Simulation of differential protections of transformers in power systems

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Abstract

In this paper the problem of wrong actions of relay protection (RP) and emergency automation (EA), including the transformer differential protection (TDP), is considered. It was found that this problem is caused by the discrepancy of TDP settings from the real operation conditions, associated mainly with the use of several gross simplifications in existing method of TDP settings calculation. Based on the research, presented briefly in this paper, it is concluded that the adequate mathematical models considering peculiarities of the specific implementations and processes in current transformers (CT) and integrated into the appropriated aids, in particular, into the program – mathematical modeling of TDP designed by the author of the article, are effective tools for testing and optimizing of TDP settings.

1 Introduction

Generators, transformers (autotransformers), power transmission line and other equipment of electric power systems (EPS) are continuously connected in the process of production, transmission, distribution and consumption of electrical energy. Power transformers and autotransformers, beside their inherent features, are technological "hubs" and the most expensive elements of EPS. Therefore, unjustified disconnection or failure of transformers and autotransformers is associated with a significant technological and economic damage. Correct operation of relay protection (RP) allows minimizing these effects. It's especially true for major RP of transformers and autotransformers – transformer differential protection (TDP).

Meanwhile, according to the displayed on the diagram (Figure 1) generalized statistics of accidents in the Russian and foreign EPS, approximately 25% of severe accidents are the result of improper actions of RP and emergency automatic (EA) [1] – [4]. TDP is not working properly in about 20% of cases. Moreover, 50 - 70% of incorrect operations of RP lead to the development of emergencies in severe systemic crashes.

Breakdowns and defects in the above statistics are accounted separately from incorrect operation of RP. Because of it the discrepancy of RP's settings and real operating conditions becomes the main reason for wrong actions of RP. This discrepancy is determined by two main factors:

- usage of incomplete and inaccurate information about the regimes and processes in the equipment and EPS for RP's settings calculation;
- inadequate accounting errors generated by specific implementations of RP and measuring transformers (MT).

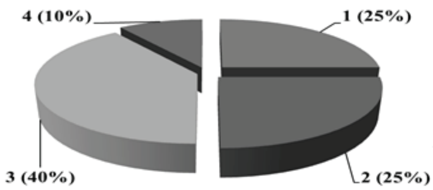

Figure 1: Generalized statistics of accidents in the Russian and foreign electric power systems: 1 – wrong actions of dispatching personnel; 2 – incorrect operation of RP and EA; 3 – breakdowns and defects in the equipment; 4 – natural disasters.

The problem of the first factor minimizing is common for all RP devices. Solution of this task depends on the properties and capabilities of software and hardware-software simulation systems of EPS [5] - [11], which are provided by the complete and adequate modeling of processes in the equipment and EPS for all possible normal, emergency and post-emergency regimes during an unlimited time interval.

This work is mainly devoted to the problem of the second factor minimizing solution.

2 Simulation of transformer differential protection

2.1 Purpose

The purpose of research is improving the efficiency and reliability of the TDP due to their settings using the detailed mathematical models that take into account the specific protections implementation and processes in MT.

2.2 Materials and methods

In accordance with the differential protection principle in the absence of damages or presence of damage outside the TDP operational zone measured currents compensate each other.

Due to this reason differential current is equal to zero and no tripping occurs. It is obvious that the ideal situation is unreachable in real devices and the differential current is equal to some current of imbalance. The main causes of imbalance are linked with some features of the protected object and measuring current transformers (CT):

1) Inrush current (IC), which appears in the supply winding of power transformer (PT). IC is the highest when the PT is unloaded and under voltage. Another reasons for IC: external short circuit (SC); recovery of voltage level after turning off the external fault; transition of SC from one form to another; non-synchronous generator connection to the EPS. IC is characterized by a long-decaying DC component and the contents of various harmonics, as well as large amplitude at the initial time. IC can lead to deep saturation of CT and the distortion of the waveform of the secondary current.

