A POWER TRANSFORMER MODEL FOR INVESTIGATION OF PROTECTION SCHEMES

Bogdan Kasztenny Eugeniusz Rosołowski · Murari Mohan Saha Birger Hillström

The Technical University of Wrocław
Wyb. Wyspianskiego 27
50-370 Wrocław, POLAND

ABB Relays
S-72171 Västeras, SWEDEN

Abstract **- A three-phase transformer model for the calculation of electromagnetic transients for the purpose of developing, setting and testing of transformer protection has been presented. The model enables to simulate turn-to-turn, inter-winding as well as earth internal faults. The main features of the model include: (a) representation of both saturation and hysteresis loop of a transformer core, (b) feasibility for inputting a residual flux, (c) representation of main CTs, (d) representation of relay input circuits with relay CTs and anti-aliasing analog filters. The model is expressed as an appropriate configuration of standard EMTP components, what enables to incorporate it into a more complex power system model. For validation of the model, the main characteristics, properties and relations between the signals have been checked against those reported in the literature.**

Key words: power transformer model,
ATP-EMTP,
transformer differential protection

I. INTRODUCTION

Proper design and setting of a differential relay for power transformers are recognized as challenging problems for protection engineers. In the case of a power transformer, detection of a differential current does not provide a clear distinction between internal faults and other conditions. Biased differential characteristic combined with 2nd and 5th harmonic restraints constitute a classical approach to the problem. Searching for better relay sensitivity, selectivity and speed of operation, initial designs conceptually similar to the conventional technique have shifted to new recognition methods both in the domain of signal estimation and decision making. Recently introduced approaches utilize advanced recognition and decision making techniques including artificial neural networks [1] and fuzzy set theory [2].

The more sophisticated a protection algorithm is, the more information is required for its proper designing, setting and testing.

In the case of a power transformer, the most important cases to be studied include [2]:

(a) transformer energizing (both switching a unit on and clearing a near external fault),

(b) stationary over-excitation of a transformer core due to short-term steady-state overvoltage and/or frequency reduction,

(c) internal faults including turn-to-turn and inter-winding short-circuits,

(d) external faults combined with transformer and CTs ratios mismatch and/or on-load tap changer operation and/or CTs saturation.

Because field recordings of transformers abnormal conditions, especially for internal fault patterns, are seldom available, the information needed for protection investigation practically may be achieved by means of digital simulation.

The main streams in the computer modelling for analysis and design of transformers can be classified as based on [3]:

(i) self and mutual inductances,

(ii) leakage inductances,

(iii) the principle of duality,

(iv) measurements,

(v) electro-magnetic fields.

Unfortunately, most of the models primarily have been developed as global models: they give only a terminal equivalent of a transformer. However, in order to simulate disturbances such as internal faults, one needs a model with inner nodes in its windings rather than proper representation of eddy currents losses or imitation of a transformer frequency response.

Taking into account the main circumstances affecting the operation of a transformer differential relay (a)-(d), we precise the requirements for the complete model of a transformer itself and its secondary measuring deviceas follows:

(1) representation of core saturation and feasibility for inputting a residual flux by employing a simplified hysteresis loop of a transformer iron core,

(2) proper winding connections and structure of a magnetic circuit,

(3) saturation of CTs, but not necessarily their hysteresis loop and residual magnetism,

(4) representation of relay input circuits including input transformers and anti-aliasing analog filters,

(5) frequency range of analyzed signals up to few kHz.

In addition, bearing in mind the application field for the model, we seek for:

(6) numerical simplicity (large number of cases to be run is anticipated),

(7) feasibility for including the model into a standard electro-magnetic transient program so that the model

can be easily combined with models of other elements in power system.

In this paper, ATP-EMTP [4,8] has been chosen as a simulation tool for implementation of the transformer model.

The following sections of the paper address: the structure of the developed transformer model (Sec.II), simulation results and validation of the model done by analyzing and confirming the most relevant phenomena in a transformer operation (Sec.III), model of a simple digital differential relay implemented in MODELS and simulated interactively with the protected element (Sec.IV).

II. THE TRANSFORMER MODEL

In this study the transformer model is combined from standard elements of the EMTP package.

