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Power transformer differential protection with integral approach

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ABSTRACT

This paper presents a new approach to differential protection of power transformers with use of the integral principle. The required criteria signals are calculated directly from the operational and restraining currents in particular phases. Additional support of the second harmonic is also used. The proposed integral principle is simple and exhibits superior performance against other commonly applied algorithms. The theoretical investigations are followed by testing with simulation runs as well as recorded signals.

1. Introduction

The investigations related to differential protection of power transformers are presented in this paper, whereas special attention was put to relay performance for:

- external fault cases with CT saturation,
- magnetizing inrush due to transformer energization,
- internal transformer faults.

The problem of differential protection behavior for power transformer energization as well as for external faults with CT saturation is not new. There have been a lot of cases reported when transformer differential protection maloperated despite of the use of typical characteristics and stabilization approaches. Apart from the percentage differential characteristic, the commonly accepted solution for transformer protection stabilization is the second harmonic ratio principle, which is applied in products of most relay manufacturers, e.g. [1]. Other approaches (being mostly literature proposals) may include:

- usage of higher harmonics content in the differential currents to restrain and/or to block differential protection and differentiate between fault and inrush condition [2,9],
- application of a combined restraint/blocking method, whereas even harmonics of the differential current provide restraint, while both the fifth harmonic and DC component block protection operation [3],
- discrimination internal fault current from inrush current by comparing the similarity between the actual wave of differential current and two reference waves under two different frequency conditions per half cycle [4],
- schemes based on correlation algorithm where fault current is distinguished from the inrush current by usage of the waveform correlation coefficient between the first half-cycle and the latter-half-cycle of the differential current [5],
- stabilization based on the correlation coefficients between the differential current waveform in the non-saturation zone and two structured sinusoidal waveforms [6],
- usage of multi-criteria self-organized fuzzy approach [7],
- fuzzy-based transformer differential protection algorithm employing flux-differential current derivate curve, harmonic restraint and percentage differential characteristic curve [8],
- wavelet transform approach [10,11],
- Clarke's and modified hyperbolic S-transformations [12],
- current and voltage ratios (VTs needed) [13].

One can also find proposals of protection improvement by appropriate compensation of CT saturation errors:

- based on least error squares (LES) filter aimed at estimating phasor parameters of the CT secondary current [14],
- with use of transient bias technique designed to overcome the effects of CT saturation [15].
- with use of algorithmic reconstruction of unsaturated primary current waveforms [16],
- with use of the normalized rotated current histograms [17].

From the viewpoint of this paper goal one has to say that at the

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moment three most common practical approaches for transformer differential protection stabilization, except for the basic percentage characteristic, are: harmonic restraint, asynchronous operation principle (operation sequence) and current phase comparison. These methods improve protection security, but they also have some major disadvantages:

- decreased sensitivity during faults combined with inrush, and generally slower operation for internal faults (harmonic restraint),
- inefficiency when fast CT saturation occurs (within less than one third of the fundamental cycle) and when CT saturates due to long lasting DC component (operation sequence method),
- requirement for additional voltage measurement and possibility of incorrect decisions under low-current short-circuit cases (current phase comparison technique).

As a remedy for the problems mentioned a protection proposal based on integral principle is here introduced. The idea of integral stabilization of generator differential protection has already been described in [18,19]. Here, this approach is used for transformer protection.

The structure of this paper is as follows. In Section 2 the new integral-type protection algorithm is introduced. Sensitivity analysis and comparison with traditional differential percentage schemes is also provided. Next, in Section 3, the algorithm's operation is studied for a range of cases including inrush conditions, other cases of external disturbances, as well as internal faults. The scheme validation is done with both EMTP-generated and registered signals. Final conclusions and application recommendations are provided at the end of the paper.

2. Proposed new solutions

The transformer differential protection performs its task by examining the level of the differential current in relation to the through current (percentage characteristic). Additionally, a number of additional criteria are checked in order to exclude other situations with potentially significant differential current (inrush conditions, external faults with CT saturation, overexcitation) for which the protection should not react.

In [18] the use of integral criteria for efficient stabilization of the differential protection of generators was proposed. The block scheme of adopted differential protection with additional stabilization path is shown in Fig. 1, [18]. Blocks 1 and 2 are typical units of a standard differential relay where the calculated differential and through currents are compared in relation to the specifically set single- or dual-slope percentage characteristic. The final decision about generator tripping is issued when additionally the introduced integral criteria (Block 3) meet pre-defined conditions. The scheme, intended for generator protection, has additional stabilization introduced to deal better with troublesome cases of close external faults, near-by transformer energization or starting of closely located group of supplied drives.

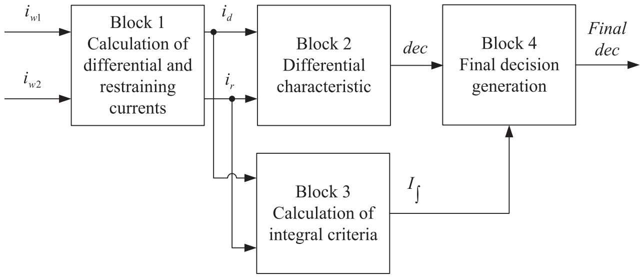

Fig. 1. Block scheme of the generator differential protection with integral stabilization [18].

