Fyodor ROMANYUK [1], Ivan NOVASH [1], Mikhail LOMAN [1], Paweł WĘGIEREK [2], Marek SZROT [3]

Belarusian National Technical University, Minsk, Belarus (1), Lublin University of Technology, Lublin, Polska (2), Power Engineering Research Centre Ltd., Piekary Śląskie, Polska (3)

Validation of mathematical model of differential protection

Abstract. *Comparison of results of mathematical modeling and field tests of a transformer differential protection is presented in this paper. An inrush current mode, external two-phase and three-phase faults are considered. Proposed mathematical model can be used to test differential protection in different modes of transformer operation.*

Streszczenie. *W artykule przedstawiono porównanie wyników badań i rezultatów modelowania matematycznego zabezpieczeń różnicowych transformatorów. Rozpatrzono przypadki prądów rozruchowych oraz zwarć dwufazowych i trójfazowych. Zaproponowany model matematyczny może być używany do testowania zabezpieczeń różnicowych w różnych trybach pracy transformatorów. (**Walidacja modelu matematycznego zabezpieczenia różnicowego**).*

Keywords: relay protection, transformer differential protection, mathematical model, field experiment.
Słowa kluczowe: przekaźnik, zabezpieczenie różnicowe transformatora, model matematyczny, pole doświadczalne.

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Introduction

Differential stage is one of the main protections of power transformers. Problems of a choice of analog and digital filters, a type of operating characteristic, offsetting algorithms from inrush current, from overexcitation of the transformer core, from external faults accompanied with current transformers (CT) saturation have to be solved during the development of a transformer differential protection [1]. An important step of differential protection device development is a complex testing of protection algorithms in a wide range of transformer operation conditions.

Testing methods include:

- laboratory tests with some special test equipment (for example, Omicron CMC 356 or RETOM-61), which generates currents corresponding to different operation modes of power transformer. It is possible to check operation characteristic and the second and fifth harmonics restrain in laboratory. Also using test equipment allows checking differential protection operation with inrush current and faults recordings which were obtained on real objects. But such tests include only some of the possible modes of power transformer operation.
- field experiments in a power network: switching on no-load transformer and external faults. Field tests can provide only some possible modes of the power transformer operation because of the risk to damage expensive equipment.
- mathematical modeling of transformer operation modes and differential protection. Mathematical model has to include a model of power transformer, CTs, differential protection, provide the normal operation mode, short-circuits at various points inside and outside of protected area. Mathematical model has to meet the requirements of reliability and adequacy to a real object. In this case, mathematical model provides possibility to study the differential protection operation in all required extent of possible modes.

The paper represents the validation of the mathematical model of transformer differential protection. The validation is based on a comparison of the field experiment results with the mathematical modeling results.

Field experiment

Field tests of the transformer differential protection terminal MR801 (produced in Belarus) were carried out at 110 kV substation of the Belarusian power network [2]. A reducing transformer 110/10 kV 6.3 MVA was used for MR801 field tests. Before tests the transformer had been protected by the electromechanical differential relay DZT-11 (ДЗТ-11). According to a test program terminal MR801 was connected with DZT-11 current circuits in series. The purposes of the test were to check protection operation in different real conditions: during the inrush current process and switching on to different types of external faults (including CT saturation).

The experiments below have been carried out to achieve these goals:

- switching on no-load transformer;
- switching on the transformer by 10 kV circuit breaker to two-phase external fault on 10 kV side;
- switching on the transformer by 10 kV circuit breaker to three-phase external fault on 10 kV side;
- switching on the transformer by 110 kV circuit breaker to two-phase external fault on 10 kV side.
- The field tests results showed that both relay protection devices:
- were blocked reliably during inrush current process and external faults;
- did not trip when saturation of the CTs occurred which were installed on 10 kV side of the power transformer.

During the field tests oscillograms were recorded. Oscillograms includes waveforms of currents of high and low transformer's sides, signals of differential protection's measurement units, signals of the second and fifth harmonics blocking.

The mathematical model of the input signals for the differential protection

The mathematical model of the input signals for transformer differential protection is based on integrated mathematical model of a power object which includes a power transformer with its power supply, loads and CTs. Protection's input signals are generated for all types of faults on the transformer's bushings and external faults, transformer's switching-on modes and switching-of external faults modes. The mathematical model takes into account a fault resistance.

The mathematical model is based on a system of differential and algebraic equations which describe transient processes in electrical circuits of the power object.

The differential equations are solved by Runge-Kutta second-order method. In the second step linear extrapolation is performed to calculate the values of right-hand sides. Non-linear system of the algebraic equations is solved at each step by the iterative method with providing the necessary convergence by Wegstein formula.

