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Adaptive differential protection of three-phase power transformers based on transient signal analysis

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ABSTRACT

This paper presents a three-phase power transformer percentage differential protection formulation based on transient signal analysis. The proposed formulation uses discrete wavelet transforms (DWT) to extract transitory features of non-stationary signals with fast transition, mapping the signal in time–frequency representation. The proposed formulation was implemented on MATLAB® environment and evaluated through a case study using BPA'S ATP/EMTP software. Comparative test results are presented showing that the proposed formulation is highly reliable, fast, accurate and easy for real-life construction.

1. Introduction

Power Transformers (PT) play an extremely important role on the reliability and energy supply continuity of electric power systems (EPS). The inherent characteristics of power transformers introduce a number of unique problems that are not present in transmission lines, generators and motors protection [1]. When internal faults occur in PT, immediate disconnection of the equipment is necessary to avoid extensive damage and/or preserve power system stability and power quality. Furthermore, the replacement of a faulted transformer is very expensive and time consuming. Therefore, PT protection can prevent great economic losses and also avoid long power outages [2].

Currently, percentage differential protection is a common practice for power transformer protection. However, nonlinearities in the transformer core or in the currents transformers (CTs) core, can generate a substantial differential current causing a percentage differential relay miss-trip [1]. Thus, the differential relays are equipped with harmonic restraint, where magnitudes of the second and fifth harmonic components are compared with the fundamental frequency component magnitude to discriminate internal faults from magnetizing inrush currents and transformer overexcitation, respectively [3].

Aiming to improve the efficiency of PT differential protection a significant number of relaying formulations have been proposed [4–24]. These formulations are based on finite elements, artificial neural networks, fuzzy systems, dynamical principal components analysis, wavelet transforms (WTs), hybrid systems, symmetrical components, space vector and power-based protection methods. In [25] is presented a review on computational intelligence techniques applied on oil-immersed PT conditions evaluation for operating costs reduction, to enhance operational reliability and to improve power supply and customer service. However, all mentioned relaying formulations have hard to design parameters, which make real life construction difficult. Ref. [26] present a Discrete Wavelet Transform (DWT) application for PT differential protection, however the proposed scheme does not have adaptive characteristics. In [27] is proposed an adaptive differential protection scheme, however not all possible PT operational conditions were tested and evaluated.

In this paper, a simple to implement percentage differential relaying algorithm for three-phase power transformers protection based on DWT is proposed. The proposed algorithm formulation uses logical decision criteria based on wavelets coefficient spectral energy variation to identify and discriminate correctly internal and external faults, inrush currents and incipient internal faults all under or not current transformer saturation. In order to analyze the proposed algorithms efficiency, the formulation was built in MATLAB® platform [28] and tested with simulated fault cases under BPA'S ATP/EMTP software [29]. Comparative test results with a traditional percentage differential relaying with harmonic restraint formulation [1] shows the proposed algorithms efficiency and its easiness for real life construction.

The remaining of this paper is divided as follows. Section 2 describes the percentage differential protection formulation. Section 3 describes the DWT used. The proposed algorithm is presented on Section 4, while Section 5 presents the case study. Section 6

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presents the test results and discussions. The conclusions of this work are presented on Section 7.

2. Percentage differential protection

The percentage differential relay can be implemented on PT through overcurrent relays (**R**) with operation (**o**) and restriction coils (**r**), as illustrated in Fig. 1. Here, N1 and N2 are the primary and secondary windings number of turns, respectively.

The differential relay operation is based on two currents [1,2]:

1. *Restraint current* (i_r):

$$i_r = \frac{(i_{2P} + i_{2S})}{2} \tag{1}$$

where i_{2P} is the CT secondary current connected to the power transformer primary winding, and i_{2S} is the CT secondary current connected to the power transformer secondary winding.