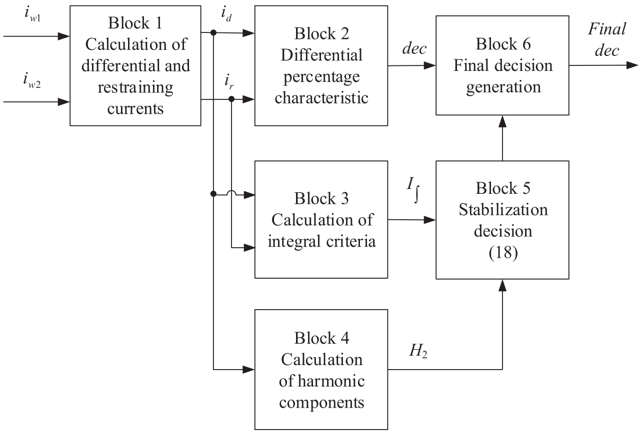

Fig. 2. Block scheme of the proposed transformer differential protection with integral and harmonic stabilization.

The scheme described above is here modified to suit transformer operating conditions. It is clear that for transformer protection additional blocking for overexcitation conditions should be added (mostly based on analysis of the fifth harmonic level [2,9]). Of course, the main attention is also transformer energization for which not always the even-order harmonic restraint is good enough, especially when transformers with amorphous material cores are to be protected [20].

The proposed protection scheme for power transformers is shown in Fig. 2. The final decision (Block 6) is here made taking into account stabilization information from Block 5. The integral criteria and harmonic signals that are calculated in Blocks 3 and 4. The details of the scheme algorithms and logic, along with respective relay settings are provided below.

The proposed stabilization solution is based on calculation of the full-cycle integral being function of the operational (4) and restraining (6) currents, as follows [19]:

$$I_\int = \frac{1}{T_1}\int_{t-T_1}^{t} (i_{op} - Ki_r)dt \tag{1}$$

where: K - constant coefficient responsible for stabilization strength.

With such a definition an extensive effect of stabilization is achieved since the variables under integral (1) cover full cycle of the fundamental frequency. Therefore, the integral includes also periods of time when the CTs are not saturated, which increases the effect of restraint.

The calculated integral (1) is compared with threshold H:

$$I_\int < H \tag{2}$$

where H - constant pre-defined value. The relay tripping decision is blocked when condition (2) is met, i.e. for integral values lower than H.

The differential currents in particular phases are determined in standard way:

$$i_d = i_{w1} - i_{w2} \tag{3}$$

where: i_{w1}, i_{w2} - longitudinal (terminal) currents at both sides of the protected unit.

For transformer applications one should of course remember to use appropriate phase shift compensation according to given transformer group connection, as well as zero sequence current elimination. The two tasks are standard for protection engineers, thus they are not described in detail in this paper.

The operational currents being a function of differential currents may be defined in various ways, [18]. Initial studies revealed that the best option is to adopt:

$$i_{op} = \frac{1}{\omega_1}|i_d'| \tag{4}$$

where i_d' - derivative of the differential current, which gives additional removal of DC components, being especially effective for longer time constants of their decay.

The differential current derivative may be numerically determined from:

$$i_d'(n) = [i_d(n) - i_d(n-1)]/T_s \tag{5}$$

with T_s - sampling period.

The restraining currents may be determined as:

$$i_r = \max[|i_{w1}|;\ |i_{w2}|] \tag{6a}$$

or

$$i_r = |i_{w1} + i_{w2}| \tag{6b}$$

or

$$i_r = \frac{1}{\omega_1}\left|\frac{d}{dt}(i_{w1} + i_{w2})\right| \tag{6c}$$

which often depends on the policy of the relay manufacturer. The option (6c) matching the way of the operational current calculation (4) is proposed by the Authors of this paper.

The issue of proper selection of the algorithm version and respective constants and thresholds is quite difficult to deal with basing on theoretical investigations. Therefore simulation studies were used in order to verify the use of selected solutions. The scheme proposed has been initially tested with EMTP-ATP-generated [21] and then also with real-world registered cases of transformer internal and external events. It is obvious that for all external events, including transformer energization, the protection should restrain from tripping.

In Fig. 3 the courses of integral (1) are plotted for the operational and restraining currents defined by (4) and (6c), respectively. The blue curves are obtained for internal faults, where the protection should operate, while the red ones – for external faults and other events, e.g. magnetizing inrush cases, where no tripping is expected. The simulation studies were performed for the EMTP-ATP model of YNd11 transformer unit, equipped with appropriate magnetizing characteristic (see Appendix A for more details). Only high current faults were taken into account (terminal events).

