Modeling Differential Protections of Power Transformers and Their Testing Using PSCAD/EMTDC Software

A. Smolarczyk, and E. Bartosiewicz

***Abstract*—**Differential protections are the main protections for large and great power transformers and against the effects of internal short circuit. They should act fast and sensitive during internal short-circuit single and multiphase, but during external short circuit, switching on the unloaded transformer and over-fluxing the differential protection function should not operate. Their proper operation should not depend on the saturation of current transformers to which they are connected. The paper describes the construction and principle of operation of power transformers' numerical differential protections against the effects of internal short circuit. On the basis of that description, in PSCAD/EMTDC software was modeled the differential protection of transformers with different: nominal powers, nominal voltages of the higher- and lower side, and vector groups. In the paper was described the selected and modeled in PSCAD/EMTDC software protection. In addition to that were described proposed and modelled in PSCAD/EMTDC software test systems for testing transformer differential protection. The proposed test systems can be used to test new transformer differential protection algorithms and the actual differential relays available on the market. Modeled transformer differential protection and test systems can also be used for educational purposes. At the end of the paper, the results of the selected action for modeled differential relay were presented.

***Keywords*—**Differential protection of power transformers, Modeling of power system relays, Power system relays, PSCAD/ EMTDC software

I. Introduction

SIMULATION software environments give the opportunities to represent the entire power systems (PS) or selected fragments thereof. They allow to analyze: switching overvoltage, the correctness of the design and operation of protection devices and automatics, failures, electrical energy quality, drive system control, FACTS system control. MATLAB/Simulink environment is often used for the study of control strategies or new protection algorithms. In this program, particular elements of the constructed part of PS (generators and control systems, transmission lines, power transformers, etc.) can be modeled independently or some ready-to-use elements available in the SimPowerSystems library (toolbox) can be used. For example, in [1] all the elements of the PS for the test systems (single-and multi-machine) has been independently modeled to check the fast generator resynchronization automatics, in [2] to verify the control strategy of braking resistors for damping of power swings, in [3] to check the control of FACTS elements to dampen power swings and in [4] - to check the control of power transmission through direct current lines (HVDC). Unfortunately, single-handedly modeling of power system components is very time-consuming and usually allows to model the elements used for mapping the phenomena of symmetric character (power swing, symmetrical faults, changes of working system load, etc.). The advantage of this type of modeling is, however, full control of the modeled system and use of the only necessary parameters for mapping the modeled phenomenon.

In case of need for mapping the asymmetric phenomena (phase-to-ground or phase-to-phase short circuits, conductor openings or cut-offs, etc.) in modeled parts of PS, more accurate models of PS components are needed. There are many simulation programs used for modeling of dynamic quickly-varying (electromagnetic) and slowly-varying (electromechanical) transients phenomena. One of them is PSCAD/EMTDC software. [5]. This program has well-equipped library of PS components and elements of both the process of the simulation and modeling elements of PS controls. It is used to map both slowly- and quickly-varying phenomena (for example to test the travelling-wave fault location algorithms [6]).

Power system relays and operation algorithms used in their protection functions must be tested according to specific procedures. Extensive split of the tests which the protection devices should be subjected to is shown in [7]. Among the tests that the relays should be subject to there are functional performance tests and scheme performance tests.

These tests are related to validation of the relay operation correctness in particular PS work conditions and for the particular fault process in PS. It can be done in such a way that the time-courses of electrical quantities just before and during

A. Smolarczyk is with the Faculty of Electrical Engineering, Warsaw University of Technology, Warsaw, Poland (corresponding author to provide phone: +48-22-2345795; fax: +48-22-2345617; e-mail: adam.smolarczyk@ien.pw.edu.pl).

E. Bartosiewicz is with the Faculty of Electrical Engineering, Warsaw University of Technology, Warsaw, Poland (e-mail: emil.bartosiewicz@gmail.com).

the disturbances can be obtained using a computer simulation of the entire PS or corresponding fragment thereof (e.g. using the PSCAD/EMTDC software). Microprocessor tester forces the recorded voltage and current time-courses by converting digital signals to analog and enhancing it to the proper level for analog inputs of tested relay. These signals are injected into the relay and its operation is observed by recording the pick-up and tripping signals. In the case of systemic performance tests the real time simulations are also used for checking the power system relays [8, 9]. Of course besides of power system relay testing the real time simulations can be used e.g. for testing control systems for protection devices [15, 16] and smart grids [17, 18].

In order to verify the operation correctness of the differential relays for power transformer protection and of the protection functions algorithms implemented therein the microprocessor testers software can be used [10]. This software usually gives an opportunity to validate the operating characteristics of the differential function by using the not-distorted sine waves of fundamental frequency. For a more sophisticated tests of differential relays and protection functions algorithms implemented therein it is the appropriate to use test-scheme models made in simulation programs and voltage/current waveforms generated during modeling distinct types of system faults.

II. Submission Structure of Numerical Differential Protection for Power Transformer

For the numerical differential protection, before a direct comparison of differential currents I_{diff} and biased/stabilized currents I_{bias} (for each phase), there must be realized a mathematical processing of the measured current signals. Algorithm for measurement and adjustment of the measured currents performed in the modern numerical differential protection (for example for Siemens devices) is shown in Fig. 1 [11]. Each module of the differential relay is in charge for a particular mathematical operation. It should be noted that all the calculations are done relative to the reference winding which for the Siemens differential relays (e.g. 7UT512 [12]) is always the first winding (*WINDING 1* in Fig. 1). This means that the elimination of the phase shift of currents is always realized on the side of second winding. (*WINDING 2* in Fig. 1).

