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Sensitive Protection of Power Transformers for Internal Inter-Turn Faults

A. Wiszniewski, W. Rebizant, *Senior Member, IEEE* and L. Schiel

***Abstract*--In the paper new sensitive algorithms for detection of internal inter-turn faults in power transformers are described. Such faults are extremely difficult to detect since they induce negligible increase of the currents at the transformer terminals, although the currents flowing at the fault place are very high and dangerous for the transformer. The algorithms developed are based on the differential equation of the equivalent circuit of the transformer. In one version additional information from a CT installed inside of the triangle of delta side windings is used, which brings very promising results. Theoretical investigations are supported and illustrated with simulation studies performed with EMTP-ATP.**

***Index Terms*--fault detection, internal faults, transformer protection, transient analysis**

I. INTRODUCTION

SINCE the time when first differential relays were applied, short-circuit protection of power transformers have faced a dilemma: how to make them capable of fast detecting all internal short-circuits, and insensitive to magnetizing currents, particularly the inrush ones. The problem exists because in case of some internal faults – for example single-turn short-circuits – the differential currents are comparatively small, often substantially lower than the rated transformer current [1]. On the other hand, during sudden jump of the terminal voltages the transformer magnetizing inrush currents may cause differential currents, which are several times greater than the rated level, and decay to that level within several seconds. Presently the standard solution is the use of the discrimination based on the ratio of the second to the first harmonic in the differential current [2, 3]. Second harmonic stabilization is a clever solution; however, there are some cases when it does not prevent maloperations, which may bring disastrous consequences.

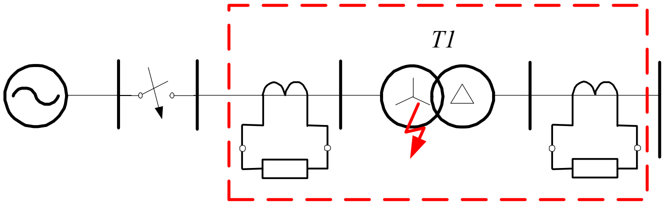

Fig. 1. Transformer energization with internal winding short-circuit.

The problem is especially significant in case of energization of a transformer which suffers an internal short-circuit (Fig. 1). In fact, the fault may be caused by the vibration of windings caused by high inrush currents. If the short-circuit involves a small number of turns – in an extreme case just one turn – the differential current is dominated by the inrush magnetizing currents, while the short circuit current makes only a small portion of the sum. Therefore high level of the second harmonic typical for an inrush may block the relay operation for several seconds. In fact if the fault lasts for more than one second, gases developed by the internal arc burning in the oil may cause an explosion of the transformer tank [4]. Therefore during energization of a transformer, sensitivity of the differential protection is the lowest, in spite of the fact that high inrush currents increase probability of the internal short-circuits.

The case mentioned demonstrates that in the protection of power transformers there is still a room for improvements. In [5] a solution based on non-linear models of power transformer is proposed. An interesting approach to internal fault detection is also presented in [6]. The Authors developed the criterion based on the fact, that during the internal short-circuit the current, which flows in the short-circuited turns, generates the magnetic flux that change terminal voltages. This idea may be developed further, eliminating weak points it has. The fundamental line of development is in the observation that the inter-turn short-circuit is always unsymmetrical, thus the zero sequence current and voltage may be used for detection of the internal faults.

The research described in this paper relates to: derivation of three new criteria signals for detection of internal winding shorts based on three-phase and zero sequence approaches (Section II) as well as their simulative testing (Section III). Final conclusions and application recommendations are proposed in Section IV.

II. NEW APPROACH TO INTERNAL FAULT DISCRIMINATION

A. Three-phase approach

The following winding arrangement of a three phase Yd transformer is assumed for analysis of internal turn-to-turn faults (Fig. 2a). Since such faults are always unsymmetrical (single-phase) events, the internal short-circuit equivalent is marked in one phase only. Additional CT inside the triangle is also installed; however, its secondary current is in general not always used for protection of the transformer.