A. Single-phase model of a transformer

The transformer model available in EMTP can represent a multi-phase multi-winding transformer composed from single-phase elements of the same structure. Excitation losses are modelled by resistance branches, while saturation effect is simulated by non-linear inductance branch (*Pseudo-Nonlinear Reactor*: PNR [4]) both included in primary winding. Unfortunately, in such a model there is no opening to take into account a residual flux.

In order to by-pass this constraint, instead of PNR (which can represent the main current-flux characteristic only) the *Pseudo-Nonlinear Hysteresis Inductor* (PNHI [4]) was used in model [5]. As input data pairs of magnetizing current - core flux for the lower branch of the hysteresis loop as well as the residual flux are provided [4]. Bearing in mind the application domain for the model, the very detailed hysteresis representations [6,7] have been ignored in this study.

With reference to Fig.1, an internal inter-turn fault in a single-phase transformer is simulated by dividing the secondary winding proportionally to the amount of turns to be involved in a short circuit and closing an appropriate switch (or switches).

In the figure, the secondary winding has been subdivided into three sections, what enables to locate a short-circuited part of the winding in any place along it.

Certainly, the earth faults (the winding-to-core faults) are also modelled by means of this scheme.

It is also worth to remember that changing places between HV and LV sides of a transformer is allowed, what enables to place the non-linear branch PNHI representing both saturation and hysteresis at the secondary winding, sub-divide the primary one, and thus, investigate faults in it.

B. Three-phase model of a transformer

The model of a three-phase transformer is developed as an appropriate connection of single-phase models.

With reference to Fig.2 illustrating this approach, it is assumed that inter-turn faults in the phase L1 on the Y-side of the three-phase Yd connected transformer are to be modelled. For simplicity of the figure, the winding L1 on Y-side of the unit is sub-divided between two sections only and the fault resistances are not shown at all.

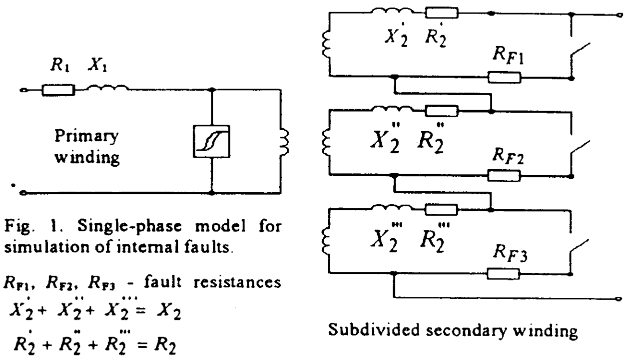

Fig. 1. Single-phase model for simulation of internal faults.

R_{F1}, R_{F2}, R_{F3} - fault resistances

$X'_2 + X''_2 + X'''_2 = X_2$

$R'_2 + R''_2 + R'''_2 = R_2$

It is to be remembered that the structure of all phases in a standard EMTP transformer model has to be the same [4]. Therefore, it becomes necessary to divide the windings of the remained phases L2 and L3 in the same manner. They are treated as healthy by avoiding switching operations within them. In addition, the internal terminals created in this way, are used for inter-winding fault simulations.

The alternative way to develop the three-phase model is to use three single-phase transformers, with one phase represented by a three or more winding unit as shown in Fig.2.

Regardless the approach used, one must realize the limitations of such a model: the magnetic structure of a transformer core is not taken into consideration. Moreover, the elements of the equivalent circuits are represented by lumped parameters. Nevertheless, the above simplifications are allowed owing to the assumption that the magnetic flux for all three transformer phases is autonomous and zero- and positive-sequence impedances of a transformer equal. This postulate, however, is acceptable in the case of five-leg core-type transformers and those built using three separate single-phase units. If one of the transformer sides is Δ -connected, also other structure of the core can be efficiently simulated, extending the application field of the developed model.