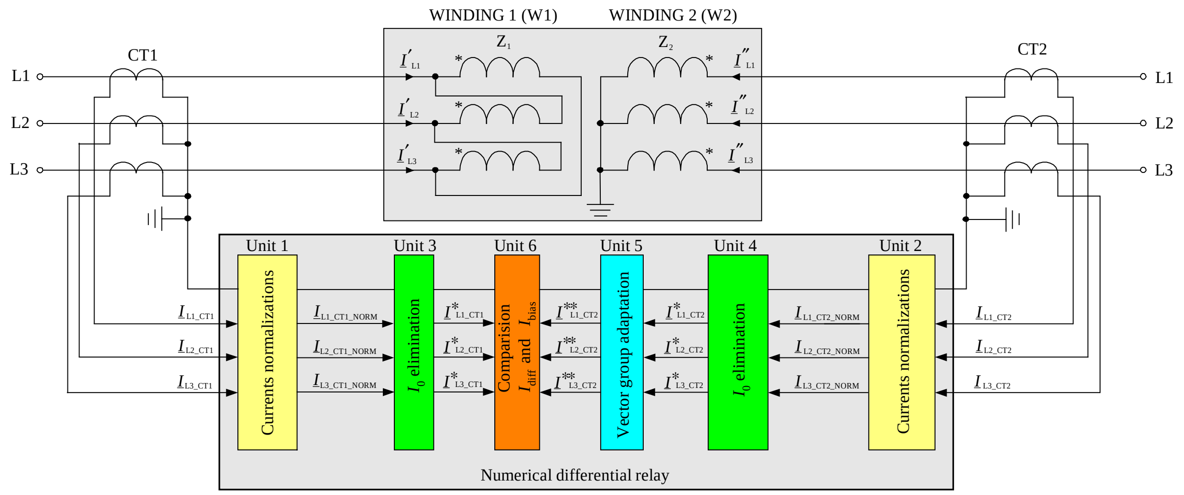

Fig. 1. The processing of current signals in differential relay; *CT1* and *CT2* – current transformers, *Unit 1 – 6* – current-processing units; *WINDING 1*, *WINDING 2* – protected transformer windings; basis on [11]

Computational algorithm used in numerical differential relay presented in Fig. 1 can be divided into the following steps [11]:

- determination of amplitude matching factors on the basis of rated currents of protected power transformer (for lower- and higher-voltage sides) and using rated currents of each current transformer primary windings (*Unit 1*, *Unit 2*);
- the adjustment of phase currents amplitude, having regard to the current ratio of current transformers and amplitude matching factors (*Unit 1*, *Unit 2*);
- elimination of zero-sequence current symmetrical component I_0 of normalized phase currents. Zero-sequence current of the phase currents is eliminated only when the protected transformer winding is wye-connected and its star point is solidly grounded (*Unit 3*, *Unit 4*);
- vector group adaptation of the *WINDING 2* phase currents to phase shift of the reference winding (*WINDING 1*) of the transformer, by using additional phase shift (elimination of phase shift basing on the transformer vector group) via programmable coefficients matrix (*Unit 5*);
- computing of differential currents I_{diff} and biased (stabilized) currents I_{bias} for each phase separately according to the relations $I_{\text{diff}} = \left|\underline{I}_{\text{I}} + \underline{I}_{\text{II}}\right|$ and $I_{\text{bias}} = \left|\underline{I}_{\text{I}}\right| + \left|\underline{I}_{\text{II}}\right|$ (formulas for Siemens relays) wherein

the L1 phase in accordance with Fig. 1 current $\underline{I}_{I} = \underline{I}^{*}_{L1\text{-}CT1}$ and current $\underline{I}_{II} = \underline{I}^{**}_{L1\text{-}CT2}$ (*Unit 6*);

- checking the position of operating point described by I_{diff} and I_{bias} currents (for each phase separately) with respect to the pick-up characteristic $I_{diff} = f(I_{bias})$ and decision (after taking into account the conditions associated with the 2nd and 5th harmonic content in the I_{diff} current) with tripping the pulse for opening a circuit breakers located on both sides of the protected transformer (*Unit 6*).

III. Modeled Schemes for Testing the Transformer Differential Protection Algorithms

In [13] thesis there are presented the descriptions of simulation systems projects containing transformers and modeled differential relays for their protection. These projects, made in the PSCAD/EMTDC software, reproduce the power transformers with different vector groups and rated powers, lines (as PI-type two-terminal-pair networks), power source and the load on lower- and higher-voltage sides. For the modeled systems there are possibilities of switches control in both a manual and automatic (by simulating differential relay) way.

In addition, depending on the transformer vector group and its rated power, there have been used proper algorithms for appropriate operation of modeled transformer differential protection in simulation projects. The signals injected to the differential relay may be brought from actual or ideal current transformers (depending on the requirements). In separate simulation projects, following test schemes have been prepared:

- a scheme of two-winding transformer (15 kV/6 kV) with Yy0 vector group - scheme 1,
- a scheme of two-winding transformer (400 kV/110 kV) with YNy0 vector group - scheme 2,
- a scheme of two-winding transformer (110 kV/15 kV) with YNd11 vector group - scheme 3,
- a scheme of autotransformer (230 kV/120 kV) - scheme 4,
- a scheme of two-winding transformer (22 kV/250 kV) with Dyn11 vector group - scheme 5,
- a scheme of two-winding transformer (22 kV/250 kV) with Dyn5 vector group, build of three single-phase units - scheme 6.

Classical approach of transformer modeling has been used in schemes 1, 2, 3 and 4. This approach allows the reproduction of windings placed on the same column, which does not take into account the interactions between the individual phases [5]. For this kind of models, three-phase two-winding transformer is equivalent to a combination of single-phase two-winding transformers. In scheme 5 there has been exploited the model of 5-limb transformer, that uses the unified magnetic equivalent circuit. Transformer model of this type as distinct from conventional transformer models, does take into consideration the transformer core geometry, the magnetic coupling between the phase windings and internal coupling of each phase winding [5]. In system 6, due to a lack of available proper model in PSCAD/EMTDC main library, the three-phase two-winding transformer with Dyn5 vector group has been built of three single-phase units. Depending on the type of modeled transformer, and thus its application, the proper feeding (one- or two-way) has been envisaged.

Fig. 2 shows the appearance of a typical primary circuit for the project of power transformer with YNd11 vector group (scheme 3). In addition to the elements shown in the figure, in the simulation project there are blocks which contain the following elements:

- elements of modeled differential relay,
- diagrams of analog signals (currents and voltages on higher- and lower-voltage sides of the transformer and signals made available in the transformer model) and binary signals (states of switches),
- elements related to the control (choice of location and type of fault, breakers control, control of saving the analog variables waveforms to COMTRADE-format files).