2) Different connection scheme of PT. Thus, there is a shift between currents from different sides of the transformer and the current of imbalance appears.

3) The difference between the currents in the "shoulders" of protection due to the operation of the transformer taps changer (TTC). Moving TTC leads to transformation coefficient changes. Due to it the primary and secondary currents ratio changes and the current of imbalance appears.

4) The difference between the currents in the "shoulders" of protection due to inequality of measuring current transformers. Currents on the sides of a power transformer considerably differ from each other. Because of it the selected CT has different transformation coefficients, designs, characteristics and errors.

The measures taken to correct the reasons for imbalance depend on the particular implementation of the TDP. In addition to the hardware and software setting the reasons for imbalance are taken into account in the existing methods of calculation of TDP settings. The analysis of these methods revealed the following simplifications:

- the errors of CT, which, obviously, are not constant and depend on the value and character of the load and the input current, are taken into account as fixed approximate coefficients;
- the impact of DC component which is determined by the specific operating conditions of protection is taken into account as the approximate coefficient;
- in the digital TDP's terminals in the calculations approximate and insufficiently reasoned coefficients are used;
- the errors introduced by specific implementations of TDP are not considered.

Due to the indicated assumptions the calculated settings are very rough and approximate. This leads to the wrong operation of TDP. Because of it the calculated settings must be checked and adjusted. That can be performed very efficiently using mathematical models, which adequately simulate the processes in the particular implementations of TDP and CT. For the development of adequate mathematical models which take into account the features of specific implementations and processes in CT the corresponding concept is formulated. The following methodology is a concentrated expression of the mentioned concept:

1) Analysis of TDP schemes for the adequate equivalent circuits creation.

2) Creation of the equivalent circuits which take into account the CT and features of the implementation.

3) Synthesis of transfer functions (TF) of the specific implementation of TDP and CT using the method of graphs and Mason's formula.

4) Synthesis of the mathematical descriptions on the basis of TF simulated TDP for their time or frequency domains analysis.

5) Preliminary study of mathematical models obtained through Mathcad, MATLAB Simulink, EMTP, PSCAD etc. programs for testing the adequacy of their functioning and caring out the necessary adjustments.

6) The formalization of mathematical descriptions obtained in the form of program code to implement the mathematical models of TDP in the means of their application.

7) Experimental investigation of the developed models of TDP in the means of their application.

Fragment of the synthesis of the mathematical model of DZT-21(Russian electronic TDP) is shown in Figure 2. This fragment includes the equivalent circuit of operation circuit of DZT-21, its graph, TF (1) and the corresponding differential equation (2).

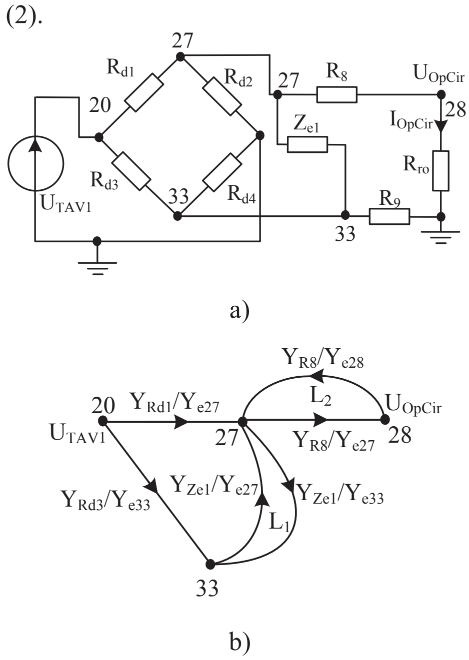

Figure 2: Fragment of the synthesis of the mathematical model of DZT-21: a) equivalent circuit of operation circuit: U_{TAV1} – output voltage of transreactor; R_{d1}, R_{d2}, R_{d3}, R_{d4} – diodes resistances; R_{ro} – input resistance of operating element; U_{OpCir}, I_{OpCir} – output voltage and output current of operation circuit; Z_{e1} – equivalent resistances of part of scheme of operation circuit; b) graph of equivalent circuit of operation circuit.