For the application presented in this paper it seems quite difficult to predict reliably the residual flux after switching-off a transformer [8], the residual flux in the

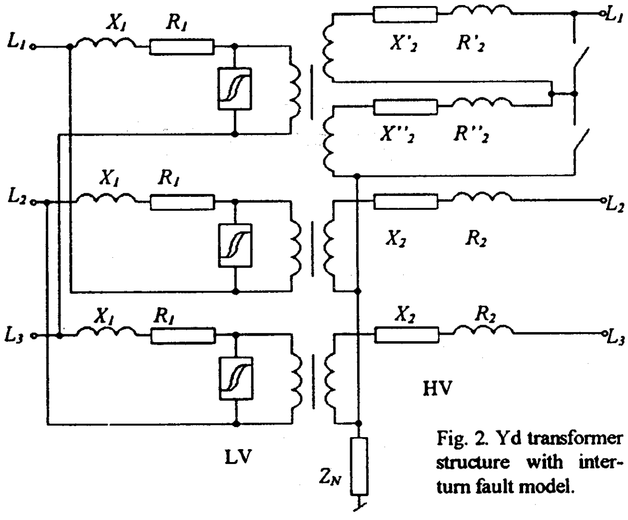

Fig. 2. Yd transformer structure with inter-turn fault model.

model is provided as an input data and during the simulation (for consecutive cases) it is treated as a more or less random factor. In addition, this initial flux must be somehow distributed between the phases of a transformer. In this study, the flux phasors in the separate phases are assumed to be symmetrical during switching-off a unit and so are the residual fluxes during switching-on.

The expected differences between positive-sequence and zero-sequence impedances are recommended to be modelled by appropriate value of a grounding impedance switched between ground and the neutral point of a transformer [8].

In spite of the above limitations, the model can be successfully applied for transient studies related to protection testing for the majority of power transformers.

C. CTs modelling

The CTs performance during short-circuit conditions is very important with regard to protective devices in power system, especially when a differential scheme is considered: if one out of few CTs connected so that they generate a differential signal, gets saturated, this signal increases dramatically even though an external fault is observed. In the case of a power transformer, the CTs may get saturated during both internal and external faults as well as during inrush conditions. When saturated, the CTs increase the amount of higher harmonics in their secondary currents, what may lead to missing or delayed operation of a relay. Thus, as the most important part of a measurement chain, the CTs ought to be carefully simulated when analyzing transient behaviour of a transformer differential relay [9,10].

In general, one may require the CT model to represent both core saturation and hysteresis loop and even its residual magnetism [9]. In this paper, however, the CTs are represented by single-phase saturable transformers without hysteresis and residual flux. This representation delivers the most important phenomena expected to be caused by the CTs and at the same time, it may be easily implemented using EMTP single-phase transformer model with PNR for saturation effect.

D. Modelling of relay input circuits

Relay auxiliary CTs are represented in the same way the main CTs are. For severe short-circuits, the protection CT may operate in its non-linear range, thus its saturation branch should be taken into account.

An analog low-pass anti-aliasing filter is the second element in the relay measurement chain most affecting processed signals. The cut-off frequency of the filter depends on the sampling rate, and for power transformer digital protection it is usually set at few hundred Hz. Second order approximation is usually recommended for the transfer function of the filter. As far as EMTP is considered as a simulation tool, the filter may be simulated as [4]:

(a) a transfer function block either in TACS or MODELS,

(b) a RLC four-port in electrical network itself.

The later approach, for which a steady state solution is provided, is used in this paper.

III. VALIDATION OF THE TRANSFORMER MODEL

The developed transformer model is considered to be verified if it is capable of delivering the most important phenomena affecting the operation of transformer protection: both in qualitative and quantitative aspects. The model has been extensively tested under variety of operating conditions; in this section some results and characteristics are presented.

A. Parameters

The transformer has been simulated as located in a simple power system shown in Fig.3.

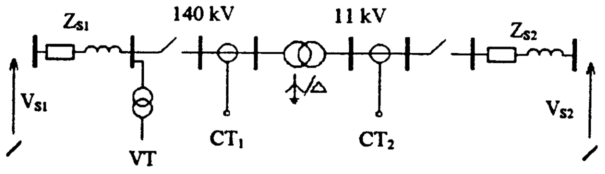

Fig.3. One-line diagram of the simulated power system.