2. *Differential current* (i_d):

$$i_d = i_{2P} - i_{2S} \tag{2}$$

In this protection philosophy, CTs transformation errors, CTs mismatch and power transformer variable taps can cause a differential current to flow in the overcurrent relay (**R**). To consider these effects, the differential protection formulation compares the value of *differential current* to a fixed percentage value, named *K*, of the *restraint current*. This percentage value is the slope of the percentage differential characteristic and determines the relay trip zone [1]. The *K* value is used as safety margin and is defined by:

$$K = \frac{i_{2P} - i_{2S}}{(i_{2P} + i_{2S})/2} = \frac{i_d}{i_r} \tag{3}$$

Typical values for *K* are 10%, 20% and 40%. Differential protection relays identify internal faults when the *differential current* exceeds this pre-determinate *restraint current* percentage value, as show by:

$$i_d \geq K \cdot i_r = K \cdot \frac{(i_{2P} + i_{2S})}{2} \tag{4}$$

3. Discrete wavelet transform

EPS fault generated signals are associated with fast electromagnetic transients, are typically non-periodic and with high-frequency oscillations. These characteristics present a problem for traditional Fourier analysis techniques [30]. The wavelet transform (WT) is a powerful tool that can be used in power systems transient phenomena analysis. It has the ability to extract information from transient signals simultaneously in both time and frequency domain and has replaced the Fourier analysis in many applications [31]. This ability can greatly help the detection of signal features which may be useful in characterizing the source of the transient or the state of the post-disturbance system [30].

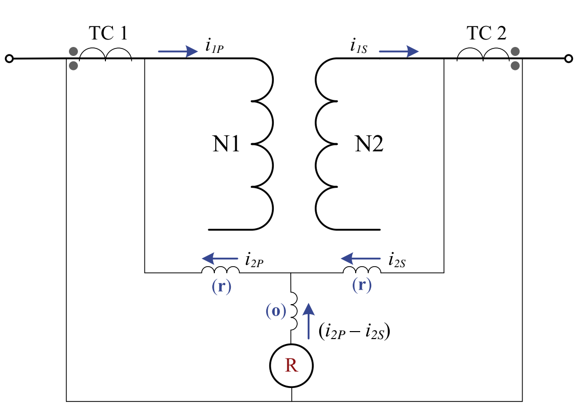

Fig. 1. Schemes of a single-phase transformer using a percentage differential protection relay.

Discrete wavelet transform (DWT) is derived from a continuous wavelet transform and is defined as:

$$DWT[m,n] = \frac{1}{\sqrt{a_0^m}} \sum_{k=-\infty}^{+\infty} x[k]\psi\left(k - \frac{a_0^m n b_0}{a_0^m}\right) \tag{5}$$

where ψ is the mother wavelet and, $x[k]$ is the discretized signal function. The mother wavelets may be dilated and translated discretely by selecting the scaling and translation parameters $a = a_0^m$ and $b = nb_0a_0^m$ respectively (with fixed constants $a_0 > 1$, $b_0 > 1$, m and n belonging the set of positive integers) [32].

3.1. DWT and filters bank

Since the purpose of the discretization process is to eliminate the redundancy of the continuous form and to ensure inversion, the choice of a_0 and b_0 must be made so that mother wavelets form an orthonormal basis. This condition originates a signal processing technique named multi-resolution analysis of Mallat (MRA) [33]. DWT can be implemented by a multistage filter bank, as illustrated in Fig. 2.

The Mallat algorithm consists of series of high-pass (HP) and the low-pass (LP) filters that decompose the original signal $\boldsymbol{x[k]}$ into approximation $\mathbf{a}(\boldsymbol{k})$ and detail $\mathbf{d}(\boldsymbol{k})$ coefficient each one corresponding to a frequency bandwidth. The first detail has $n/2$ samples and the dth detail has $n/2^d$ samples, since for each frequency scale that the DWT is computed, the original signal is decimated leaving a total of n points of the signal in the wavelet domain.

3.2. Detail coefficient energy

The wavelet coefficient energy, named detail-spectrum-energy (DSE), can be calculated by means of a moving data window that goes through the detail coefficients shifting one coefficient at a time [16]. Thus, the DSE is expressed as:

$$\varepsilon_w(k) = \sum_{n=k}^{k+N_\omega/2^j} d_j^2(n) \tag{6}$$

where j is the scale factor, N_w is the number of samples contained in one cycle of the fundamental frequency of the original signal, N_s is the total number of samples of the original signal, n is the sample number and $k = \{1, 2, \ldots, (N_s - N_\omega)/2^j\}$.