An equivalent circuit for analysis of the inter-turn short-circuits (here in the phase A) is presented in Fig. 2b. The sym-

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W. Rebizant and A. Wiszniewski are with the Wroclaw University of Technology, Wroclaw, Poland (e-mail: waldemar.rebizant@pwr.wroc.pl, andrzej. wiszniewski@pwr.wroc.pl).

L. Schiel is with the Siemens AG, PTD EA, Berlin, Germany (e-mail: ludwig.schiel@siemens.com).

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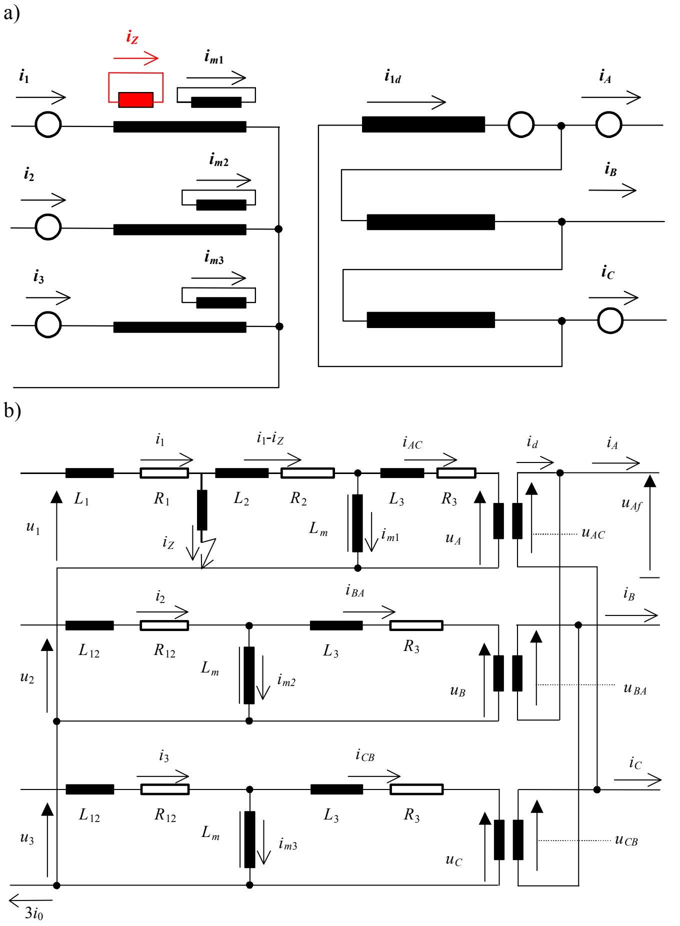

Fig. 2. Yd transformer with internal short-circuit: a) basic scheme, b) equivalent circuit for algorithm design.

bols used in further considerations are the following:
N – turn ratio of the transformer;
i_z – equivalent short circuit current;
i_{m1}, i_{m2} i_{m3} – magnetizing currents in particular phases;
i_1, i_2, i_3 – phase currents at the star side;
i_0 – zero sequence current at the star side;
$3u_0$ – a sum of the transformer star side voltages;
i_A, i_B, i_C – phase currents at the delta side;
u_1, u_2, u_3 – phase voltages at the star side;
u_{AC}, u_{BA}, u_{CB} – inter-phase voltages at the triangle side;
i_d – current measured in the triangle winding (if available);
L_3 – leakage inductance between the internal delta winding and the core;
$L_{12} = L_1 + L_2$ – leakage inductance between the star winding and the core;
R_{12} – resistance of the transformer star winding;
R_3 – resistance of the transformer delta winding.