Transformer data:
- power rating: 5.86MVA
- rated voltage: 140/10.52kV,
- rated current: 24.17/321.6A
- short-circuit voltage: 10%
- excitation losses: 7.3kW
- excitation current: 0.65%
- core structure: five-leg

System Data:
- $Z_{S1(0)} = Z_{S1(1)} = 1.8+j20\ \Omega$
- $Z_{S2(0)} = Z_{S2(1)} = 0.1+j1.0\ \Omega$

CTs data (main):
- CT1: 25/1A, 10VA
- CT2: 400/1A, 20VA

CTs data (auxiliary):
- turn ratio 9/815

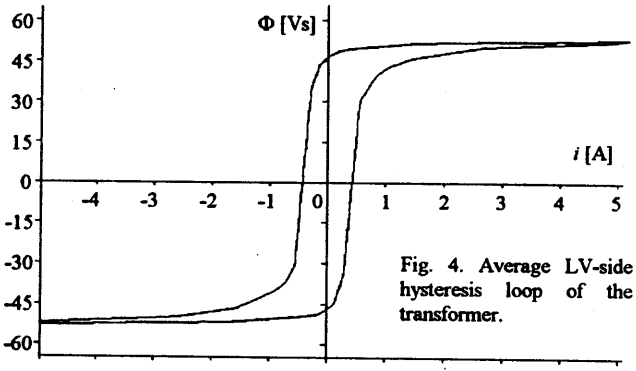

Fig. 4. Average LV-side hysteresis loop of the transformer.

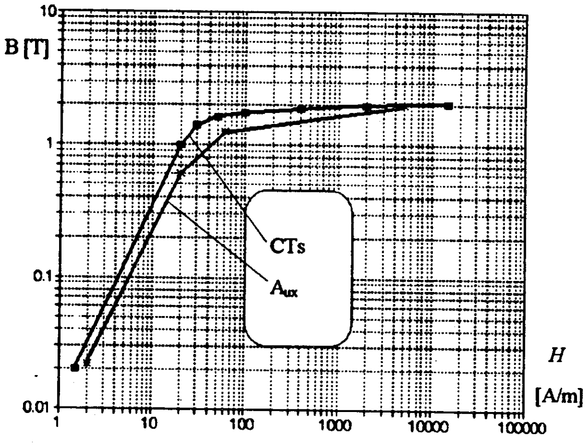

Fig. 5. Magnetizing characteristics for main and auxiliary CTs.

Figures 4 and 5 present current-flux loop of the transformer core and magnetizing characteristic for the main and auxiliary CTs, respectively.

B. Magnetizing current inrush

The inrush current violating the basic principle of the differential relaying can be caused by any abrupt change of magnetizing voltage including transformer energizing, removal of a near external fault, change of character of a fault and out-of-phase synchronization [12].

The following factors controlling the harmonic content, magnitude and damping of the inrush current have been checked and confirmed in this sub-section: (a) sign and value of the residual flux in a transformer core as well as its magnetic characteristic, (b) the source impedance, (c) the switching-on phase.

The inrush current appearing as the differential signal may reach tens of the rated value and it is higher when the inner winding is switched-on. In addition, this current is higher when the direction of the residual flux is the same as the sign of the new forced flux: the higher the residual flux is, the larger is the magnetizing current. Both magnitude and duration of the current are significant for powerful systems supplying a transformer. Moreover, the inrush current is present longer for larger transformers rather than for small units. Switching-on a transformer at zero-crossing of the terminal voltage is the worst case and generates both higher values and DC component of the magnetizing current.

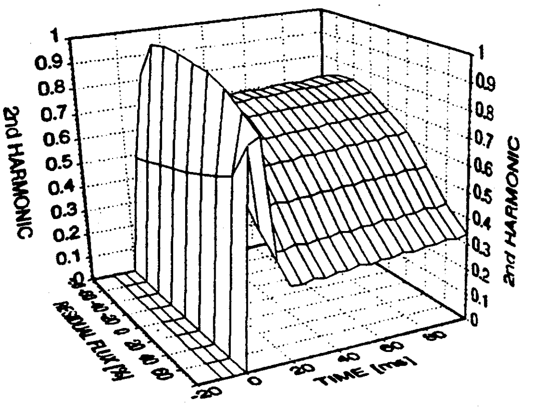

Fig. 6. 2nd harmonic in the differential current during transformer energizing from its Y-side as a function of time and residual flux (switching-on when the terminal voltage crosses zero).