$$W_{\mathrm{opCir}}(p) = \frac{U_{OpCir}(p)}{U_{TAV1}(p)} = \frac{\dfrac{Y_{Rd1}}{Y_{e27}} \cdot \dfrac{Y_{R8}}{Y_{e28}} + \dfrac{Y_{Rd3}}{Y_{e33}} \cdot \dfrac{Y_{Ze1}}{Y_{e27}} \cdot \dfrac{Y_{R8}}{Y_{e28}}}{1-(L_1+L_2)} = \tag{1}$$
$$= \frac{K_1 \cdot p + K_2}{K_3 \cdot p + K_4},$$

here K1, K2, K3, K4 – coefficients determined by RLC-parameters of scheme of the operation circuit of DZT-21.

$$\frac{d\left(u_{OpCir}(t) \cdot K_3 - K_1 \cdot u_{TAV1}(t)\right)}{dt} + \tag{2}$$
$$+ u_{OpCir}(t) \cdot K_4 - K_2 \cdot u_{TAV1}(t) = 0$$

TDP mathematical models development is associated with development of tools of their implementation, for example software tools. In this case such a program should have the following features:

1) Ability to use external data files, including COMTRADE-files that are used in emergency registrars and some simulators of EPS.
2) Implement the element-wise of the TFs of key functional units of TDP's scheme.
3) Visualization of signals at the inputs and outputs of the key functional units of TDP's scheme for analysis and recording.
4) Simple and intuitive user interface.
5) Ability to work in common operating systems such as Windows XP, Windows 7 and others.

These requirements define the structure and functionality of specialized program of mathematical modeling of transformer differential protection (MMTDP). This program is meant for researching TDP on the basis of the differential protection relay RNT-560/DZT-10 (Russian electromechanical TDP), DZT-21/DZT-23 (Russian electronic TDP) and digital TDP, as well as checking and setting these protections in the actual conditions of their operation. The last opportunity is realized due to the ability of downloading COMTRADE-files. For development of MMTDP one of the most advanced and widely used programming language C # (C Sharp) was used.

The structure of the developed program is shown in Figure 3. The algorithm of the program is shown in Figure 4. The program window which is shown in Figure 5 illustrates a fragment of the user interface of MMTDP for digital TDP (control forms of other TDP models look similar).

Solution of differential equations in MMTDP is done by Euler's method. The applicability of Euler's method is determined by the low (in mathematical terms) the complexity of systems of differential equations of mathematical models of TDP. Usage of this method allows minimizing of the requirements for computational resources. The nonlinearity of the magnetization of the CT's core and intermediate inverters is taken into account in the program in the following way: 1) instantaneous value of the magnetizing current is derived from the magnetomotive forces balance equation; 2) according to the relation $Z_\mu = f(i_\mu)$, calculated from B = f (H), magnetization circuit resistance is selected based on the value of the magnetizing current.

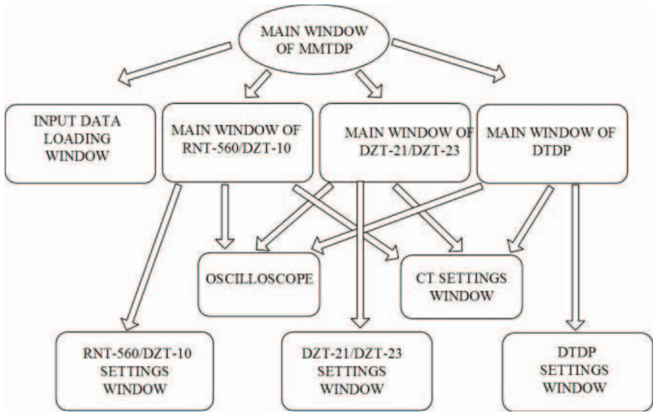

Figure 3: The structure of the MMTDP.