With the scheme from Fig. 2b in mind one can write the following equations expressing HV side voltages in particular phases:

$$u_1 = L_1 i_1' + R_1 i_1 + L_2\left(i_1' - i_Z'\right) + R_2\left(i_1 - i_Z\right) + L_3 i_{AC}' + R_3 i_{AC} + u_A \quad (1)$$

$$u_2 = L_{12} i_2' + R_{12} i_2 + L_3 i_{BA}' + R_3 i_{BA} + u_B \quad (2)$$

$$u_3 = L_{12} i_3' + R_{12} i_3 + L_3 i_{CB}' + R_3 i_{CB} + u_C \quad (3)$$

One may note that $i_{AC} - i_{BA} = -i_A / N$ and $u_B - u_A = N\left(u_{BA} - u_{AC}\right)$, therefore subtracting (1) from (2) yields:

$$\begin{aligned} L_2 i_Z' + R_2 i_Z &= \left(u_2 - u_1\right) - N\left(u_{BA} - u_{AC}\right) - L_{12}\left(i_2' - i_1'\right) + \\ &\quad - R_{12}\left(i_2 - i_1\right) - \left(L_3 i_A' + R_3 i_A\right)/N \end{aligned} \quad (4)$$

On the left hand side of (4) there is a factor (voltage) proportional to the non-measurable short circuit current i_Z. If there is no internal fault, the right hand side of (4) should be zero.

The three phase approach presented above has three weak points:

- first, calculation of the right hand side of (4) requires processing of high values of voltages and currents, and small errors of processing may result in large errors in the final outcomes;
- second, to calculate the short-circuit voltage, the reactance L_3 ought to be known, what is very seldom the case;
- third, the results depend on the transformer ratio N, therefore information derived from the tap changer is required.

To reduce/obviate the problems one may use the zero sequence approach that is outlined in next subsection.

B. Zero sequence approach

The HV side transformer terminal voltages can also be expressed by the equations incorporating the magnetizing currents in the following way:

$$u_1 = L_T i_1' + R_T i_1 - \left(L_2 + L_3\right) i_Z' - \left(R_2 + R_3\right) i_Z - L_3 i_{m1}' - R_3 i_{m1} + u_A \quad (5)$$

$$u_2 = L_T i_2' + R_T i_2 - L_3 i_{m2}' - R_3 i_{m2} + u_B \quad (6)$$

$$u_3 = L_T i_3' + R_T i_3 - L_3 i_{m3}' - R_3 i_{m3} + u_C \quad (7)$$

where: $L_T = L_{12} + L_3$ – leakage inductance between the two windings; $R_T = R_{12} + R_3$ – resistance of both windings.

Summing the equations (5), (6) and (7) one gets:

$$\begin{aligned} \left(L_2 + L_3\right) i_Z' + \left(R_2 + R_3\right) i_Z &= 3 L_T i_0' + 3 R_T i_0 - 3u_0 + \\ &\quad - L_3\left(i_{m1}' + i_{m2}' + i_{m3}'\right) - R_3\left(i_{m1} + i_{m2} + i_{m3}\right) \end{aligned} \quad (8)$$

Under the assumption that the transformer delta winding is internal (the winding to core leakage inductance L_3 is very small or even it is negative, resistance R_3 is also very small), one arrives at another the very simple formula:

$$L_2 i_Z' + R_2 i_Z \approx 3 L_T i_0' + 3 R_T i_0 - 3u_0 \quad (9)$$

where: $L_T = L_{12} + L_3$ – leakage inductance between the two windings; $R_T = R_{12} + R_3$ – resistance of both windings.

The right hand side of (9) becomes an indicator of the internal short-circuit. Advantages of the formula (9) are that it does not process high phase signals, it also does not depend on the transformer turn ratio N and it does not require knowledge of the L_3 inductance. However, even for the transformers in which the delta windings are internal, the assumption that L_3 and R_3 are close to zero may be a source of some error when magnetizing inrush currents appear. This error is equal to

$$e = L_3\left(i'_{m1} + i'_{m2} + i'_{m3}\right) + R_3\left(i_{m1} + i_{m2} + i_{m3}\right) \tag{10}$$

and is often tolerable. However, one may observe that in case of inrush in each fundamental frequency cycle there is a time span when the error e is close to zero. Therefore, if there is no such a span in the signal represented by right hand side of (2), it means that there is a case of an internal fault. The internal fault can be confirmed when over the full fundamental frequency cycle the following relation holds:

$$\left| L_2 i'_Z + R_2 i_Z \right|_{t-0.02 \to t} > H \tag{11}$$

where H – certain threshold.