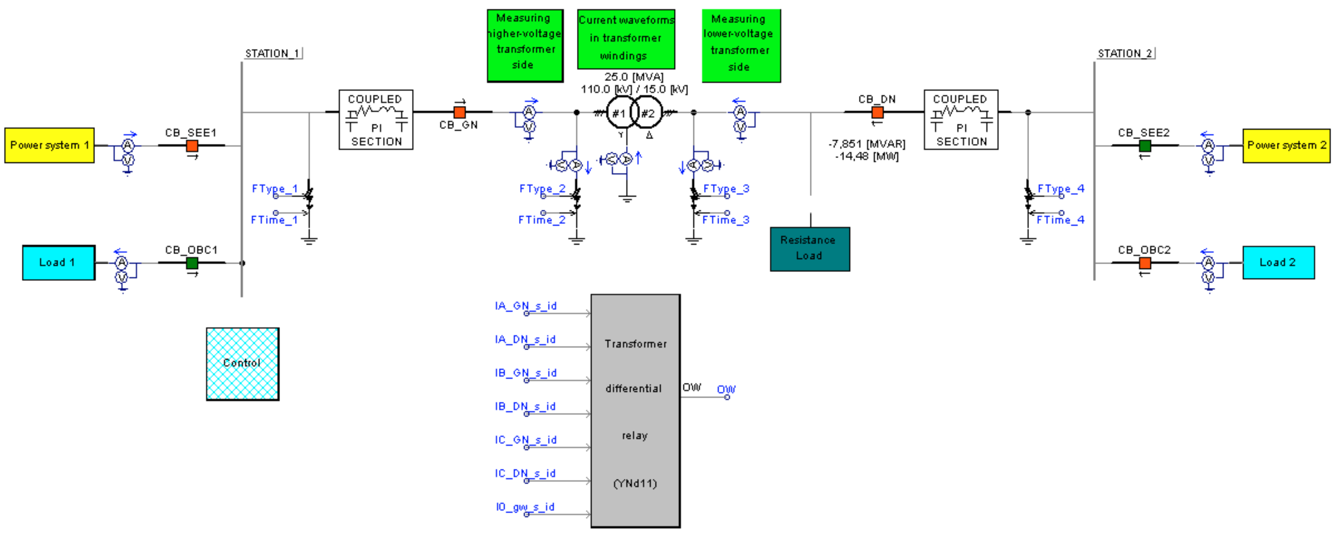

Fig. 2. Primary circuit of simulation model using the 110 kV/15 kV transformer with YNd11 vector group - scheme 3; derivate from [13]

In all the modeled systems with transformers it is possible to visualize all the courses of currents and voltages on the higher- and lower-voltage sides and in the fault point. The observed voltage and current time-courses at relaying points, on the secondary side of current and voltage transformers, can be saved as the COMTRADE format. As a result this time-courses can be retraced by microprocessor testers, and thus be used to test the real differential relays (functional performance tests [7]).

Additionally, there is a possibility in modeled systems to observe variation of differential current (I_{diff}) as a function of stabilized current (I_{bias}) for the A, B, C phases, occurring during disturbances, with respect to the beginning characteristics $I_{diff} = f(I_{bias})$ for modeled differential protections.

With the modeled test schemes can be checked (within the functional performance tests) the operation correctness of the differential protection functions in case of:

- internal and external single and multi-phase faults, with current transformers saturation absence and for various pre-load of transformer (the impact of the appearance of non-periodic current component in fault current),
- metallic and resistive internal faults,
- various level of saturation of the CTs (on one or both sides of the transformer) and various pre-load of transformer, in the case of external faults (whether there is no unnecessary pick-up of differential function),
- external single-phase faults on the transformer side of a grounded star-point (whether there is no unnecessary pick-up of differential function, and thus the differential function correctly eliminates the zero-sequence component of the current),
- switching on (energizing) the unloaded transformer (whether there is no unnecessary pick-up of differential function during the inrush of magnetizing current and appearance of a high content of 2nd harmonic in differential current),
- transformer over-fluxing (whether there is no unnecessary pick-up of differential function due to the large rise of supply voltage and the emergence of a high content of 5th harmonic in the differential current).

IV. A Scheme of Modeled Transformer Differential Protection

Differential relays, designed to protect the transformers from the schemes described in Sec. III of this paper, have been modeled in thesis [13]. For modeling the protection device, shown in Fig. 1 block diagram of signal processing in numerical differential protection has been used. In addition to the stabilized differential function, the non-stabilized differential function has been modeled as operating in case of exceeding the high value of differential current (e.g. $10I_n$).

The protection modeling process has been focused on the protection operation logic, not on digital signal processing in order to computing the 1st, 2nd and 5th harmonics of phase currents. For the calculation of particular harmonics of phase currents (phasors), the *On-Line Frequency Scanner* module (from PSCAD/EMTDC *Master Library*, [5]) has been used. The description of direct calculation method for measurement signals (current phasors), without using the *On-Line Frequency Scanner* module, may be found in [14].

Fig. 2 shows the location of differential relay model in the simulation project. Example of implementation in PSCAD/EMTDC software of the modelled relay (for scheme 3, Fig. 2) is shown in Fig. 3. This implementation includes signal processing shown in Fig. 1.

To build a simulation model of differential relay, there were used ready-to-use modules from PSCAD/ EMTDC *Master Library* such as:

- logic gates, timers, summing/difference junctions, multipliers, dividers,
- module which can determine the harmonic magnitude and phase of the input signal as a function of time (*On-Line Frequency Scanner*),
- modules from the *Relays* (*Dual Slope Current Differential Relay*, *Over current detection block*).

Algorithms of elements for elimination of the zero-sequence current and for vector group adaptation, was written using a programming language Fortran.