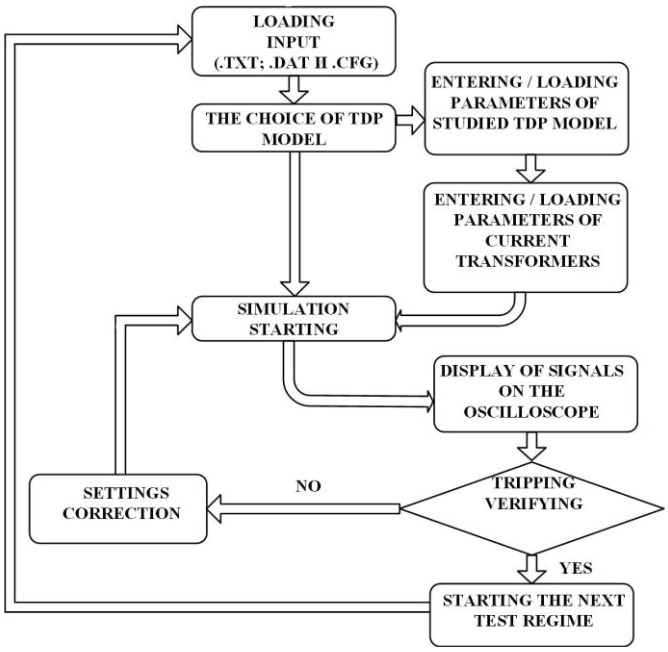

Figure 4: The algorithm of the MMTDP.

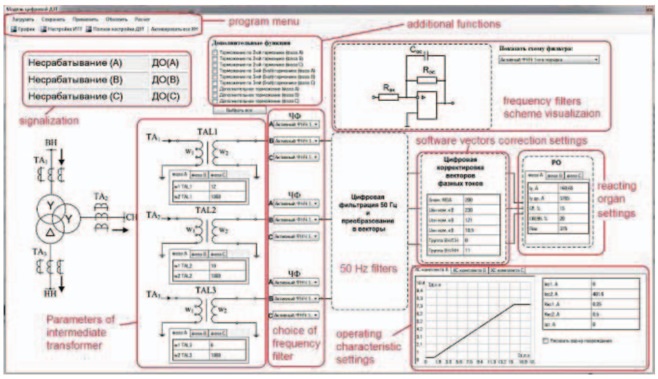

Figure 5: The program window for digital TDP model.

3 Research results

Figures 7-12 presents fragments of the test results of digital TDP's (SIEMENS SIPROTEC 7UT62) setting using MMTDP. Calculation of settings of this protection is carried out in accordance with the Russian state guidelines. Calculation of the short circuit currents done with the specialized program ARM SRZA which is widely spread among the specialists in relay protection in Russia. Checking these settings carried out using the model of Tomsk region EPS implemented in Hybrid Real-Time Power System Simulator (HRTSim) [12] - [19]. As the protected object accepted powerful autotransformer (S = 200 MVA) of the main grid substation - Zonalnaya substation (see Figure 6). The results presented below were obtained in external three-phase short circuit on the 220 kV buses of Zonalnaya substation. Studies in other regimes: for all possible three-phase, two-phase and single-phase external and internal short circuits as well as when the protected object under voltage at idle; also carried out. The volume of this article does not allow presenting the all results of these studies.