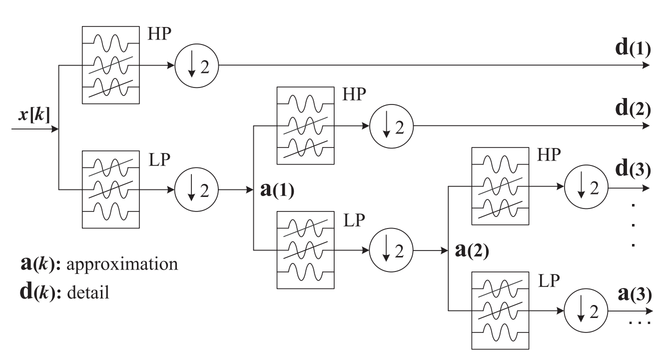

Fig. 2. DWT filter bank framework.

4. Proposed protection algorithm

The identification and discrimination between internal faults, external faults and inrush currents in PT can be made by the three-phase differential current signals analysis. A change in the spectral energy of the wavelets components of the current differential is verified when different electrical events (external faults, internal faults and/or inrush current) occur on PT [12]. Thus, the discrimination criteria proposed in this work is based in the spectral energy level generated by the event type.

The proposed algorithm consists of two sub-routines, named blocks. The flow chart of the proposed methodology is presented in Fig. 3.

4.1. Disturbance detection (BLOCK 1)

In this subroutine the on-line differential current, Id_{A-B-C}, is calculated for phases A, B and C considering the percentage characteristic K and the restraint currents, as shown by:

$$|Id_{A,B,C}| \geqslant |K \cdot i_r| = \left| K \cdot \frac{(i_{2p} + i_{2s})^{A,B,C}}{2} \right| \quad (7)$$

where $Id_{A,B,C}$ is the differential current on phases A, B and C, K is the percentage differential characteristic and i_r is the restraint current.

When condition expressed on (7) is fulfilled by any of the three-phase differential currents, the algorithm initiates the second subroutine to classify the detected event type.

4.2. Disturbance identification (BLOCK 2)

In this subroutine, the three-phase differential currents are initially processed through a DWT. After, a restraint index R_{ind}, is calculated. This index quantifies the relative magnitude characteristic of the differential signals in the 1st detail (D_1) and is defined as the relation between the maximum detail coefficient from D_1 and the DSE of the wavelet coefficient. Thus, R_{ind} is defined as:

$$R_{ind} = \frac{d_{\max,D_1}}{\sum_{c=1}^{M} |d_{(c)}|^2 \Delta t} \quad (8)$$

where $d_{\max,D1}$ is the maximum detail coefficient from D_1, M is the total number of wavelet coefficients from D_1 and Δt is the sampling period.

DWT is used to extract useful information from high frequency components of the differential currents. The DSE of detail coefficients in the wavelet decomposition is calculated and the change in these spectral energies is used to discriminate transient disturbances of PT internal faults. The discrimination is made through the comparison of the index R_{ind} with a threshold value (Th), considering a pre-defined number of consecutive data windows (N_W). In this work, $N_W = 3$ was used on the first detail the DWT