The modeled relay consists of (Fig. 3):

– the amplitude adjustment of the lower- (LV) and higher-voltage (HV) power transformer side (*blocks no 1*),
– systems to eliminate zero-sequence current symmetrical component on the higher-voltage transformer side (grounded transformer windings connected in star): mathematically or using current from the transformer star point (*blocks no 2*),
– adaptation to vector group made on the lower-voltage transformer side (*block no 3*),
– transformation of instantaneous current values (the upper- and lower-voltage transformer sides) to a phasor (amplitude and phase separation) for harmonic 1st, 2nd and 5th (*blocks no 4, 5*),
– calculation of the differential currents (I_{diff}) and stabilized currents (I_{bias}) for the 1st harmonic currents of phases A, B, C, and checking the performance criteria for each phase, i.e., whether the point of the calculated currents I_{diff} and I_{bias} are above the operating characteristics $I_{diff} = f(I_{bias})$ of the relay (*blocks no 6*),
– calculation of the differential currents (I_{diff}) for 2nd and 5th harmonic currents of phases A, B, C, and checking the performance criteria for each phase, i.e. whether the differential currents calculated 2nd and 5th harmonic with respect to the corresponding differential currents 1st harmonic exceeds the set threshold (*blocks no 7–10*),
– checking whether the current differential 1st harmonics for each phase exceeds the set threshold, i.e. checking the performance criteria of non-stabilized differential relay function (*blocks no 11*),
– checking the performance criteria of the stabilized differential function for at least one of the three phases (calculated differential 1st harmonic currents are in the

area of operation for stabilized characteristics of relay, the content of the 2nd and 5th harmonic does not exceed the threshold values), and the verification of the performance criteria for the non-stabilized differential at least one of the three phases and sending an impulse to open breakers signal (signal *OW*) on the higher- and lower-voltage transformer side (*block no 12*).

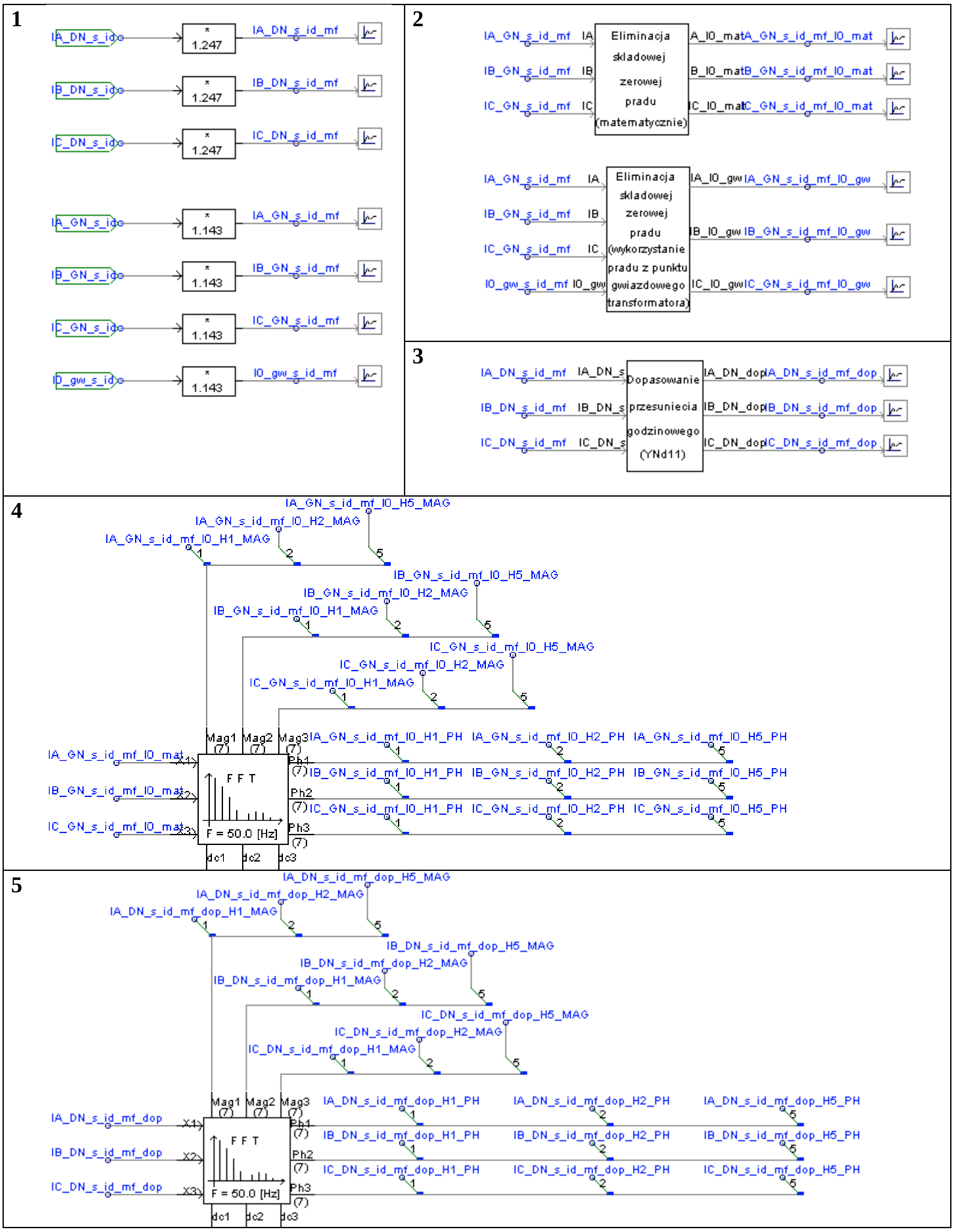

Fig. 3a. Implementation in PSCAD/EMTDC software the modelled relay for protecting the 110 kV/15 kV transformer with YNd11 vector group - scheme 3 (Part 1)