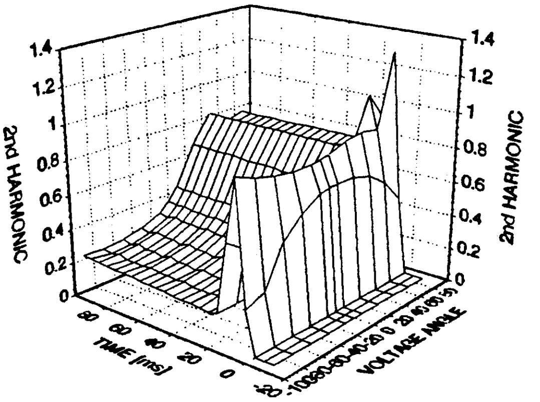

Fig. 7. 2nd harmonic in the differential current during transformer energizing from its Y-side as a function of time and voltage phase (residual flux at 75% of its maximum).

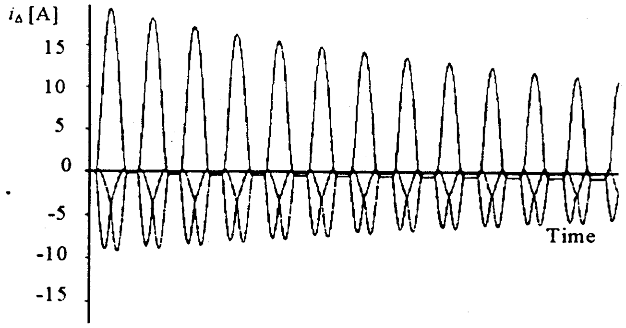

Fig. 8. Sample magnetizing inrush current pattern.

Significant 2nd harmonic is observed in the differential current (10-40%). The minimum amount of this harmonic depends mainly on the highest residual flux in the core but decreases to 12-15% for high differential currents. To illustrate this, Figures 6 and 7 show the 2nd harmonic quantum of the differential current during transformer energizing as function of residual flux in a core and voltage phase, respectively. In the figures one may see the measurement dynamics as well as steady-state dependence of the 2nd harmonic on these two most relevant random factors.

Analyzing Fig.8 presenting a sample inrush pattern, one may conclude that the model confirms also well-known direct wave-shape recognition criteria for inrush detection, for example [2]:

- in every cycle of the differential current there is an interval (lasting not less than 3.5ms) in which the current and its derivative are comparatively low; moreover, these periods are synchronized between the phases,
- the consecutive peaks of the current: (1) are of the same sign, (2) do not occur at about 7.5-10ms from each other and (3) differ from each other by less than 25%.

C. Stationary overexcitation

When the transformer voltage rises above its normal value, the excitation current increases dramatically and a transformer becomes overexcitated. The excitation current

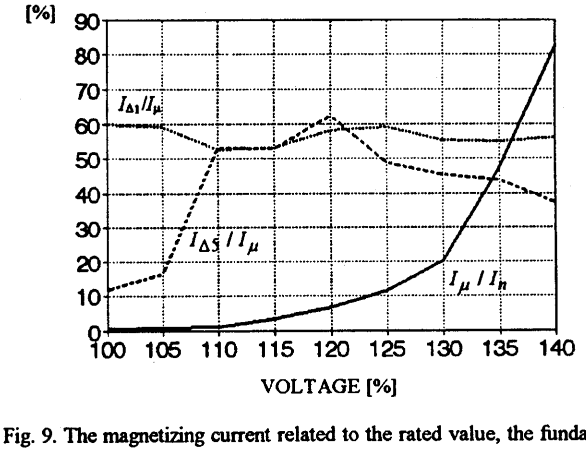

Fig. 9. The magnetizing current related to the rated value, the fundamental component of the differential current, $I_{\Delta 1}/I_\mu$ and the 5th harmonic quantum, $I_{\Delta 5}/I_{\Delta 1}$ as functions of steady-state short-term overvoltage.

which is observed by the relay as the differential signal, shows heavy quantum of odd harmonics with 5th as dominant, and consequently:

- the 5th harmonic content in the differential current is not less than 30-40%,
- the RMS value of the differential current is usually not higher than 50% of the rated quantity,
- the maximum value of the differential current does not exceed 60%, while the rectified value - 30% of the rated current.

Fig.9 presents some properties of the differential current during stationary overfluxing of a transformer core. This characteristic known from the literature validates the model presented in this paper as far as stationary overexcitation is considered.