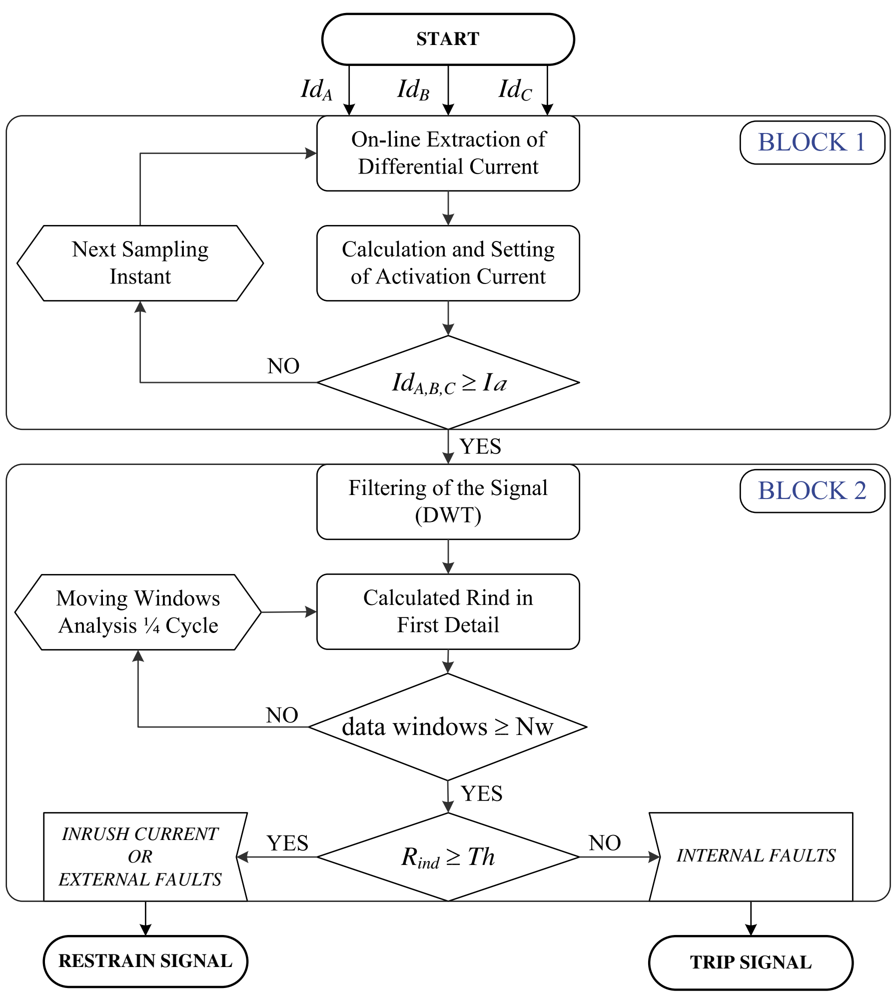

Fig. 3. Proposed algorithm operation scheme.

filter to calculate the restraint index in a fixed data windows of 1/4 cycle (0.005 ms at 50 Hz), as illustrated in Fig. 4a.

4.3. Adaptive relay characteristic

In the proposed methodology, an adaptive threshold value called Th is used. This is necessary so the proposed methodology can become more robust. The adaptive threshold value is defined by:

$$Th = k_1 \cdot |(i_{2p} - i_{2S})| = k_1 \cdot i_d \quad (9)$$

where k_1 represents the a sensibility characteristic and is a fixed percentage value.

External faults can generate a small differential current, i_d. Thus, the adaptive threshold value decreases, increasing the restriction zone of the relay as illustrated in Fig. 4b. On the other hand, internal faults generate high differential currents increasing the relay trip zone. Fig. 4c illustrates the Trip Signal to relay for a internal faults conditions.

In this proposed formulation, internal faults are identified if at least two of the three calculated values of R_{ind} index are lower than the adaptive threshold value Th, as illustrated in Fig. 4b. On the other hand, external faults and inrush currents are identified when the restraint index R_{ind} is greater than Th in at least two analyzed windows.

4.4. Implementation

The proposed algorithm was implemented in MATLAB® platform [28]. Fig. 5 illustrates the graphical user interface (GUI) developed.

The GUI can be divided in three modules, namely:

(1) Disturbance type: used to select the basic characteristics of the simulated disturbance (internal or external fault location, fault resistance value, fault type and instant of energization of the three-phase power transformer);
(2) Wavelet analysis: to define the mother wavelet type (Daubechies, Symlet, Harr, Coiflet or Morlet) and the decomposition level of the filter bank used in the differential current analysis;
(3) Algorithm output: presents the trip or restrain relay signal after the disturbance analysis.