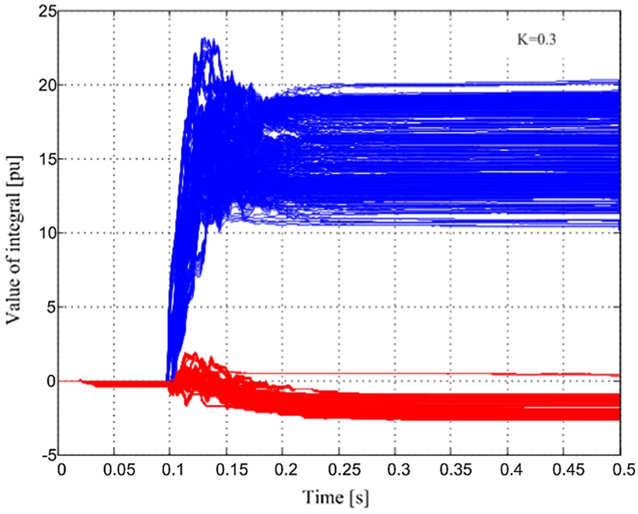

Fig. 3. Integral (1) values for internal faults (blue) and external events (red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

One can see that for most external events the integral values are negative; however, for some inrush cases the integral (1) may be a small positive number, slightly higher only during transient just after event inception (after $t = 0.1$ s). Such a situation is advantageous, since one can easily set the discrimination threshold at the level of, say, $H = 2.5$ to assure proper support of the protection. It is to be stressed that the blue and red curves in Fig. 3 should be separated to some reasonable grade, which is dependent on the stabilization constant K. Too high value of K, though providing higher decision margin, would cause too strong stabilization and slower protection response for internal faults. On the other hand, too low value of K would decrease the stabilization effects too much. The analyses show that the optimal level of this constant is $K = 0.3$.

With the above defined constant values H and K the proposed stabilization algorithm offers required security for external events. The expected sensitivity of the scheme for internal faults should also be discussed. In order to determine the algorithm sensitivity let us consider an internal fault with supply from one side only, which represents the worst conditions from the differential relay viewpoint since the restraining current is then lower than for double-side transformer supply. For such conditions it holds:

$$i_{w1} \neq 0,\ \ i_{w2} = 0 \tag{7}$$

and

$$i_{op} = i_r = \frac{1}{\omega_1}\left|\frac{d}{dt}(i_{w1})\right| \tag{8}$$

Assuming the simplest current signal model containing only the fundamental frequency component $i_{w1} = -A\cos(\omega_1 t)$ one obtains

$$i_{op} = i_r = \frac{1}{\omega_1}A\omega_1\ |\sin(\omega_1 t)| = A\ |\sin(\omega_1 t)| \tag{9}$$

and

$$I_f = \frac{1}{T_1}\int_{t-T_1}^{t}(1-K)i_{op}dt = \frac{1-K}{T_1}A\int_{t-T_1}^{t}|\sin(\omega_1 t)|\ dt \tag{10}$$

which after simple rearrangements yields:

$$I_f = \frac{1-K}{T_1}A\frac{4}{\omega_1} = \frac{2(1-K)}{\pi}A \tag{11}$$

One can conclude that the integral (11) is a linear function of the signal magnitude A, whereas the slope of this function depends on the relay setting K. For assumed value $K = 0.3$ it gives:

$$I_f = \frac{2(1-K)}{\pi}A = \frac{1.4}{\pi}A \approx 0.45A \tag{12}$$

Comparing (12) with $H = 2.5$ one can calculate the level of detectable internal fault currents:

$$A_{\min} = \frac{2.5}{0.45} \approx 5.56\ [\text{pu}] \tag{13}$$

It is clear that the fault current magnitude is very high for faults at the source side, thus such faults should not pose any problems for protection operation. The fault current level for faults at the secondary side of protected transformer is much lower, being limited by the transformer longitudinal impedance (reactance) that is proportional to short-circuit voltage of the transformer. Assuming infinite power of the source (source impedance close to zero) the fault level $A_{\min}$ is not exceeded for transformers with short-circuit voltage

$$u_{k\%} \geqslant 1/5.56 \approx 18\% \tag{14}$$

Lower level of fault current can also be observed for internal short-circuits, e.g. inter-turn faults. In Fig. 4 the above calculations are illustrated with a sensitivity diagram. It is confirmed that the lowest level of integral (1) is observed for single-side supply or for the cases of weak

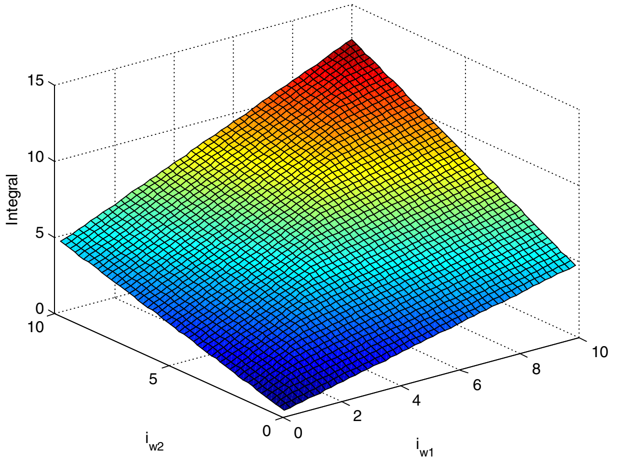

Fig. 4. Integral values (1) for pure sinusoidal input signals (internal fault) for transformer protection and $K = 0.3$.