The mathematical model of the differential protection

The mathematical model of the differential protection considers:

- the model of the analog second-order filters with 1 kHz cut-off frequency;
- the model of the digital filter of orthogonal components (first, second and fifth harmonics of current) based on Goertzel algorithm [3];
- an amplitude and a phase currents compensation;
- an operation characteristic;
- inrush current restrain based on the second harmonic evaluation;
- transformer's overexcitation restrain based on the fifth harmonic evaluation;
- external faults detection algorithm.

RMS-value of currents is calculated in 10-millisecond cycle on the basis of 20 samples with 1kHz sampling rate. The model implements the functions of the differential stages with and without (cut-off) restraining.

Analysis of a two-phase fault experiment

The field experiment and mathematical model oscillograms of the external two-phase fault are shown in Figs. 1 and 2, correspondingly.

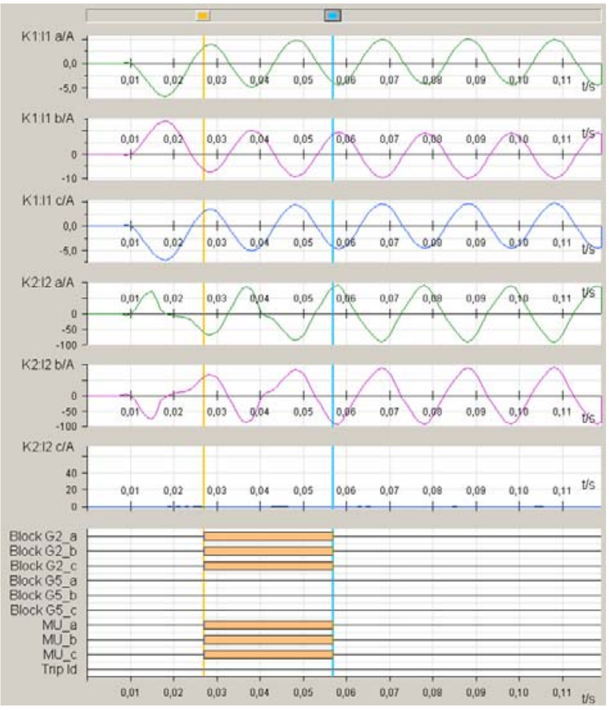

Fig.1. Oscillograms of external two-phase fault (field experiment)

The oscillograms present secondary CT currents in three phases of 110 kV (I1) and 10 kV sides (I2) of the transformer, signals of second harmonic blocking Block G2 in three phases, signals of fifth harmonic blocking Block G5 in three phases and signals of differential protection's measurement units MU in three phases. A combined signal of the differential protection tripping Trip I_d is shown on the field experiment oscillograms. The signal Trip I_d includes tripping signals of the three phases of the differential stage with restraining and differential cut-off. The calculated oscillograms present the tripping signals of the differential stage with restraining Trip $I_d >$ in three phases, the trip signals of the differential cut-off Trip Id>> in three phases. Additionally signals EXT of external faults detection are shown on the mathematical model oscillograms (external faults detection algorithm had not been implemented in the device MR801 at the time of the field experiments).

Aperiodic component of the current leads to CT saturation at the fault initial period which results to differential protection measuring units MU activation. Trip action is blocked by the second harmonic Block G2 in three phases. Additionally the external fault detector EXT operates in the mathematical model.

Signal MU_b of the mathematical model is reset earlier than in the field test which can be connected with an error of modeling.

The error of the mathematical model are caused by:

- errors of the mathematical description of the object;
- errors of the differential equations solution;
- inaccuracy of the object parameters defining (parameters of power supply system, transformer, CTs, initial fault phase, values of the residual magnetic flux in the power transformer's core and in CTs' cores).

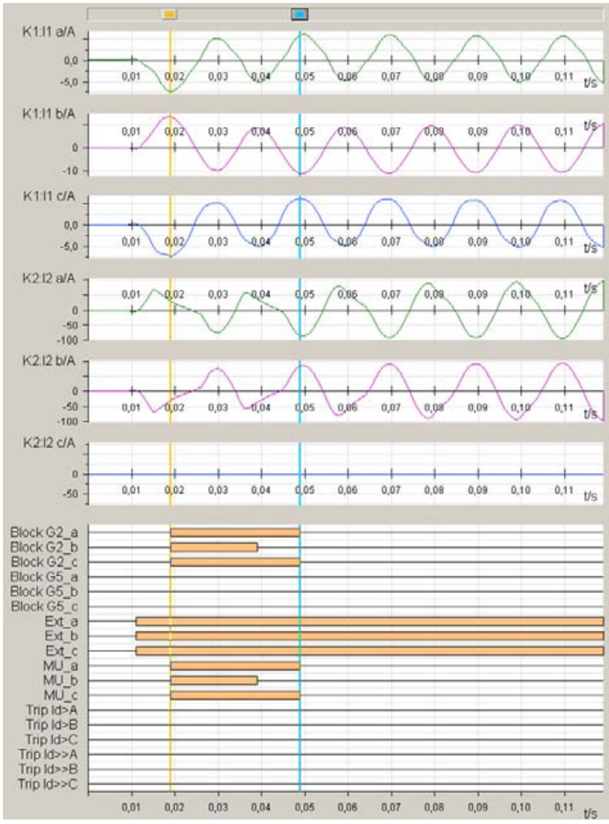

Fig.2. Oscillograms of external two-phase fault (mathematical model)