In the transformers consisting of three separate units the circulating current i_d, which flows inside the triangle, is measurable (additional CT is to be installed). Then, taking the phase voltages defined by (1), (2) and (3) into consideration, the following formula can be derived:

$$L_2 i'_Z + R_2 i_Z = 3L_{12} i'_0 + 3R_{12} i_0 - 3u_0 + L_3 i'_d / N + R_3 i_d / N \tag{12}$$

The right hand side of (12) is also an indicator of the inter-turn short-circuit. The formula is free of the error (10), does not process high values of voltages; however, it requires the knowledge of L_3 and the actual turn ratio N of the transformer.

C. Implementation aspects

It has been found that successful application of the proposed voltage criteria for internal transformer faults detection is conditioned on appropriate numerical calculation of the derivatives of the signals. It is commonly known that the simplest way of digital approximation of the derivative is given by

$$x'(n) = \frac{x(n) - x(n-1)}{T} \tag{13}$$

where T – sampling period.

The beauty of equation (13) is the fact that to obtain signal derivative one needs two samples of the signal only. Determining the transfer function of procedure (13) in frequency domain one gets

$$H(j\omega) = 2je^{-j\omega T/2}\,\frac{\sin(\omega T/2)}{T} \tag{14}$$

From (14) it follows that algorithm (13), apart from expected 90 deg phase shift, brings additional undesired signal delay by half of the sampling period. If the protection algorithm (especially (4)) is sensitive to phase displacement, this may lead to high errors that cannot be corrected. Therefore it is suggested to use three samples of the signal to calculate its derivative, namely:

$$x'(n) = \frac{x(n) - x(n-2)}{2T} \tag{15}$$

With (15) additional phase shift corresponds to full sampling period, which can easily be compensated by taking the values of other signals delayed also by one sampling period. The equation for calculating fault voltage (4) can now take the following digital form that includes the proposed corrective signal shift:

$$V(n) = [u_2(n-1) - u_1(n-1)] + N\,u_{Af}(n-1) - L_{12}[i'_2(n) - i'_1(n)] - R_{12}[i_2(n-1) - i_1(n-1)] - \frac{1}{N} L_3 i'_A(n) - \frac{1}{N} R_3 i_A(n-1) \tag{16}$$

The ideas described above may be applied not only for the transformers with grounded star points (directly, through a resistor or inductor) but also when the transformer star point is isolated (certain refinement of the formulae (9) and (12) is then needed). It is to be stressed here that the algorithms proposed ought to supplement the existing differential criterion, not to replace it. They may prove to be particularly effective if there is an inter-turn short-circuit after energization of the transformer, which will be illustrated in the next section with the signals obtained from simulations.

III. SIMULATION STUDIES WITH EMTP-ATP

The simulation studies have been performed with EMTP-ATP package [7] for a three-phase power transformer (S_n=32 MVA, ϑ=115/22kV, YNd11 connection, X_T=45.3Ω, u_{sc}=11%, five-leg core) and the power system structure as shown in Fig. 3. The simulation model was equipped with suitable non-linear models of CTs being equivalent of standard current transformers 5P20 with transformation ratio ϑ_{CT}=200:1 (A/A).

The transformer to be protected was represented with appropriate model expressed by R, L matrices of 8x8 size (two additional nodes were introduced in the winding to enable simulation of inter-turn faults at any location). The way of determining the R, L values is described thoroughly in [8] and verified in [9, 10]. The model was not described in the paper due to space shortage. It has been thoroughly tested, even for the cases of single-turn faults (high current in the short-circuited turn, almost negligible at the transformer terminals).