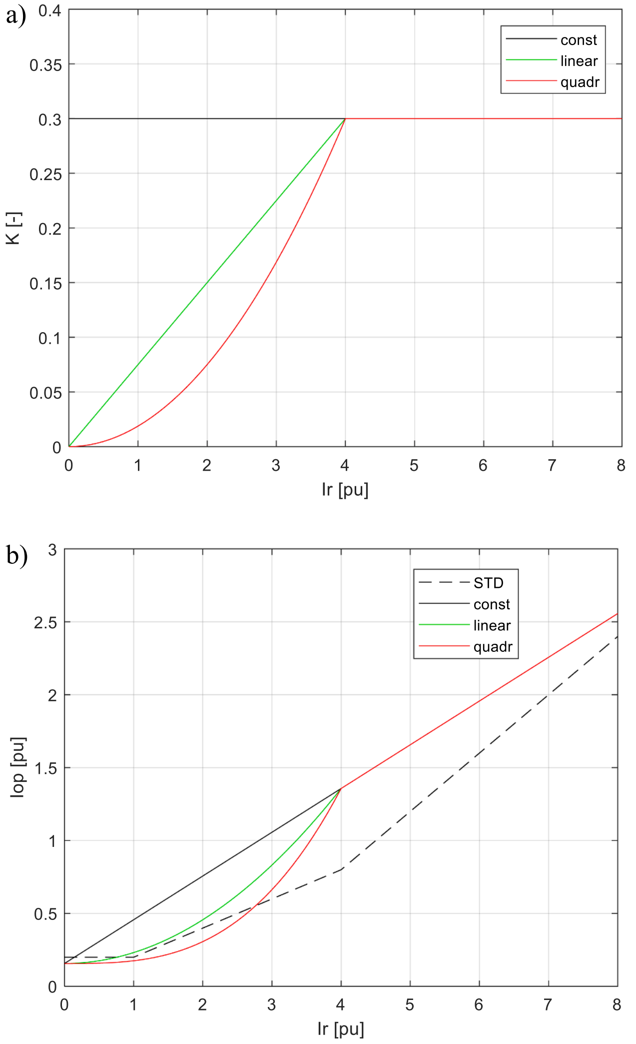

Fig. 5. Considered adaptation versions (a) and resulting relay characteristic (b).

sources from both sides of protected plant.

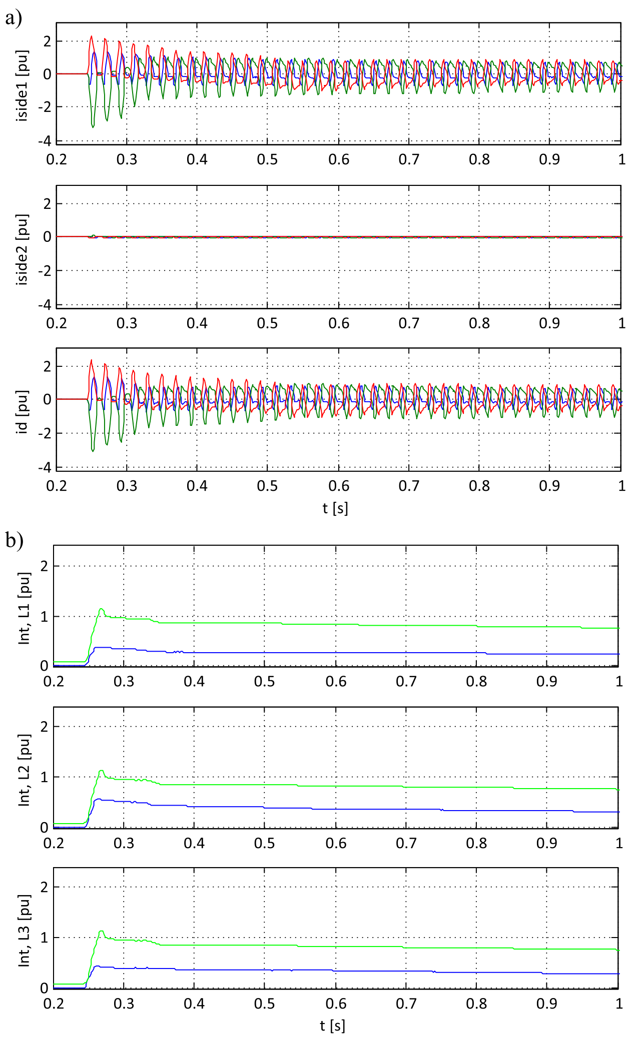

Fig. 6. Transformer energization case no. 1: (a) terminal and diff currents, (b) integral (1) with thresholds.