The current waveform at the fault initial period is caused by the action of the aperiodic component which leads to CT saturation. The current waveform at the initial period of the fault differs between the mathematical model and field experiment oscillograms. When the saturation point is reached, the current on the field experiment oscillograms approaches zero faster than the current on the mathematical model oscillograms. As seen from the oscillograms (Fig.1, Fig.2) this error does not affect the modeling results significantly.

Analysis of a three-phase fault experiment

The field experiment and mathematical model oscillograms of the external three-phase fault are shown in Figs. 3 and 4, correspondingly.

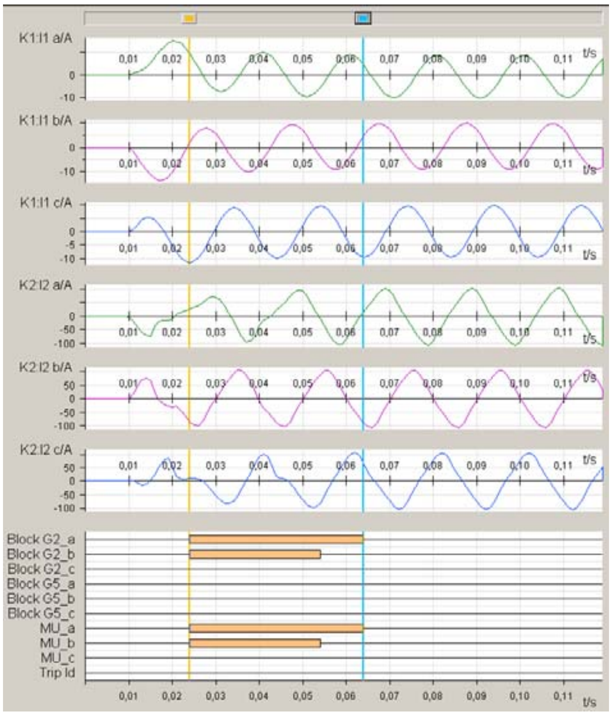

Fig.3. Oscillograms of external three-phase fault (field experiment)

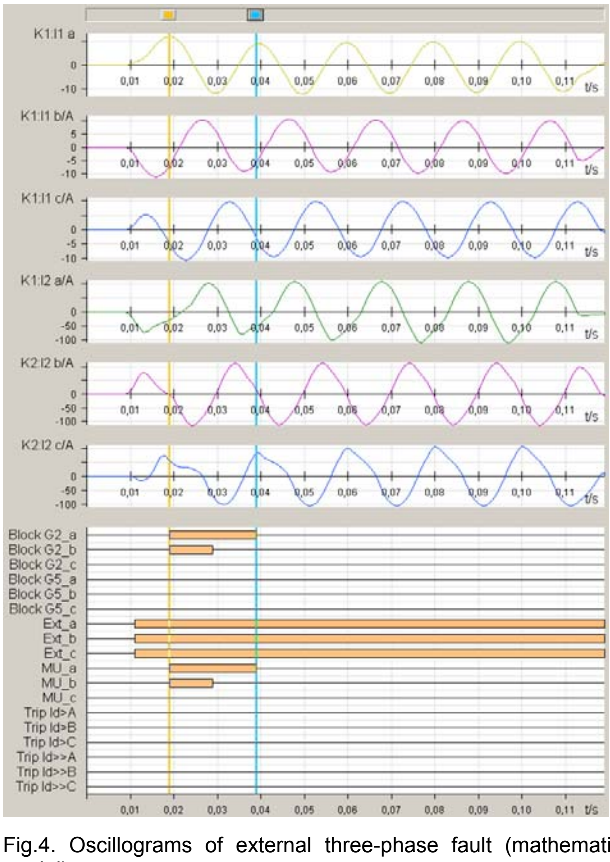

Fig.4. Oscillograms of external three-phase fault (mathematical model)

Aperiodic component of the current leads to CT saturation in three phases at the fault initial period. Differential protection measuring units MU operate in A and B phases. The current waveform in the C phase is less distorted and the measuring unit MU_c does not operate due to restrain characteristic. The trip actions in A and B phases is blocked by the second harmonic Block G2. Additionally the external fault detector EXT operates in the mathematical model.