A number of cases of internal faults as well as other phenomena (including transformer energization) have been prepared. The criteria signals as defined with equations (4), (9) and (12) are shown below for the simulation cases considered. First, the protection scheme is evaluated when the criteria signals are calculated with use of the system primary signals. This was done to enable scheme assessment (criteria quality evaluation) without taking into account possible signal distortions due to CT saturation. The values of L_3 and R_3 are considered as known (close to zero) and matched to those set in equations (4) and (12).

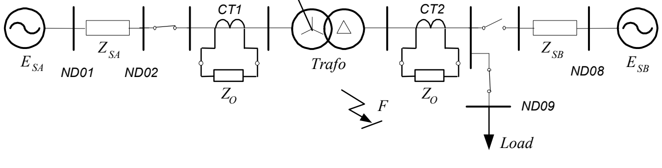

Fig. 3. Schematic diagram of the HV/MV system under study.

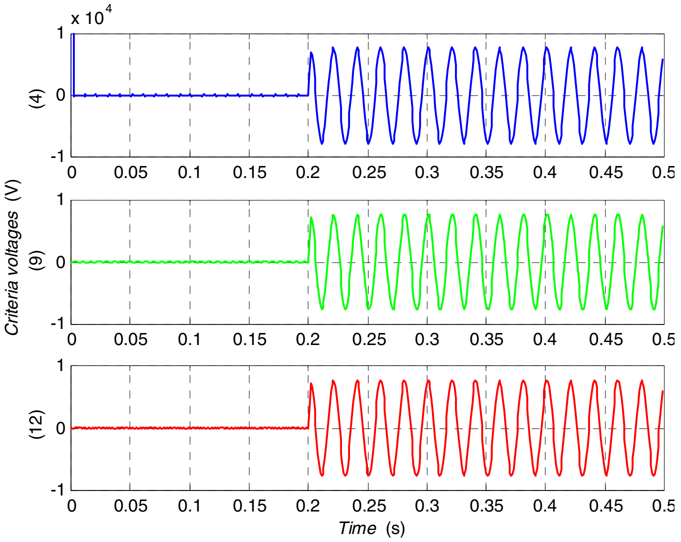

Fig. 4. Criteria voltages in case of inter-turn fault at the star side.

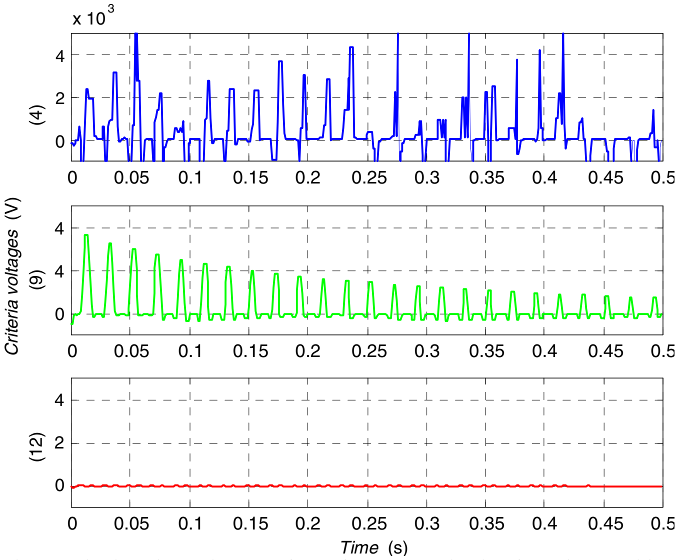

Fig. 5. Criteria voltages in case of transformer energization from the star side.

Fig. 4 shows the proposed criteria signals for the case of internal inter-turn fault at the transformer star side, occurring 0.2 sec after simulation start. One can see that the criteria voltages due to fault are high enough for fault detection (pick values at the level of 8.5kV). Moreover, Fig. 4 delivers a proof that all the criteria proposed are equivalent and bring identical information under ideal conditions (transformer parameters and turn ratio known, primary signals available, no deterioration due to CT saturation).