In order to increase the algorithm sensitivity one may assume that the stabilization coefficient K is adaptive with respect to the measured value of restraint current. The following two options (linear and quadratic change) have been considered:

$$K = \begin{cases} 0.075 I_r & \text{for } I_r \leqslant 4 \\ 0.3 & \text{for } I_r > 4 \end{cases} \tag{15a}$$

$$K = \begin{cases} 0.01875 I_r^2 & \text{for } I_r \leqslant 4 \\ 0.3 & \text{for } I_r > 4 \end{cases} \tag{15b}$$

After simple rearrangement of the integral protection formula

$$\frac{1}{T_1}\int_{t-T_1}^{t} (i_{op} - K i_r) dt > H \tag{16}$$

one may obtain the following inequality representing the relay trip characteristic in the form:

$$I_{op} > \frac{\pi}{2} H + K I_r \tag{17}$$

With constant value of $K = 0.3$ and small threshold $H = 0.1$ the resulting trip curve is a straight line. For K varying according to (15a) or (15b) one gets a linear or quadratic change of K (Fig. 5a) and then respective second or third power course of the relay characteristic (Fig. 5b). One can also see how the assumed versions can be compared to the standard differential relay characteristic (STD). It is obvious that

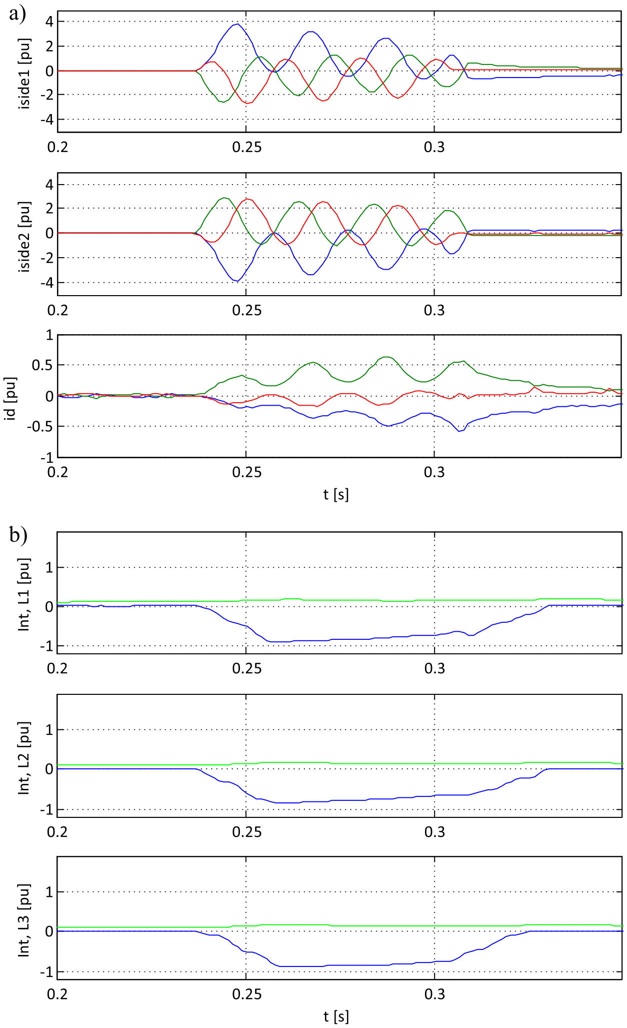

Fig. 7. Transformer energization case no. 1: (a) terminal and diff currents, (b) integral (1) with thresholds.

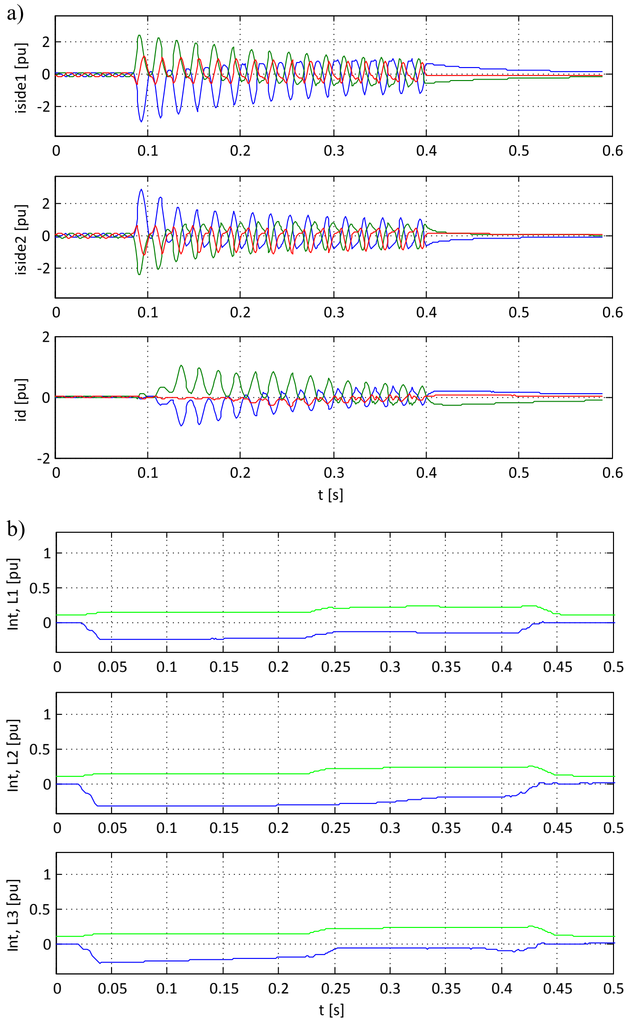

Fig. 8. External fault case no. 1: (a) terminal and diff currents, (b) integral (1) with thresholds.

introduction of the linear or quadratic version of stabilization increases the relay sensitivity for small restraining currents. Unfortunately, if due to expected transient increase of integral (1) after event inception the threshold H is set at higher level (proposed $H = 2.5$), the resulting protection sensitivity would be very low, irrespective of the adopted constant of adaptive versions of the stabilization coefficient K.