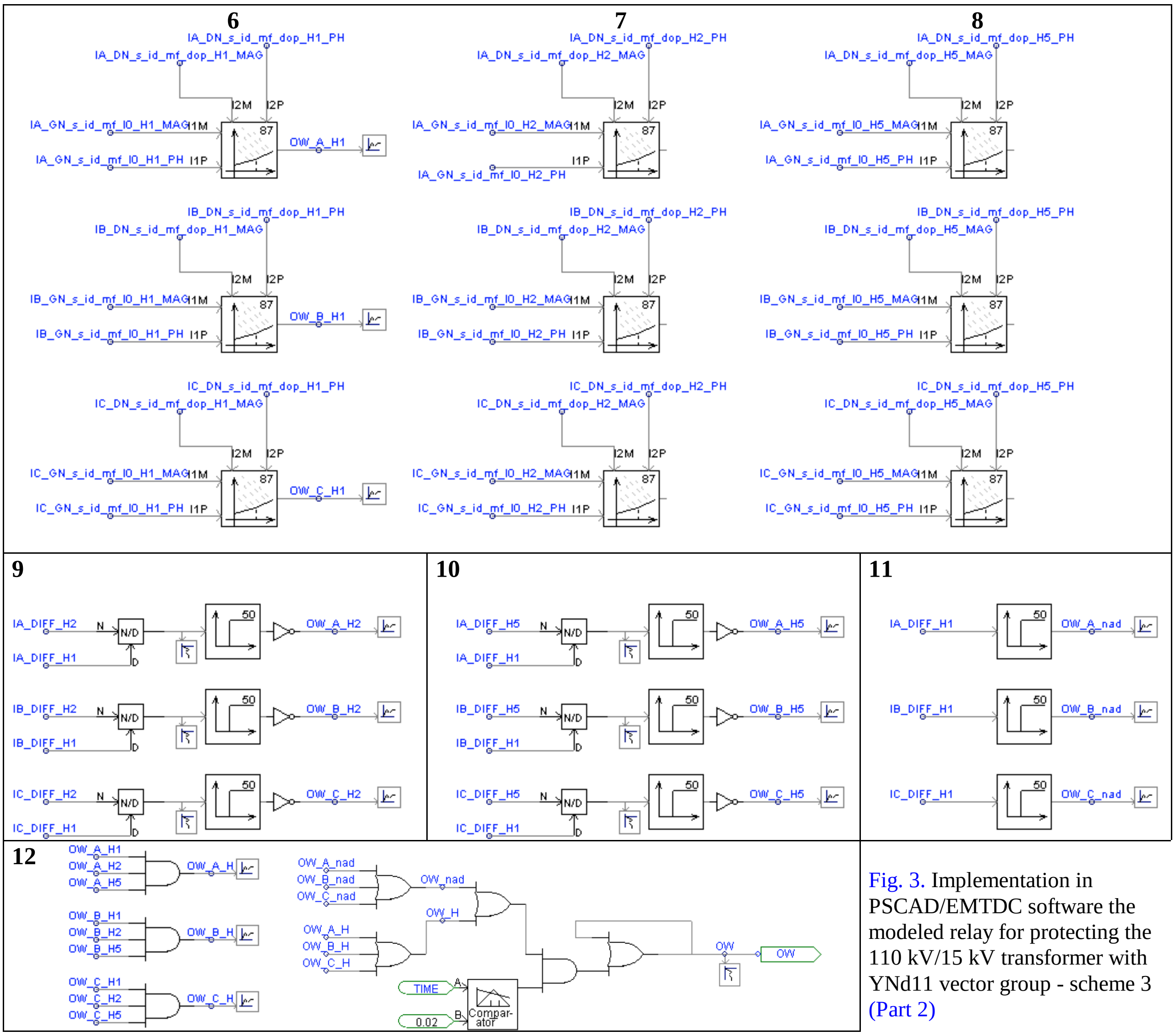

Fig. 3. Implementation in PSCAD/EMTDC software the modeled relay for protecting the 110 kV/15 kV transformer with YNd11 vector group - scheme 3 (Part 2)

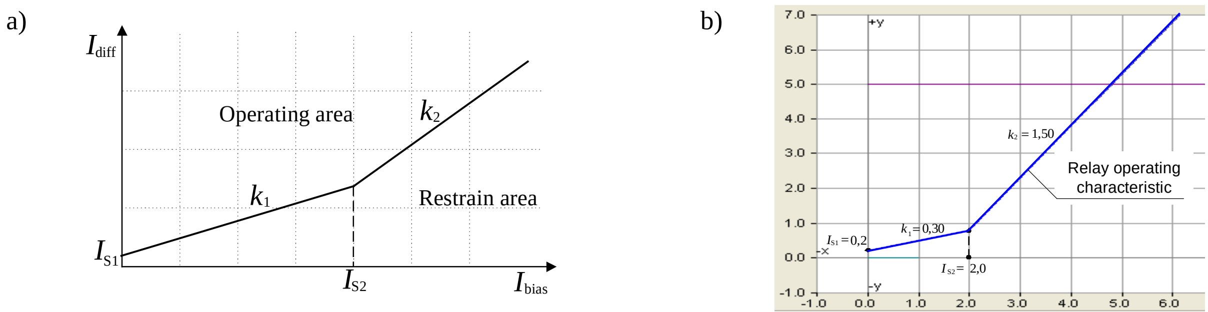

Fig. 4. Stabilized characteristic of modeled relay: a) implemented by using the *Dual Slope Current Differential Relay* module, b) characteristic reproduction in the PSCAD/EMTDC software for typical settings; I_{S1} – beginning value of differential current; I_{S2} – inflection-point value of biased current; k_1 – slope factor of first segment; k_2 – slope factor of second segment

Fig. 4a shows the operation (stabilized) characteristics $I_{diff} = f(I_{bias})$ of modeled relay, implemented by using the *Dual Slope Current Differential Relay* module from PSCAD/EMTDC *Master Library*, and in Fig. 4b its representation in the PSCAD/EMTDC software for typical settings is shown.

Formulas for differential current I_{diff} and stabilized current I_{bias} (separately for each phase), used in *Dual Slope Current Differential Relay* module and in modeled relay, have the following form:

$$I_{diff} = \left| \underline{I}_{I} + \underline{I}_{II} \right| \tag{1}$$

$$I_{bias} = \left(\left| \underline{I}_{I} \right| + \left| \underline{I}_{II} \right| \right) / 2 \tag{2}$$

where: $\underline{I}_{I}$, $\underline{I}_{II}$ – transformed phase (A, B, C) currents for the transformer sides of higher- and lower-voltage.