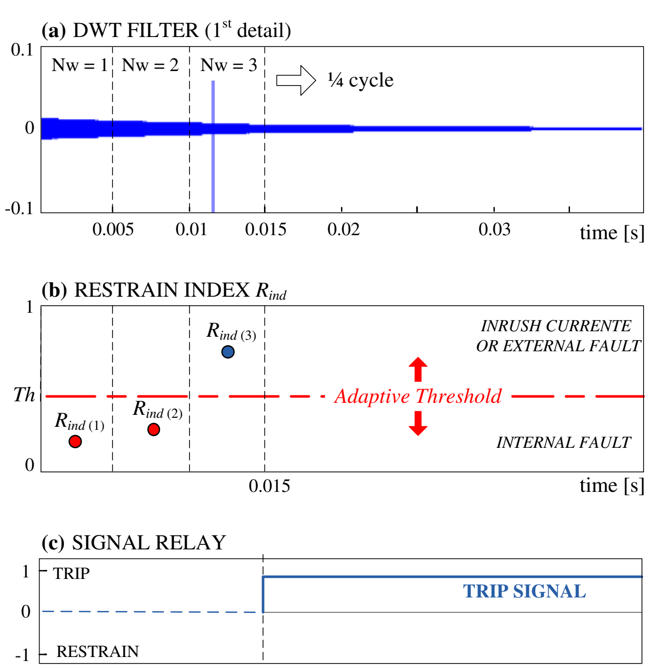

Fig. 4. (a) R_{ind} calculation process in a pre-defined number of the data windows. (b) Comparison of the R_{ind} with adaptive threshold value. (c) Trip signal relay.

5. Case study

To validate the proposed algorithm performance, a case study was carried out using the BPA'S ATP/EMTP software [29]. Fig. 6 illustrates the electrical power system studied which consists of:

(A) Three-phase generator: 13.8 kV, 30 MVA, 50 Hz;
(B) Three-phase power transformer (PT): 35 MVA, 13.8/138 kV, Y_g–Δ;
(C) Current transformer (CT) with 1200/5 and 200/5 turns ratio;
(D) Transmission line with a length of 100 km;
(E) Variable load of 3, 5, 10 and 25 MVA all with power factor of 0.92.

Switch S_1 is used to simulate the PT energization condition. In this example the PT is connected without load. Switch S_3 simulates external faults through a fault resistance, named R_f, and switch S_2 simulates PT internal faults. Switch S_4 is used to simulate load changes.

5.1. Simulation test results

All internal faults simulated in this work are introduced at the transformer windings terminals. Fig. 7a presents the three-phase voltage signals on the low voltage (LV) side of the PT caused by an external fault in phase-A. This external fault is produce at 0.5 km of the PT on the transmission line. Fig. 7b shows the three-phase differential currents generated and the CT saturation effects. Fig. 7c shows the harmonics decomposition of differential current of phase-A and Fig. 7d presents the comparison between trip/restrain signal of the conventional and proposed method. Note that the conventional method uses the second harmonic level to discriminate between inrush current and internal fault and in Fig. 7c is observed that the second harmonics level is characteristic of the inrush current.

Fig. 8a presents the three-phase voltages on the high voltage (HV) side of the PT due to an internal fault. The fault resistances (R_F) in phases are: phase-A = 1 Ω, phase-B = 0.1 Ω and phase-C = 10 Ω. Fig. 8b presents the three-phase differential currents. It can be seen that greater resistance faults produce smaller differential currents. Fig. 8c shows the harmonic decomposition of differential current on phase-C and Fig. 8d present the comparison between trip/restrain signal of the conventional and proposed protection method. Note that the second harmonic level is representing an inrush current but the real contingency is an internal fault. Thus, the conventional method is operating incorrectly while the proposed method successfully discriminates the disturbance.

Fig. 9a presents the voltage waveforms in the high voltage (HV) side, due to a PT energization condition. Fig. 9b illustrates clearly the high inrush current value compared with the internal fault current shown in Fig. 8b. Fig. 9c shows the harmonic decomposition of differential current on phase-C and Fig. 9d present the comparison between trip/restrain signal of the conventional and proposed protection method. In this case, both methods correctly discriminated the disturbance.