The above considerations lead to a conclusion that reaching a solution being secure and yet sensitive enough is hardly possible with the integral approach alone without introduction of further supporting criteria. It is therefore suggested that the maximum value of second harmonic magnitude from all phases integrated over one cycle is to be used as follows.

As the final solution it is proposed that the integral (1) is compared to the sum of a small constant $H_0 = (0.05 \div 0.1)[pu]$and the second harmonic part:

$$I_{\int} < H_0 + H_2 \tag{18}$$

$$H_2 = \frac{1}{T_1} \int_{t-T_1}^{t} (M I_{2\,\max}) dt \tag{19}$$

calculated in Block 4 (Fig. 2), with $I_{2\,\max} = \max[I_{2L1}; I_{2L2}; I_{2L3}]$ (maximum of the calculated magnitudes of the 2nd harmonic components in particular phases) and M - constant coefficient (here: $M = 2.0$). One could also add other even harmonics, e.g. the fourth, to increase the strength of stabilization.

The other version of (18) is to take the second harmonic part (19) under common integral on the left-hand side, which yields:

$$\frac{1}{T_1} \int_{t-T_1}^{t} (i_{op} - K i_r - M I_{2\,\max}) dt > H_0 \tag{20}$$

Simulation studies and algorithm testing with registered cases proved that proposed solution (18) remains stable and provide good protection stabilization under all conditions. Therefore this version is a recommended solution for transformer protection.

3. Protection testing

3.1. Transformer inrush conditions

A registered case of energization of the 2-winding, 226.7/16.5 kV, Yd11, 340MVA transformer is shown in Fig. 6. One can observe typical waveforms with slight saturation of CTs. The standard protection [1]

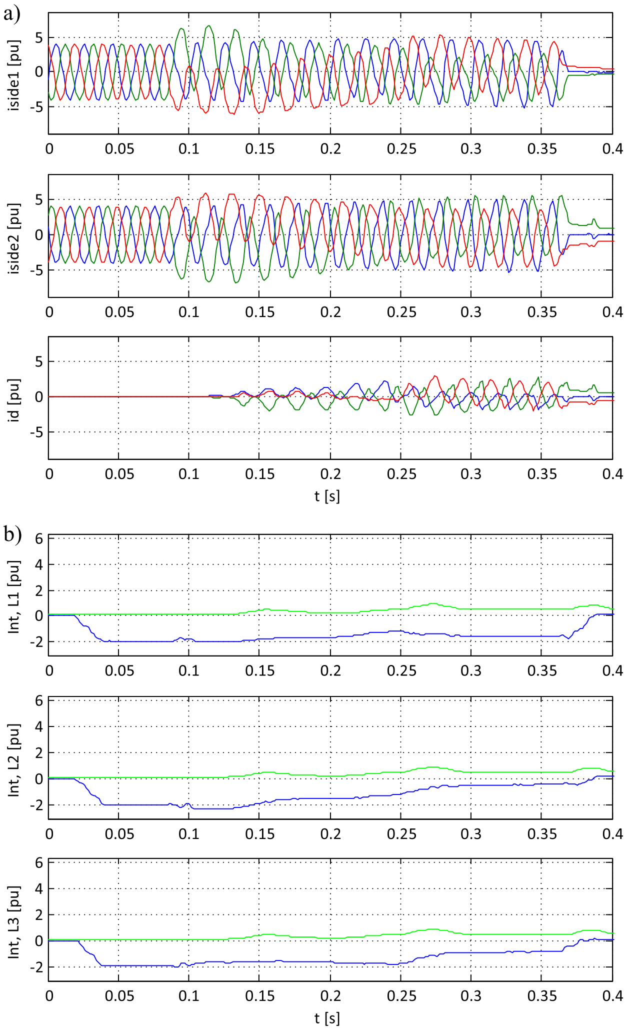

Fig. 9. External fault case no. 2: (a) terminal and diff currents, (b) integral (1) with thresholds.