The error of modeling of two- and three-phase faults is less than 10% RMS-values of CT secondary currents in the steady-state mode.

In both experiments the mathematical model has shown results similar to results of the field experiments: activation of the measuring unit MU and the second harmonic blocking Block G2 at the same phases as obtained in the field experiments.

Analysis of switching on no-load transformer experiment

The field experiment and mathematical model oscillograms of switching on no-load transformer are shown in Figs. 5 and 6, correspondingly.

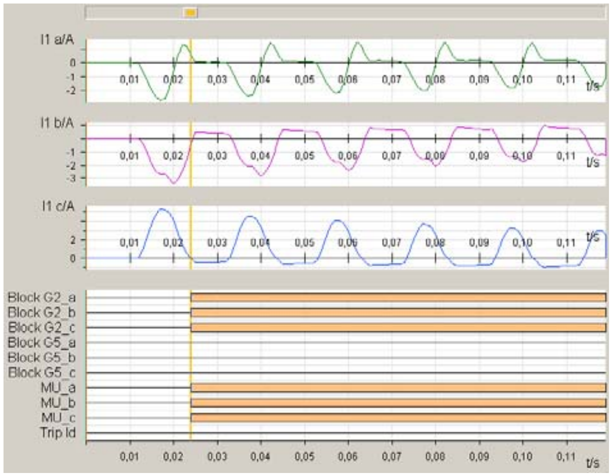

Fig.5. Oscillograms of switching on no-load transformer (field experiment)

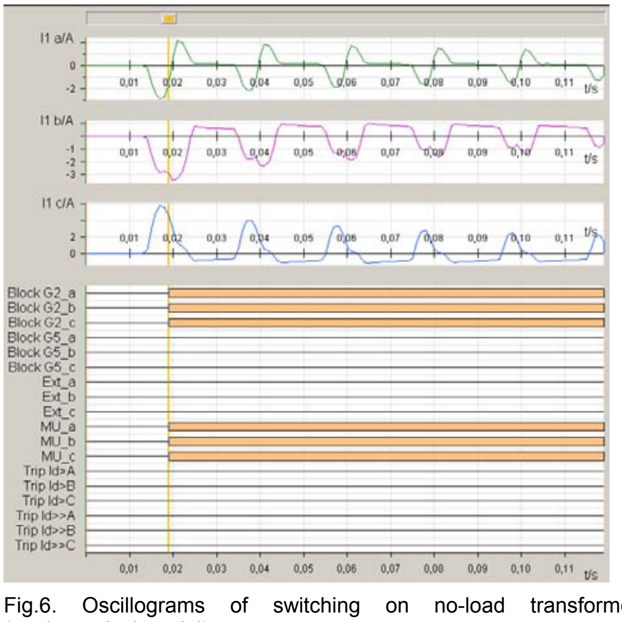

Fig.6. Oscillograms of switching on no-load transformer (mathematical model)

The current in phase A has a periodic character, the currents in the phases B and C have an aperiodic character (see Fig.5, Fig.6). In both cases the differential protection detects the second harmonic component higher than 14% within 20 ms after appearance of the current. The second harmonic blocking resets the tripping action. The mathematical model does not form a sign of external fault

EXT. The results of operation of the differential protection's logic obtained by the mathematical model are identical to the field experiment results.

The largest inrush current during the field experiment was registered in C phase, an instantaneous value reached 158 A of primary current or 5.27 A of secondary current (or 360% of the rated current of the power transformer). The largest inrush current in the mathematical model was registered in C phase, the instantaneous value reached 172 A of primary current or 5.76 A of secondary current. Thus the error of current signal modeling is less than 10%.

Conclusions

The comparison of results of the mathematical modeling results and field tests of the transformer differential protection is presented in this paper.

The proposed mathematical model has less than 10% error in current level determination and has identical results of protection logic's operation to the field experiment results.

The external faults detection algorithm (which is implemented in the mathematical model) shows the proper results for external faults (presence of blocking) and inrush current process (absence of blocking).

The proposed mathematical model can be used to test differential protection operation in a wide spectrum of modes including modes which can not be realized in the field experiments because of the risk to damage expensive equipment.

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Authors:
Prof. Fyodor Romanyuk, Doc. Ivan Novash, Eng. Mikhail Loman, Belarusian National Technical University, Nezavisimosti av. 65, 220013 Minsk, Belarus, E-mail: faromanuk@bntu.by, ef@bntu.by, mihail.loman@gmail.com;
Dr. Paweł Węgierek, Lublin University of Technology, 20-618 Lublin, 38A Nadbystrzycka Str., Poland, E-mail: p.wegierek@pollub.pl;
Dr. Marek Szrot, Power Engineering Research Centre Ltd., 41-949 Piekary Śląskie, 9 Lotników Str., Poland.