5.2. Tested case set

Different test cases comprising inrush currents, internal and external faults were simulated in order to investigate the proposed

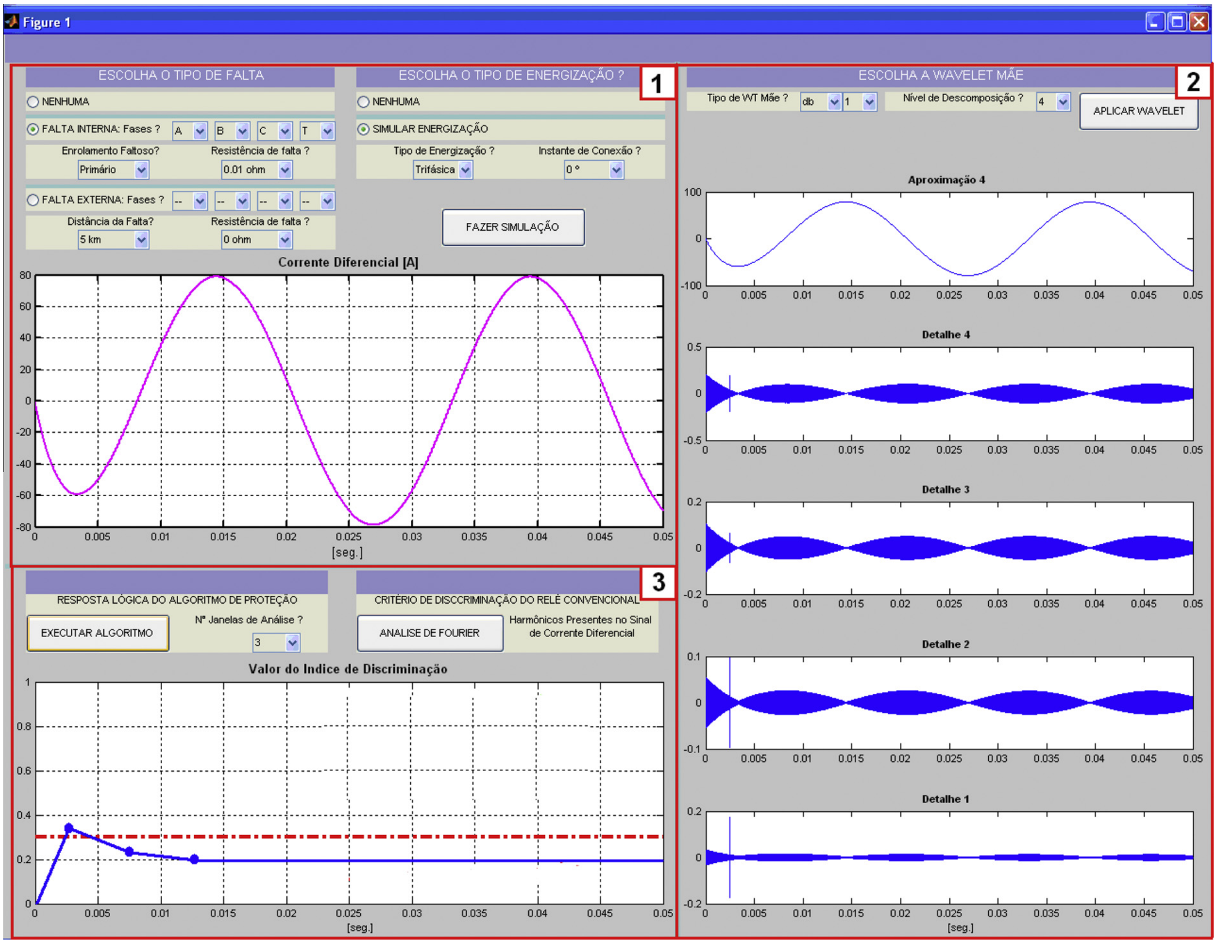

Fig. 5. Graphical implementation in MATLAB environment.