Since the designed protection schemes are expected to work properly during transformer energization (blocking expected), the tests were performed also for such cases, one of which is presented in Fig. 5. It is seen that the fault voltage (12) is close to zero, which means that the relay remains stable, as required. The shape of voltage (9) results from the course of the zero sequence current, however the voltage peak values are much lower than in case of turn-to-turn fault presented in Fig. 4. One has to understand that the level of fault voltage (4), (9) and (12) depends very much on the number of short-circuited turns and for faults involving higher number of turns the measured voltage is high enough for successful fault detection even during transformer energization. The least reliable seems the criterion signal (4) characterized by high peaks. However, also here flat periods observed can be used for generation of blocking decision.

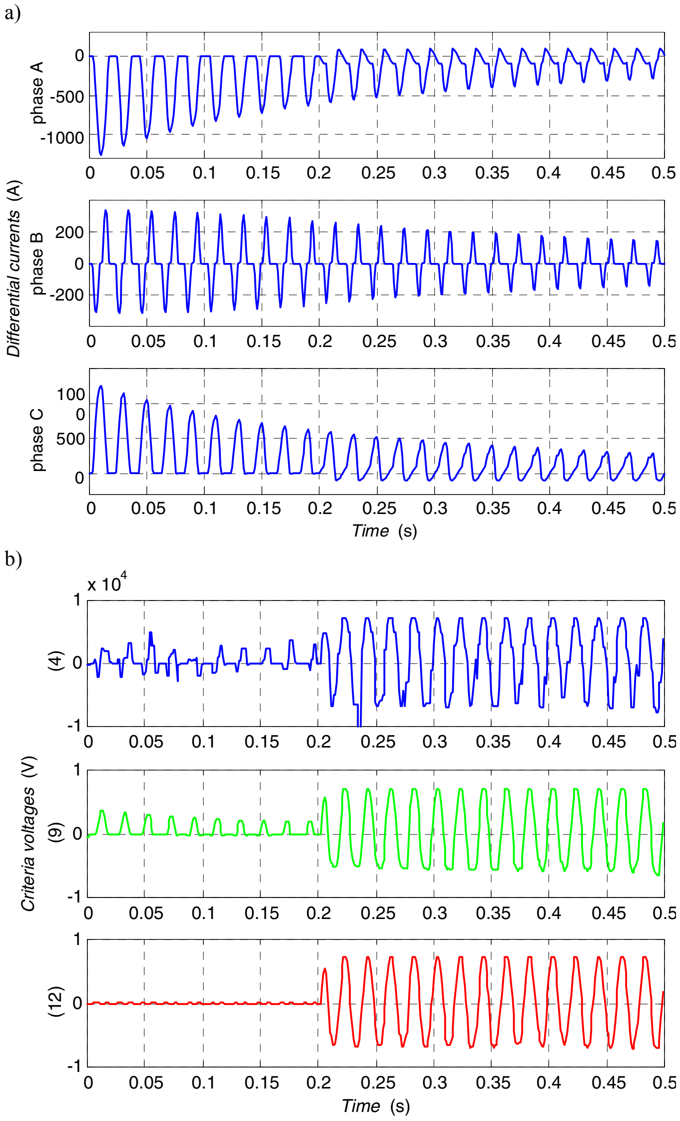

Fig. 6. Internal fault detection during transformer energization; results obtained for CT primary signals: a) differential currents, b) voltage criteria signals (4), (9) and (12).

In Fig. 6 a selected case of internal turn-to-turn fault occurring during transformer energization (fault instant at *t*=0.2s) is shown. In such a case the share of fault component in the observed differential current is quite small. The second harmonic ratio (not shown here) would block the standard relay, and thus the internal fault could not be detected. One can notice that if primary currents were available (signals not distorted by CT saturation, Fig. 6a) all the protection approaches would bring results that enable internal fault identification during inrush. The most stable and discriminative is the criterion (12) based on zero sequence quantities with additional information from delta CT. With criterion signal (9) the voltage measured is not zero before fault inception; its shape is determined by the