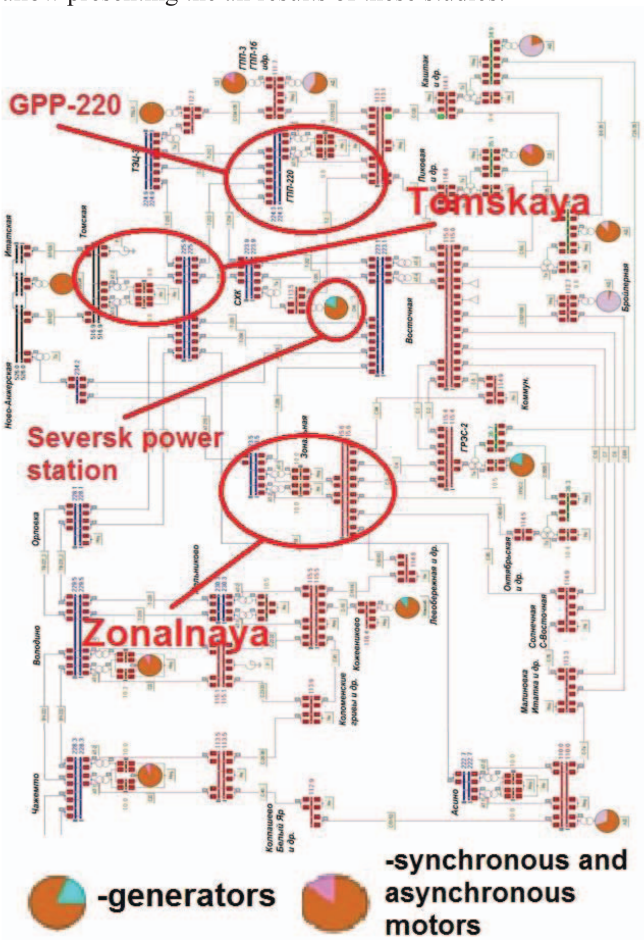

Figure 6: Model of Tomsk region power system in HRTSim.

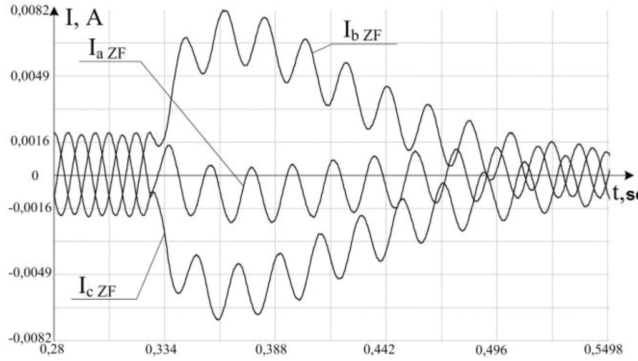

Figure 7: The oscillograms of the phase currents at the output of intermediate frequency filters ZF.

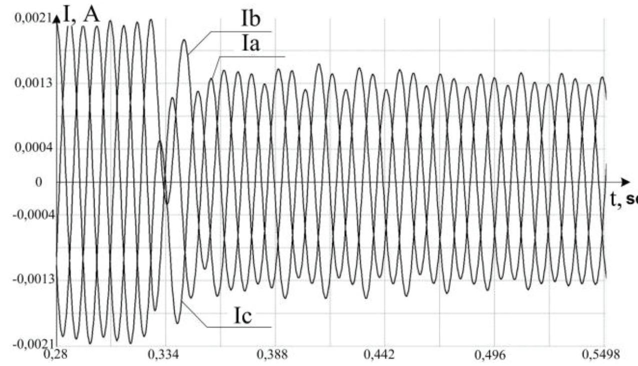

Figure 8: The oscillograms of the phase currents at the ZF filter's output after digital filtering.

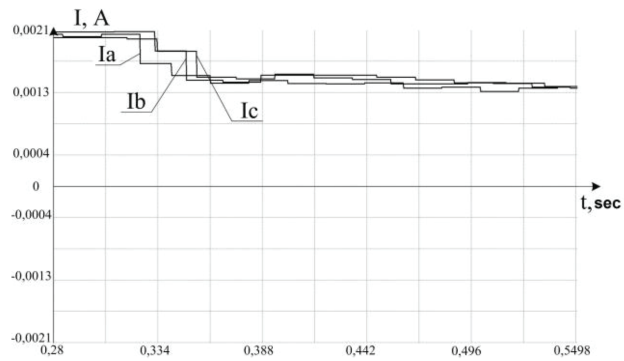

Figure 9: The magnitudes of the phase currents vectors at the ZF filter's output.

