedance decreasing (saturation). That is happens when a short circuit occurs. It is clearly seen from the figure that significant differences between the TF modules of the combinations "CT - passive ACT - Chebyshev 3rd-order LPF" and "CT - passive ACT - Butterworth 3rd-order LPF" are observed both in the pass band and stop band of LPF: "red chart" – the TF "CT-passive ACT-Butterworth 3rd-order LPF", "blue chart" – the TF "CT-passive ACT- Chebyshev 3rd-order LPF".

To study the processes in the MP, MATLAB was used. As a CT the 110 kV current transformer with transformation ratio 1000/5 is selected. The LPF parameters are determined for 250 Hz cutoff frequency. As an active ACT the current transformer LTS 15-NP is applied. Passive ACT has a similar scheme to the active, except that a resistor is connected in parallel with LPF to convert voltage to current. The 4th-order implicit Runge-

Kutta numerical method was used to solve the systems of differential equations reproducing the processes in the MP. The program codes realizing solution of mathematical models are implemented in S-Function Builder blocks in MATLAB. Below are research results from MATLAB (Figs.4 and 5).

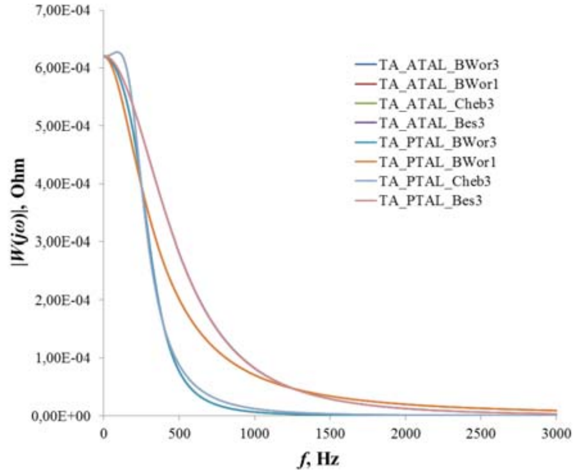

Fig. 1. Frequency responses of the TFs "CT-ACT-LPF" (from input of CT till output of LPF)

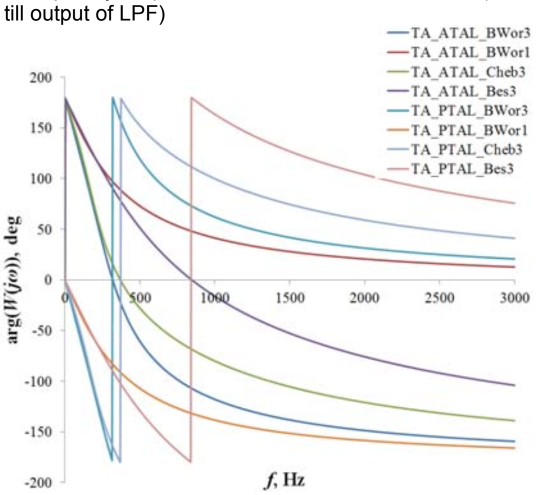

Fig. 2. Phase responses of the TFs "CT-ACT-LPF" (from input of CT till output of LPF)

The Fig.4 shows output voltages oscillograms of the MP "CT-passive ACT-Butterworth 3rd-order LPF" and the MP "CT-active ACT-Butterworth 3rd-order LPF" both for cases of ignored (fixed Z_μ=1000 Ohm) and taking into account the CT magnetizing curve. The output voltages oscillograms for the MPs with active and passive ACT and with fixed Z_μ completely coincide. This is due to the coincidence of its frequency responses (parameters are chosen to obtain close responses). Taking into account the CT nonlinearity, difference is significant, but mainly in the transient mode: varies in the range 15÷25%. At the time of appearance of frequent oscillations on the "peaks" of the output signals sine wave, this difference is in 2-3 times greater. This situation is partly due to insensitivity of active ACT to its burden changes, because of the operational amplifier at the output, in contrast to the passive ACT. The oscillations are associated with a significant drop of Z_μ at low magnetizing current i_μ in the range 0.001÷0.33 A. This particularly affects at the shape of the signal in normal mode. In the range of i_μ>> 0.33 A (close to the saturation), such oscillations briefly shows than i_μ crossing the zero.

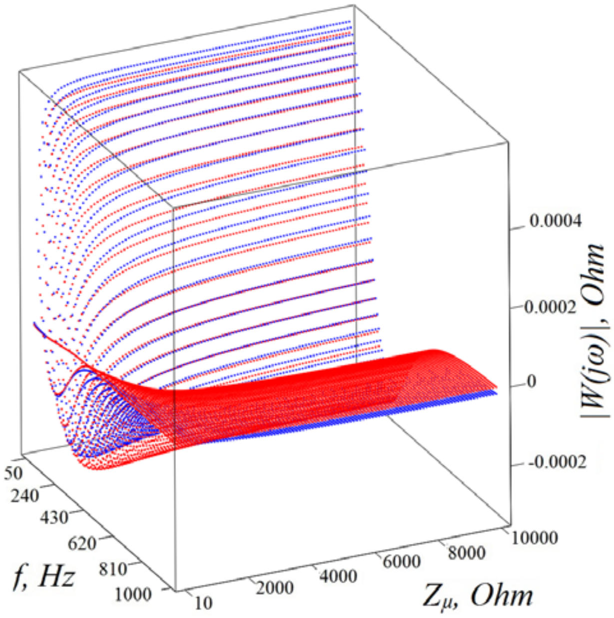

Fig. 3. Comparison of relationships $|W(j\omega)| = f(Z\mu, f)$ of the TF "CT-passive ACT-Butterworth 3rd-order LPF" and the TF "CT-passive ACT-Chebyshev 3rd-order LPF"