V. Example Results of Functional Performance Tests for Modeled Differential Protection

A. Short Circuit, B-C Metallic Type (Internal on HV Transformer Side) - scheme 3

This section presents selected results of disturbance simulations for modeled test schemes. The research, described in greater detail in [13], have been aimed to monitor and analyze the signals that occur during chosen disturbances related to transformers and to verify the operation of modeled transformer differential protection.

The scheme simulation project is illustrated in Fig. 2. In the figure are shown the default breakers states: closed breakers *CB_SEE1*, *CB_GN*, *CB_DN* and *CB_OBC2* (marked with red squares) and opened breakers *CB_OBC1* and *CB_SEE2* (marked with green squares) - what is equivalent to one-way supply of transformer on its higher-voltage side and applying the load on its lower-voltage side.

Metallic B-C fault has been simulated (internal, on the higher-voltage transformer side). Waveforms of differential (*I_DIFF_H1*) and stabilized currents (*I_BIAS_H1*) for the A, B, C phases of fundamental frequency, including waveforms of the tripping signals (*OW_A_H1*, *OW_B_H1* and *OW_C_H1*) modeled relay, are shown in Fig. 5. During the two-phase B-C fault, differential currents of these phases (*IB_DIFF_H1*, *IC_DIFF_H1*) are very similar (47.46 A) and nearly twice as high as biased currents (*IB_BIAS_H1*, *IC_BIAS_H1*), which amount to 24.16 A and 23.77 A. Differential current value for phase A (*IA_DIFF_H1*) is close to zero.

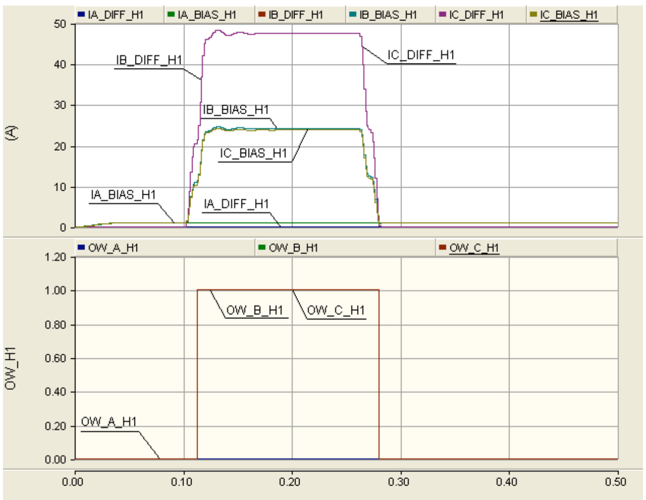

Fig. 5. Waveforms of differential and stabilized currents of fundamental frequency (for each phase) and binary tripping signals of modeled relay for internal metallic B-C fault on the higher-voltage side of transformer

Fig. 6 illustrates the relay operating characteristic of modeled differential relay and differential current as a function of biased current (for each phase separately). It shows exceeding of the relay operating characteristic by the working points, computed basing on differential and biased (stabilized) currents of faulted phases (B, C), which causes pick-up of modeled differential relay and sending the tripping signals (*OW_C_H1* and *OW_B_H1*), shown in Fig. 5. The amount of differential current in phase A does not reach the boot value (Fig. 6), so the tripping signal for this phase (*OW_A_H1*) is set to zero (Fig. 5). So operation of the modeled differential protection is consistent with the expectations.

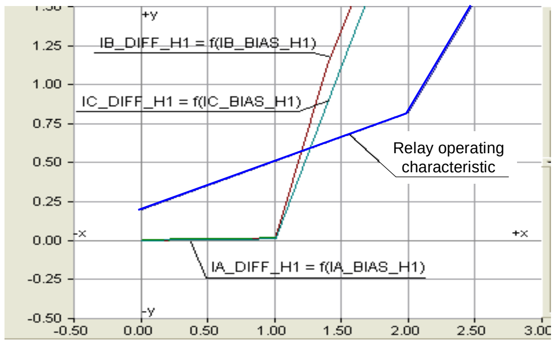

Fig. 6. Relay operating characteristic and calculated currents of modeled relay for internal metallic B-C fault on the higher-voltage side of transformer

B. Impact of Stroke Magnetizing Current During Switching On The Unloaded Power Transformer - scheme 2

In order to analyze switching on the unloaded power transformer, the possibility of saturation of the core should be activated in the settings. The test should be performed on an unloaded transformer (*CB_SEE2*, *CB_OBC1*, *CB_OBC2* and *CB_DN* breakers in the open position – Fig. 2). *CB_SEE1* breaker should be left in the closed position. At the start of the simulation *CB_GN* breaker should be left open. Switching the transformer on has followed by closing this breaker after time 0.1 s from the beginning of the simulation. In addition, before switching the transformer on, primary circuit is connected (on HV transformer side) to element named *Resistance Load* (Fig. 2). Connecting to very high load resistance allows to avoid numerical instabilities PSCAD/EMTDC software during the simulation run. The threshold value (blocking action for differential function) of the presence of 2nd harmonic component in differential current is set to 15% (0.15 pu) in modeled relay.

a)

b)

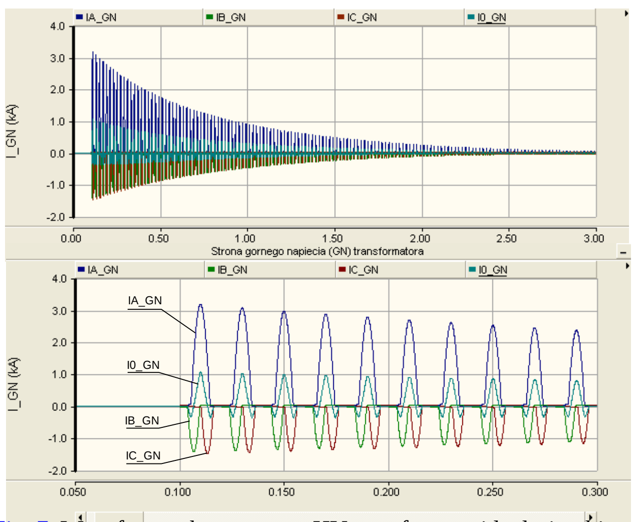

Fig. 7. Waveforms phase current HV transformer side during his switching on: a) the entire waveform, b) the initial periods of the waveform