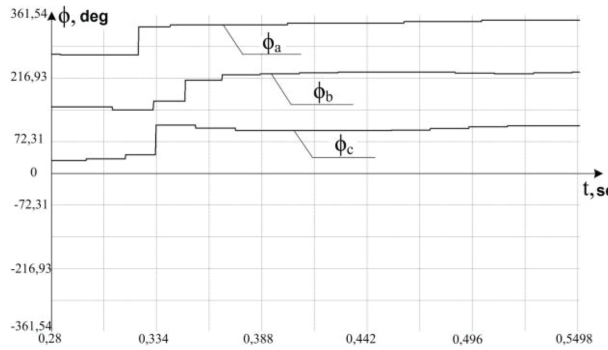

Figure 10: The phases of the phase currents vectors at the ZF filter's output.

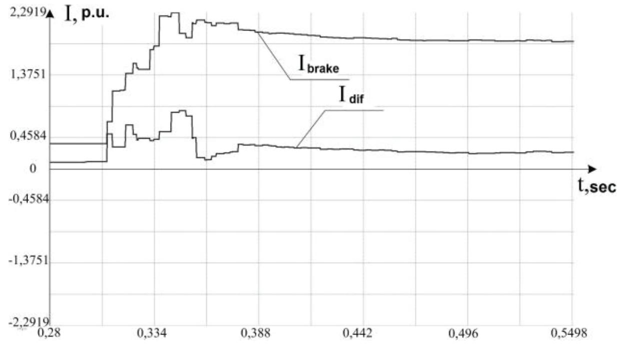

Figure 11: The magnitudes of the vectors of the differential current and brake current of the complect of the phase A.

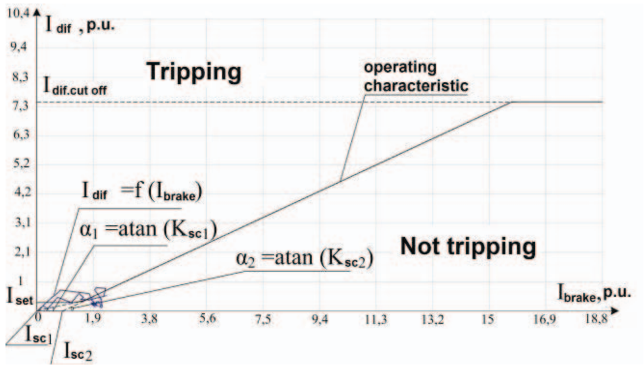

Figure 12: The operation of the reacting organ of the complect of the phase A: I_{dif} – differential current; I_{brake} – brake current; I_{set} – current setting; $I_{dif.cutoff}$ – current setting of differential cut off; K_{sc1}, K_{sc2} – coefficient of scheme; α_1, α_2 – angles of characteristic's branches; I_{sc1}, I_{sc2} – bases of characteristic's branches.

There was incorrect operation of TDP in shown regime. The main reason for this is unequal phase shift of CT installed on different sides of the protected autotransformer. Elimination of incorrect operations of TDP can be done with the following options: 1) selection of CT which provide the same phase shift; 2) implementation of the phase shift correction algorithm in TDP's software; 3) changing the settings for the operating characteristic: current setting, angles of branches. In this case the decision was made to correct the TDP's settings with the MMTDP but it is better to use combination of mentioned methods.

4 Conclusion

At present the problem of incorrect actions of TDP is not solved. The discrepancy of the TDPs settings for the actual conditions of its operation is the main reason for incorrect actions of relay protection. The discrepancy is connected with the usage of rough simplifications outlined above in the existing method of calculating TDP's settings. Existence of the problem is confirmed by the research, the results of which are very briefly presented in this paper.

The adequate mathematical models of different kinds and types of TDP are very effective optimization tools for TDP's settings correction. These models take into account the features of specific implementations and processes in CT. For practical application these models are integrated into the software tool (MMTDP) which is designed by the author of this paper.

Similar studies were carried out with a transmission lines phase-comparison protection [20].

Acknowledgements

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