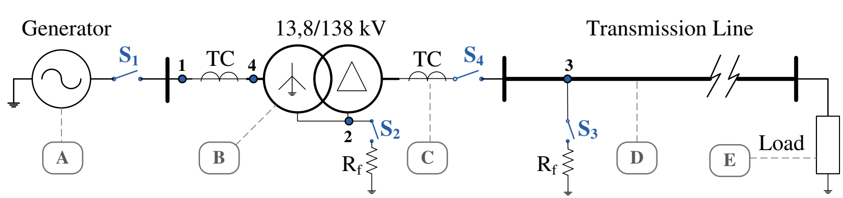

Fig. 6. Simulated electric power system.

method efficiency. A sampling frequency of the 25 kHz was used in the simulation tests. The simulated disturbances were divided in the following six different test set, which are summarized as:

- Set 1: PT energization: (E)
  - on both PT primary and secondary sides;
  - switching inception angles: 0°, 30°, 60° and 90°;
  - under operation without load;
  - total: 240 energization cases.
- Set 2: Internal faults: (IF)
  - on primary and secondary windings of PT;
  - fault resistances (RF): 0.01, 10, 50, and 100 Ω;
  - load: 3, 5, 10, and 25 MVA;
  - fault type: A–g, AB, AB–g, ABC;
  - total: 640 cases.
- Set 3: External faults: (EF)
  - on transmission line at 0.5 km of PT;
  - fault resistances (RF): 0.01, 10, 50, and 100 Ω;
  - load: 3, 5, 10, and 25 MVA;
  - fault type: A–g, AB, AB–g, ABC;
  - total: 320 cases.
- Set 4: External faults between PT and the secondary CT:
  - fault resistances (RF): 0.01, 10, 50, and 100 Ω;
  - load: 3, 5, 10, and 25 MVA;
  - fault type: A–g, AB, AB–g, ABC;
  - total: 320 cases.
- Set 5: Energization with internal fault: (E + IF)
  - switching inception angles: 0°, 30°, 60° and 90°,
  - fault resistances (RF): 0.01, 10, 50, and 100 Ω;
  - load: 50 MVA;
  - fault type: A–g, AB, AB–g, ABC;
  - total: 880 cases.

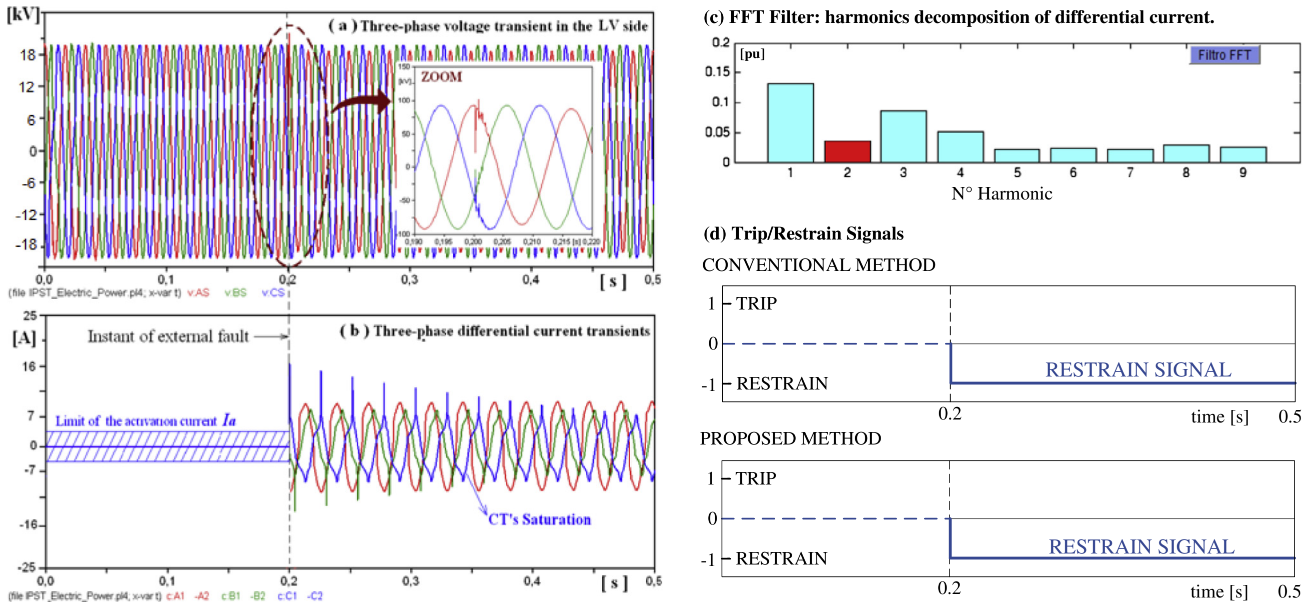

Fig. 7. Transient signal caused by external fault on transmission line.