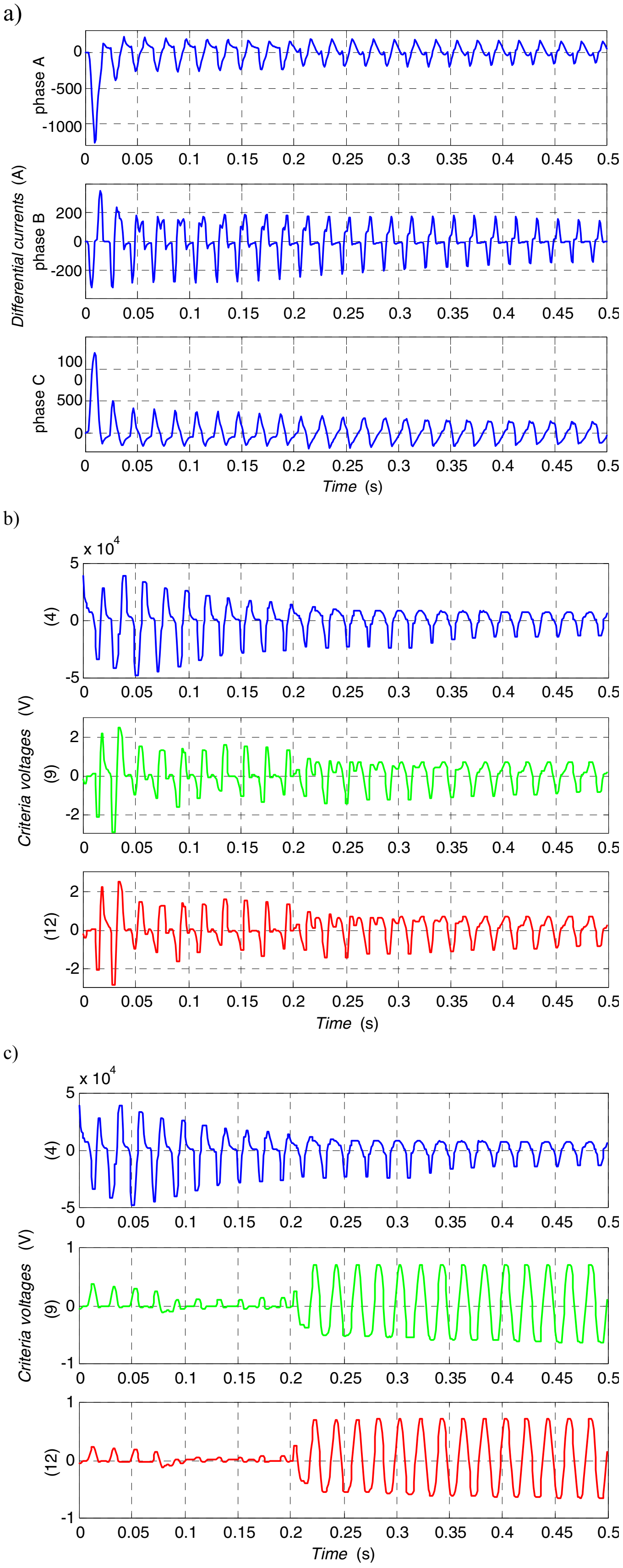

Fig. 7. Internal fault detection during transformer energization; results obtained for CT secondary signals: a) differential currents, b) voltage criteria signals (4), (9) and (12) calculated: b) for $3I_0$ calculated from phase currents, c) as b) but for $3I_0$ measured.

waveform of zero sequence current. However, also in this case proper operation (relay blocking) is possible if the condition (11) is checked. When the fault voltage is calculated with use of phase voltages and currents, according to eq. (4), the criterion signal obtained is not that perfect; however, also here making proper decision is utterly possible when additional logic conditions are introduced.