D. Internal faults

The developed model has been also extensively tested under internal fault conditions. Here, two examples follow:

(1) Winding-to-ground faults at Y-side of a transformer. The unit is supplied from Δ-side only, while a fault is injected between ground and a certain spot in a winding located *d* [%] from the neutral point. Amplitude of the differential current as function of the fault location is presented in Fig.10. The figure confirms that the maximum value of the current observed for a fault at the transformer terminals as limited by the leakage impedance does not exceed some 10 times the rated value. On the other hand, the current amplitudes below the rated quantity are measured for short-circuits located closer than 10-20% turns from the neutral spot, what implies certain difficulties in distinguishing between such faults and external short-circuits combined with the transformer and CTs ratios mismatch.

Arranging the faulted winding (or windings) for simulating turn-to-turn as well as inter-winding short-circuits, one must remember that - approximately - both the resistance and transformation ratio depend linearly on the number of turns, while the reactance is proportional to the square of faulted turns. Of course, having certain field data such as the characteristic from Fig.10, one is able to make more detailed distribution of reactance and resistance along the winding. These distributions, however, are important when considering the application of the model for transformer designing. In the application presented in the paper they can be simplified without any doubt (a protective relay does not measure a size of a damage in any sense; instead, it should operate for all internal faults regardless the exact amount of turns involved in a short-circuit).

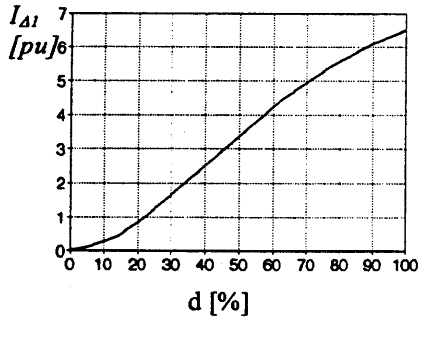

Fig.10. The differential current versus amount of short-circuited turns. Transformer supplied from Δ-side only, Y-winding short-circuited.

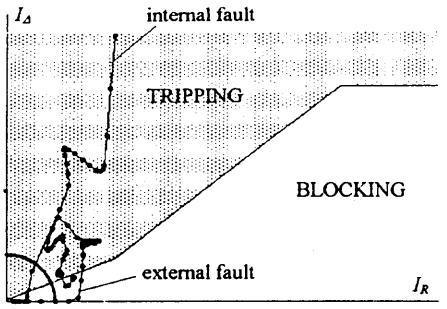

Fig. 11. Sample trajectories of internal and external faults on the $I_\Delta - I_R$ plane. Unlike the external fault trajectory, the internal fault one first enters the tripping region, then leaves the circular area.

2) Internal and external faults at the transformer terminals involving CTs saturation. CTs when deeply saturated during severe external short-circuits, upset the current balance generating significant differential signal. In this study, the dominant properties of the differential and through currents under external and internal short-circuits have been checked. CTs, regardless their further steady-state or transient saturation, transform errorless for some 3-5ms since the primary currents build-up. It means that during this period the differential current stays low, while the through current increases dramatically under external fault conditions. For internal faults, both the currents build-up almost at the same time. Consequently, the trajectories of internal and external faults on the I_Δ (differential current) - I_R (through current) plane differ from each other as shown in Fig.11, enabling to distinguish the faults in spite both of them enter the tripping zone of the relay differential characteristics.

During permanent saturation, in any fundamental frequency cycle, the CTs show - in addition - certain short periods in which they transform more or less accurately. This implies under internal fault conditions high differential current, while low through current in those time intervals (Fig.13a,b). This may be used for fault locating.

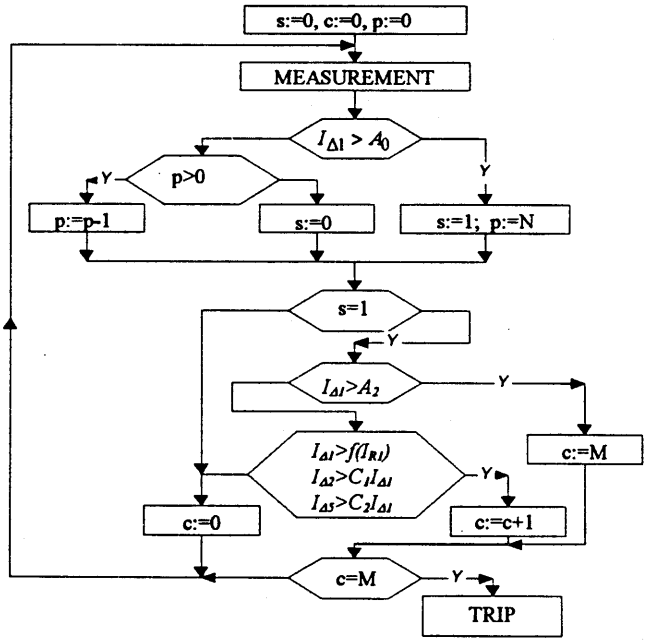

Fig. 12. Simplified flow chart of the tested digital differential relay for a power transformer (one phase only).