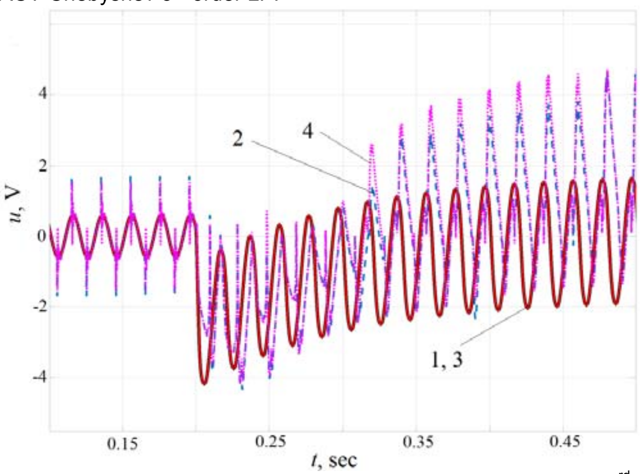

Fig.4. Output voltages of the MP "CT-passive ACT-Butterworth 3rd-order LPF" for case of ignored CT magnetizing curve (line 1) and for case of taking into account CT magnetizing curve (line 2), as well as the MP "CT-active ACT-Butterworth 3rd-order LPF" for case of ignored CT magnetizing curve (line 3) and for case of taking into account CT magnetizing curve (line 4)

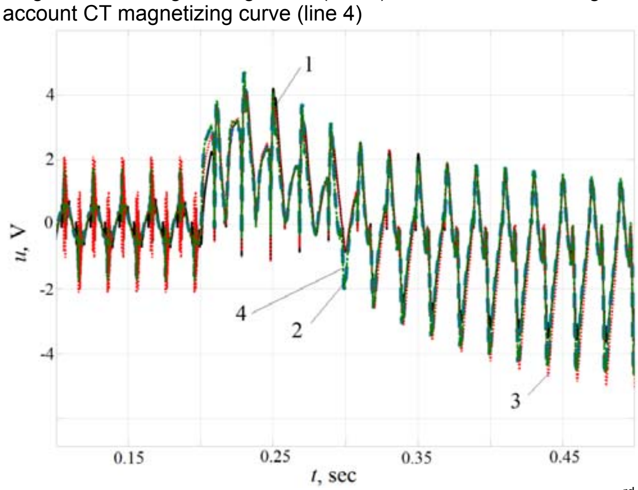

Fig. 5. Output voltages of the MP "CT-active ACT-Butterworth 3rd-order LPF" (line 1 – black), the MP "CT-active ACT-Chebyshev 3rd-order LPF" (line 2 – blue), the MP "CT-passive ACT-Butterworth 3rd-order LPF" (line 3 – red), the MP "CT-passive ACT- Chebyshev 3rd-order LPF" (line 4 – green)

The Fig. 5 shows output voltages oscillograms of the MPs for the cases of connection of the Chebyshev LPF and Butterworth LPF, as well as the active and passive ACTs. The nonlinearity of the CT magnetizing impedance is taken into account for all combinations. In the normal mode, differences between the output signals for different MPs circuits are insignificant (<2%). In the transient mode, differences between the signals are varying in the range 10-30% for different combinations. For the circuit with Chebyshev LPF in the steady-state short-circuit mode differences between the output signals when LPF connected to the active and passive ACTs are small (1÷2%). In case of the Butterworth LPF the differences are greater: in the range 25÷30%.

Conclusion

Summing up, the following main conclusions are made:

1. It has been theoretically proved that the elements of the MP have the most significant influence on the RPs operation as a whole and need to be accounted in details in protection models.

2. It has been numerically proved that the influences of MP auxiliary elements (ATs and LPFs) on the input signal processing and, potentially, on the RPs operation as a whole is significant. In addition, this influence is largely determined by the specific type of AT and LPF, which was also demonstrated. Even on the basis of the received frequency and phase responses it is possible to refute the opinion about possibility of the auxiliary elements exclusion.

3. The lack of detailed information about the particular types of LPFs and ATs in the technical descriptions for numerical RPs, according to the authors, does not prevent to formulate the main points of the corresponding methods for RPs setting up. The solution of this problem is the goal of further research. However, in order to use the RPs mathematical models created in accordance with the proposed approach for setting up specific protection devices, this information is extremely important.

The detailed mathematical models in combination with an adequate EPS simulator will also help to resolve other important tasks: research and development of RPs algorithms, training to work with RPs and its configuring, monitoring and identifying reasons of deviation of operation regimes of RP elements from normal operation regimes.

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***Authors**: associate professor of Department of Electric Power Systems, Mikhail Andreev, Tomsk Polytechnic University, 30, Lenin Avenue, Tomsk, Russia, E-mail: andreevmv@tpu.ru; professor of Department of Electric Power Systems, Alexander Gusev, Tomsk Polytechnic University, 30, Lenin Avenue, Tomsk, Russia, E-mail: gusev_as@tpu.ru; assistant of Department of Electric Power Systems, Aleksey Suvorov, Tomsk Polytechnic University, 30, Lenin Avenue, Tomsk, Russia, E-mail: suvorovaa@tpu.ru; associate professor of Department of Electric Power Systems, Nikolay Ruban, Tomsk Polytechnic University, 30, Lenin Avenue, Tomsk, Russia, E-mail: rubanny@tpu.ru; assistant of Department of Electric Power Systems, Ruslan Ufa, Tomsk Polytechnic University, 30, Lenin Avenue, Tomsk, Russia, E-mail: hecn@tpu.ru.*

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