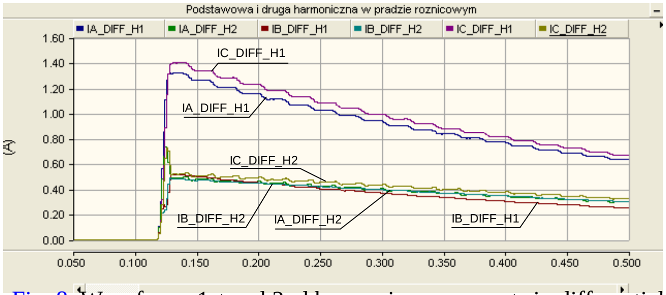

Fig. 8. Waveforms 1st and 2nd harmonic components in differential currents (phase A,B,C) during switching on the unloaded transformer

a)

b)

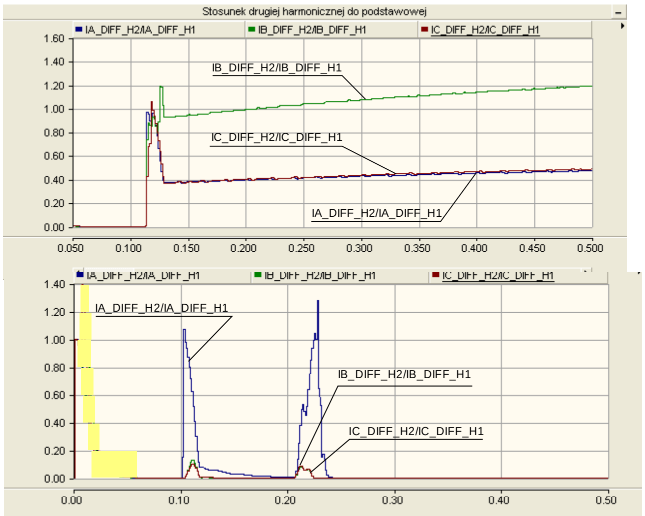

Fig. 9. The ratio 2nd harmonic differential current to 1st harmonic when: a) switching on unloaded transformer, b) an internal short circuit A-G type on HV transformer side

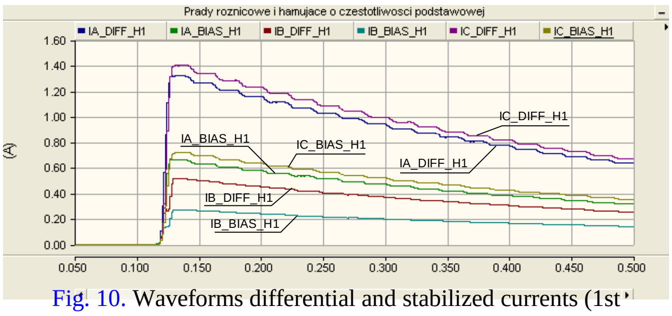

Fig. 10. Waveforms differential and stabilized currents (1st harmonic) during of the switching on the unloaded transformer

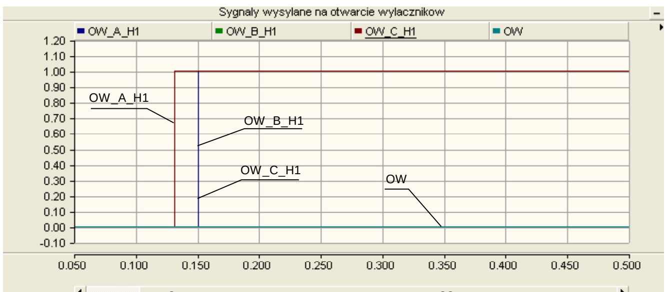

Fig. 11. Waveforms the tripping signals differential (stabilized) function (for each phase separately) during switching on the unloaded transformer, *OW* - the main relay tripping signal

Fig. 7 shows the waveforms of the phase currents on the HV (400 kV) transformer side, which are shown in Fig. 7a for the entire simulation, as in Fig. 7b - only for the first 0.4 s. Switching the unloaded transformer on was performed after time of 0.1 s from the start point of the simulation. While the switching transformer on, the significant increase of the currents values is seen, especially in the phases A and C. Determination of the waveforms occurred after about 3 s. On the diagrams are not shown the currents of the LV transformer side, because of no current flows in the absence of load.

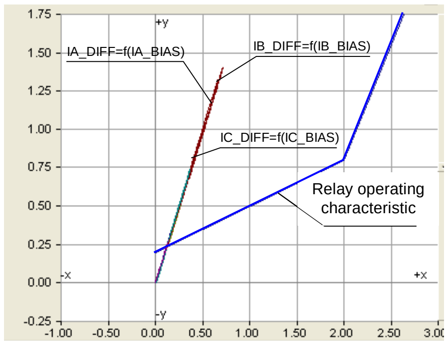

Fig. 12. Relay operating characteristic and calculated currents of modeled relay for the switching on the unloaded transformer

The recorded waveforms 1st (fundamental) and 2nd harmonic components of the differential currents were shown in Fig. 8, while in Fig. 9a – the ratio 2nd harmonic differential current in relation to 1st harmonic when switching on unloaded transformer. In Fig. 9b is shown for comparison purposes waveforms for the short circuit A-G type on HV transformer side. There are two brief moments (Fig. 9b), in which there are increases in the ratio of 2nd harmonic component to the 1st (fundamental) harmonic, which are related to: (a) the start, and (b) the end of the short circuit. However, at the time of switching transformer on (0.1 s from the start of the simulation), Fig. 9a shows a clear increase in the ratio of the 2nd harmonic to 1st. It is visible in all three phases.

Fig. 10 shows the waveforms of differential currents and stabilized currents (per phase) with a frequency of 1st (fundamental) harmonic. They show that the differential currents are larger than the corresponding stabilized currents. If the differential (stabilized) function is not blocked in the analyzed case it comes to unwanted operation of the differential relay. Evidence of this change is status of output trip signals (*OW_A_H1*, *OW_B_H1* and *OW_C_H1*) coming from all phases (with leading logical zeros to logical ones) when switching the unloaded transformer on - as shown in Fig. 11. This is also evident transition the currents through the operation characteristics of the modeled relay. Fig. 12 shows the transition of the current waveforms operating characteristics, which may correspond to unwanted tripping of modeled differential relay.