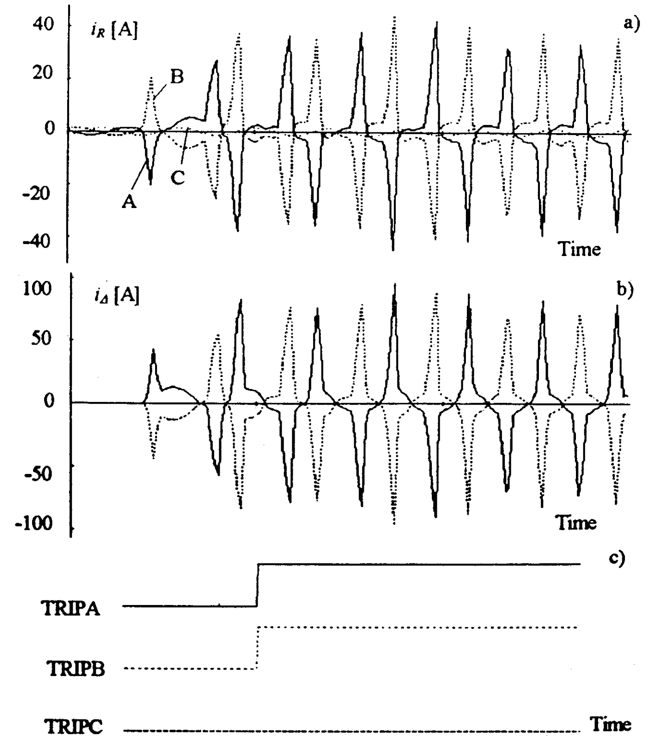

Fig. 13. Through (a) and differential (b) currents during severe internal short-circuit combined with CTs saturation. The relay response is correct (c).

IV. CLOSED-LOOP TESTING OF THE RELAY

The developed transformer model has been used as a source of testing signals for the differential relay. Second order Butterworth approximation with 600Hz cut-off frequency has been used for anti-aliasing analog filters, while the sampling rate is fixed at 1kHz. Digital measurement unit of the protection is based on full-cycle (Finite Impulse Response) orthogonal filters designed using least-squares method. Fig.12 displays the flow chart of the simulated relay, which is based on differential two-slope characteristic shown in Fig.11 and 2nd as well as 5th harmonic restraints for inrush and overexcitation, respectively. Fig.13 presents an example of relay operation showing differential (b) and through (a) currents during severe internal short-circuit as well as the tripping signals issued by the relay (c).

An advanced phase of designing a digital relay calls for testing it interactively with other protection equipment, which may generate additional transients affecting the tested relay (closed-loop testing). For this purpose, the authors recommend MODELS unit of EMTP.

V. CONCLUSIONS

A three-phase transformer model for the calculation of electromagnetic transients for the purpose of developing, setting and testing of transformer protection has been presented. The model enables to simulate turn-to-turn, inter-winding and earth internal faults and does not need any rearrangements to be capable of modelling external faults and other disturbances. The main features of the model described in the paper include:

- representation of both saturation and hysteresis loop of a transformer iron core,
- feasibility for inputting a residual flux,
- representation of main CTs in terms of their possible saturation,'
- representation of relay input circuits with relay CTs and anti-aliasing analog filters,

The model is expressed as an appropriate configuration of standard EMTP components, what qualifies to incorporate it into a more complex power system model, and thus, investigate disturbances involving other elements in such a system.

For validation of the model, every kind of transients likely to affect the operation of a transformer differential relay has been modelled (inrush currents, overexcitation, faults involving CTs saturation, etc.). During the simulations, the main characteristics, properties and relations between the signals have been checked against those reported in the literature. Delivering of appropriate relaying signals was assumed to be the primary criterion for validation of the model.

For the purpose of closed-loop testing, EMTP-MODELS could be justified to verify the relaying algorithm.

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