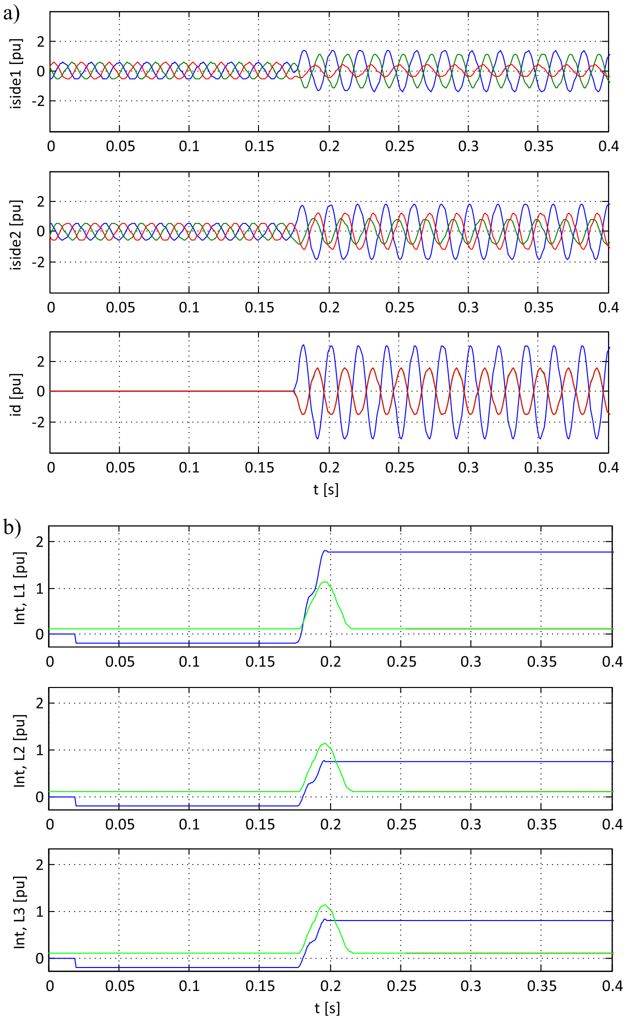

Fig. 10. Simulated turn-to-turn internal fault (5% of turns shorted): (a) terminal and diff currents, (b) integral (1) with thresholds.

picked up, but there was no trip, thanks to applied 2nd harmonic blocking. The proposed integral protection also operated correctly (no tripping), since the values of integral (blue curves, Fig. 6b) were all the time below the variable threshold $H_0 + H_2$ (green curves, Fig. 6b).

Note that the same colors for integral (1) and thresholds (blue/green) were used in all other testing cases shown below (Figs. 7–10b).

Another real-world case of 3-winding, 145/9.5/22 kV, Yd7y0, 60/60/5MVA transformer energization with false trip is shown in Fig. 7. Standard protection [1] failed here, whereas the proposed integral scheme correctly identified the case. With application of the integral approach undesired trip was avoided, which proves superiority of the developed approach.

3.2. External faults

The differential protection of the transformer should remain stable also during possible through cases (external faults). Several cases of false response of the standard differential protection for such events have been noticed.

The signals from selected case are presented in Fig. 8, registered for a 2-winding, 226.7/16.5 kV, Yd11, 340MVA transformer. Despite active second harmonic stabilization (setting 15%) the relay falsely recognized the case as internal one and tripped the protected transformer (effects seen for time over 0.4 s). Contrary to the standard solution [1] the developed integral scheme remained stable, the calculated integral (1) was all the time under the respective variable threshold $H_0 + H_2$.

Another registered external fault with quite small currents but containing long-lasting decaying DC components is shown in Fig. 9. The protected transformer was a 3-winding, 145/9.5/22 kV, Yd7y0, 60/60/5MVA unit. Also here the standard solution [1] failed, whereas the new proposed scheme was stable and no tripping command was issued. Sufficient margin between the integral curve and the threshold was provided all the time.

3.3. Internal faults

Although the protection scheme was mainly intended to improve the operation for external events, it should also perform correctly for all internal faults. A number of such events were simulated with EMTP-ATP software.

A simulated case of internal fault in transformer star winding (5% of turns shorted) is shown in Fig. 10. The protected 32 MVA Yd11 two-winding transformer was supplied from both sides. Despite the fact that the short-circuit currents were quite low the proposed integral scheme