Application (in modeled relay) of simple criterion detection of the stroke transformer magnetizing current (during switching transformer on), based on the exceeding specific content 2nd harmonic component in differential current (blocks no 9 in Fig. 3), can prevent unwanted activation of the differential relay. The lack of response course of the main tripping signal (*OW* signal) demonstrates the correct operation of the modeled relay (Fig. 11).

VI. SUMMARY

The PSCAD/EMTDC software can be successfully used to modeling the disturbances in schemes with transformers and differential relays protecting transformer from effects of this disturbances occurrence. There can be created the simulation projects of schemes with power transformers, which allow to analyze various types of disturbances that may occur in this schemes, such as internal and external faults, switching on the unloaded transformers, voltage spikes on the transformer terminals, faults with current transformer saturation, etc.

A lot of tests have been made for modeled test schemes. Example results of the tests, described in the article, have shown the usefulness of PSCAD/EMTDC for verifying the operation correctness of differential protections for power transformers. It is important that the calculations are in this program performed in the time domain. Thanks to this, instantaneous values of phase voltages and currents may be injected into the modeled protection device.

Modeled in the thesis [13] test schemes can be used for testing the protection algorithms of real protection devices (thanks to the possibility of saving the waveforms of analog and binary signal to COMTRADE files) and for designing the new differential protection solutions.

Also modeled in the thesis [13] differential relays, for protecting power transformers of different rated powers and different vector groups, and example tests results of its operating have proved that PSCAD/EMTDC can also be used for testing new protection function algorithms and verifying operating correctness of the existing algorithms (e.g. for educational or training purposes).

REFERENCES

[1] J.Machowski, A.Smolarczyk, J.Bialek, Coordinated fast valving and excitation control as an effective method to enhance transient stability after severe faults, *CIGRE Symposium „Working Plant and Systems Harder"*, London, 7-9 June 1999.
[2] J.Machowski, A.Smolarczyk, J.W.Bialek, Damping of power swings by control of braking resistors, *International Journal of Electrical Power & Energy Systems* 23 (2001), pp.539-548.
[3] S.Robak, Selection of the structure, type and parameters of robust FACTS-based stabilizer. *Electrical Review*, ISSN 0033-2097, Vol. 85, Issue: 8, 2009, pp. 76-79.
[4] Ł.Nogal, Enhancing Stability of a Weakly Connected AC Power System By Supplementary Control of Embedded HVDC Lines, *Internatio-nal Conference on Environment and Electrical Engineering*, Wroclaw, Poland, 5 - 8 May 2013, pp. 79-86, IEEE Conference Record #21360, IEEE Catalog Number: CFP1351I-CDR.
[5] Manitoba HVDC Research Centre, PSCAD v.4.2.1 Online Help.
[6] K.Glik, D.Rasolomampionona, Laboratory Test Results of Travelling Wave Fault Location Scheme", *PowerTech*, Grenoble France, 16-20 June 2013.
[7] CIGRE: *Analysis and guidelines for testing numerical protection schemes*, CIGRE Report No 159, Working Group 34.10, August 2000.
[8] RTDS Technologies Inc., Real Time Digital Simulators, Available on-line: www.rtds.com.
[9] A.Smolarczyk, A modern laboratory test bench for protection relays testing in real-time phenomena, (in Polish), *Electrical Review*, Vol.: 88, Issue: 3A, pp. 142-147, Publ.: 2012.
[10] OMICRON electronics: Test Universe Software, Available on-line (2013): www.omicron.at.
[11] G.Ziegler, *Numerical Differential Protection, Principles and Applications*, Publicis Corporate Publishing, Erlangen 2005.
[12] Siemens, *Numerical Differential Protection Relay 7UT51 v3.0*, Instruction manual Order No C53000-G1176-C99-6.
[13] K.Pyrzak, Application of PSCAD/ETMDC software for modeling of transformers and differential protective relays, The MSc thesis, (in Polish), Warsaw 2011.
[14] M.Sztykiel, C.L. Bak, Line Differential Protection Scheme Modelling for Underground 420 kV Cable Systems, EMTDC/PSCAD Relays Modeling, OMICRON electronics, *International Protection Testing Symposium (IPTS)*, Brand 2011.
[15] R.Kowalik, M.Januszewski, K.Gontarz, D.Rasolomampionona, E.Bartosiewicz, Conventional Solutions in Remote Control of Power System Protection, *17th WSEAS International Conference on Systems (part of CSCC '13), WSEAS/NAUN International Conferences*, Rhodes Island, Greece, July 16-19, 2013, pp 155 – 160.
[16] R.Kowalik, M.Januszewski, K.Gontarz, D.Rasolomampionona, E.Bartosiewicz, Tests of Remote Control Systems for Modern Protection Devices, *17th WSEAS International Conference on Systems (part of CSCC '13), WSEAS/NAUN International Conferences*, Rhodes Island, Greece, July 16-19, 2013, pp 161 – 167.
[17] M.Zahran, „Smart Grid Technology, Vision, Management and Control", *WSEAS TRANSACTIONS on SYSTEMS*, Issue 1, Volume 12, January 2013, pp. 11-21.
[18] Jang Moonjong, B.N.Ha, S.W.Lee, D.Y.Seo, „The Study on The Construction of The Smart Grid Test Plant and The Integration of The Heterogeneous Systems", *WSEAS TRANSACTIONS on POWER SYSTEMS*, Issue 2, Volume 8, April 2013, pp 95-101.

Adam Smolarczyk was born in Poland in 1970. A graduate of Warsaw University of Technology. In December 1999 he started working at the University's Institute of Electrical Power Engineering. He is currently an assistant professor at the Faculty of Electrical Engineering, Warsaw University of Technology.
He is an author and co-author of research reports on digital power relays. His research interests are related to the digital power protection automatics and the modeling of phenomena occurring in power systems.

Emil Bartosiewicz. Graduate of Warsaw University of Technology (2012). He is a PhD student. His professional interests concern the power system protection and control equipment.