The situation gets worse when the CTs at the supplying side get saturated (Fig. 7). In such a case the criteria signals are not that perfect. Here two options of zero sequence current measurement were studied: its calculation from phase currents and direct measurement with additional CT installed in the transformer grounding path. One may notice that better conditions for easier distinguishing of internal fault are ensured when additional CT for $3I_0$ measurement is installed (Fig. 7c). Unlike phase CTs, the zero sequence CT saturates with lower probability, less severely and mainly due to DC component. Thus the influence of CT saturation is less significant when $3I_0$ is directly measured than when it is calculated from phase currents (Fig. 7b). This observation is not valid for the fault voltage calculated according to (4) since here phase currents are used only, which severely influences the criterion waveform when phase CTs saturate.

In the case presented the waveshapes of both criteria signals based on zero sequence quantities (without or with additional information from delta CT) are good enough to enable distinguishing the internal winding fault, while the use of criterion (4) for the purpose would be more than problematic in this case.

IV. CONCLUSIONS

Three new algorithms for detection of turn-to-turn faults in power transformers are presented. The criterion signal is in all versions a voltage proportional to the unknown internal fault current. The most promising approaches are the ones with use of zero sequence voltage and current. In both cases single equation based on the zero sequence quantities protects all the transformer windings. Besides, the algorithm (9) does not need the correction for the tap position, does not require knowledge of the L_3 inductance, and does not process phase voltages. Though the algorithm (12) makes use of the transformer triangle winding current, the authors do not advocate installation of a CT inside the transformer tank. The algorithm (12) is suggested only for the transformer banks, which consist of three separate single phase transformers. In such a case the delta winding is perfectly available for the external installation of a CT, and the solution is quite practical.

The algorithms proposed have been tested with EMTP-ATP generated signals. The techniques presented enable detecting even small number of the short circuited turns wherever they are located. Both star and triangle side inter-turn faults can be detected, irrespective of the transformer star point grounding mode (whether solidly, non-solidly grounded, or isolated). It turned out that saturation of current transformer may deteriorate the criteria signals to some extent. If the zero sequence current is directly measured (not calculated from the saturated phase currents), then the saturation phenomenon does not write off the distinguishing abilities of proposed criteria, especially the ones based on zero sequence quantities. The speed of the algorithm may be extremely fast – one period or so – and shall not be delayed if the short circuit coincides with the inrush condition, what in case of the 2nd harmonic may delay the operation substantially. For all of the described criteria a patent application has been prepared [11] to protect the solutions developed.

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VI. BIOGRAPHIES

Andrzej Wiszniewski graduated from the Electrical Engineering Faculty of the Wroclaw University of Technology in 1957. In 1961 he received the Ph.D. degree, in 1967 the D.Sc. degree, and in 1972 the professorship in Electrical Engineering. All his life he was working in the field of power apparatus and systems, being a specialist in the protection and control of power systems. He is an author of 9 books and more than 130 scientific publications. All the time attached to the Wroclaw University of Technology he became a Rector of the University and had this position for 2 terms (1990 – 1996). In 1997 he took the position of the Minister for Science, and had it for 4 years. Prof. Wiszniewski is a Distinguished Member of CIGRE and Honorary Member of the Polish Institution of Electrical Engineers.

Waldemar Rebizant (M'2000, SM'2005) was born in Wroclaw, Poland, in 1966. He received his M.Sc., Ph.D. and D.Sc. degrees from Wroclaw University of Technology, Wroclaw, Poland in 1991, 1995 and 2004, respectively. Since 1991 he has been a faculty member of Electrical Engineering Faculty at the WUT, at present at the position of the Assc. Professor and the Vice-Dean for Development and International Cooperation. During the academic year 1999/ 2000 he was a Humboldt Foundation research fellow at the University of Stuttgart, Germany. In the scope of his research interests are: digital signal processing and artificial intelligence for power system protection.

Ludwig Schiel was born in Weimar, Germany, in 1957. He studied Electrical Engineering at the Institute of Technology Zittau, Germany, finishing with the Dipl.-Ing. degree in 1984. In 1991 he received the Dr.-Ing. degree. In the same year he joined the Siemens AG, Germany, Department of Power Transmission and Distribution, Energy Automation. He is project manager of transformer differential protection systems.