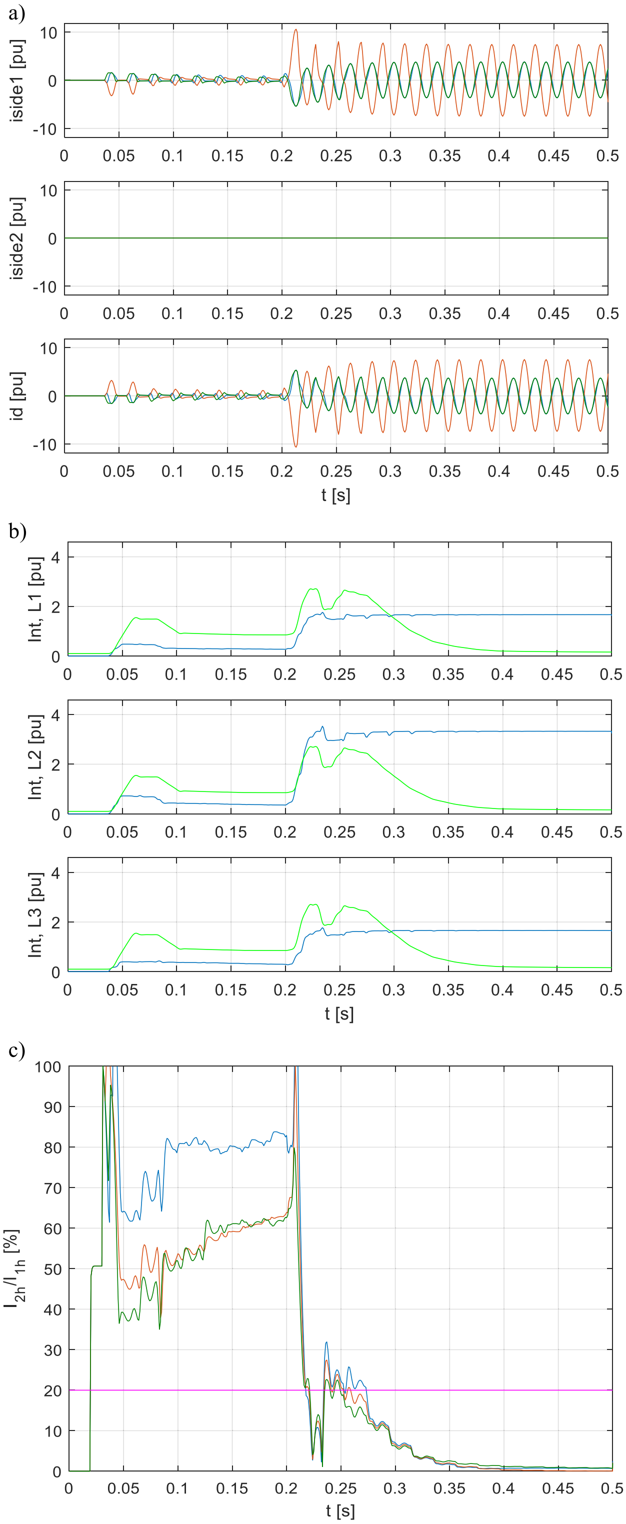

Fig. 11. Simulated phase-to-phase internal fault during inrush: (a) terminal and diff currents, (b) integral (1) with thresholds, (c) 2nd harmonic components.

was sensitive enough to detect such a fault. One can see that the calculated integrals in all phases were lower than threshold before fault inception. Then their values increased, allowing for firm detection of this internal fault.

Another case of phase-to-phase internal fault at the MV terminals of protected transformer that occurred 8 cycles after transformer energization (during inrush) is presented in Fig. 11. One can see that the calculated integral in phase L2 exceeded the variable threshold $H_0 + H_2$ within less than 20 ms, allowing for protection reaction. Additionally, here the second harmonic ratios in the differential currents are shown in Fig. 11c. Since after fault inception the I_{2h}/I_{1h} values become lower than the 20% threshold after some 20 ms, one can conclude that the new proposed solution is not slower than the standard protection with 2nd harmonic restraint.

4. Summary and recommendations

In this paper the operation of transformer differential protection was studied for numerous cases of external events creating a challenge to traditional protection relays that tended to maloperation and tripping of the healthy unit.

In order to improve the differential protection performance a new approach and detailed algorithms based on integral principle have been proposed. Numerous versions of the criteria resulting from various ways of defining the operational and restraining currents have been examined. The best results were obtained for the criteria employing derivatives of differential and restraining currents, combining also the use of integrated second harmonic component.

The algorithms proposed have also been tested for internal faults for which the protection should clear the fault promptly. The tests revealed that the solution was able to react properly for all internal events, with no additional operation delays.

The operation time of the new algorithm is very similar to the traditional methods where full-cycle measurement and 2nd harmonic restraint are used. Simulation tests show that the protection speed is comparable, yet with achieved better stabilization for inrush and other external events, for which the protection should restrain from tripping.

The testing results have proved that the proposed protection settings are suitable for transformers of various ratings and different constructions. The recommended range for setting K is from 0.2 to 0.4. If needed, additional increase of the protection sensitivity may be reached with application of the variable value of K, according to (15a) or (15b). The value of threshold H_2 is dependent on the second harmonic level and is varying. The threshold H_0 may be set lower than proposed 0.1, which should bring higher sensitivity and speed. On the other hand, this may also be a source of wrong operation during external events (loss of stabilization).

CRediT authorship contribution statement

D. Bejmert: Formal analysis, Methodology. **M. Kereit:** Funding acquisition, Resources. **F. Mieske:** Data curation. **W. Rebizant:** Investigation, Software, Writing - review & editing. **K. Solak:** Conceptualization, Software, Writing - original draft. **A. Wiszniewski:** Conceptualization, Supervision.

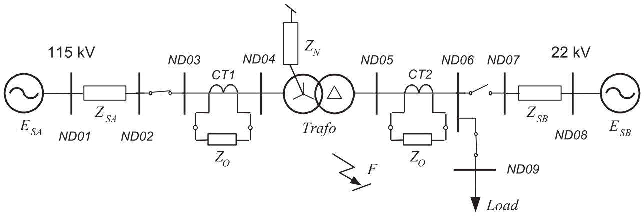

Fig. 12. Schematic diagram of the HV/MV system under study.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A

The simulation studies have been performed with EMTP-ATP package [21] for a three-phase power transformer ($S_n = 32$ MVA, $\vartheta = 115/22$ kV, YNd11 connection, $X_T = 45.3\ \Omega$, $u_{sc} = 11\%$, five-leg core) and the power system structure as shown in Fig. 12. The simulation model from Fig. 12 was equipped with suitable non-linear models of CTs being equivalents of standard current transformers 5P20 with $\vartheta_{CT1} = 200{:}1$ (A/A) and $\vartheta_{CT2} = 1000{:}1$ (A/A).

A number of cases of external and internal faults as well as other phenomena (including transformer energization) have been prepared. To consider vast range of conditions a variation of the following system parameters was taken into account: type of fault, HV/MV source impedances, CTs load, fault inception time, energization side and switching time.

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