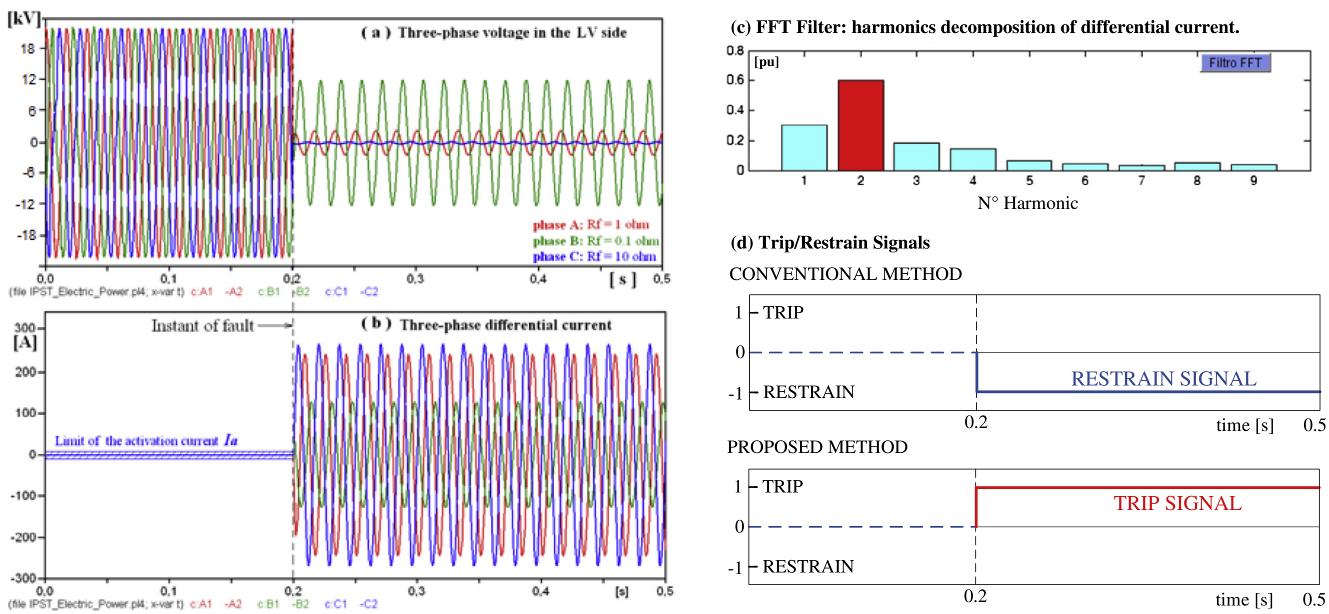

Fig. 8. Voltage and differential current signal caused by internal faults in PT.

6. Results and discussion

6.1. Switching inception angle effect

The magnitude and shape of inrush currents changes depending on several factors such as energization instant, core remnant flux, TC saturation and non-linearity of transformer core. In this work 12 (twelve) energization test cases were simulated for each switching angle and evaluated with the following mother wavelets: Daubechies (Db), Harr (Hr), Symlet (Sy), Coiflet (Coif) and Morlet (Mo).

Table 1 show the proposed method performance for test set 1 using each mother wavelet. As can be seen, Daubechies wavelet presented the best performance for all switching angles, with 97.11% of correct answers.

6.2. Fault resistance and internal faults type effect

Table 2 summarizes the methods efficiency when tested with different fault types and resistances (R_F). The performance was evaluated considering a constant load of 25 MVA at the end of the transmission line. As can be seen, there was an accuracy decrease with the fault resistance increase. For internal fault cases (set 2) fault types AB and ABC, it was observed that as the fault resistance increased, the spectral energy variation was very similar to the produced by the energization cases, hindering the correct discrimination. However, the discrimination of faults type A–g

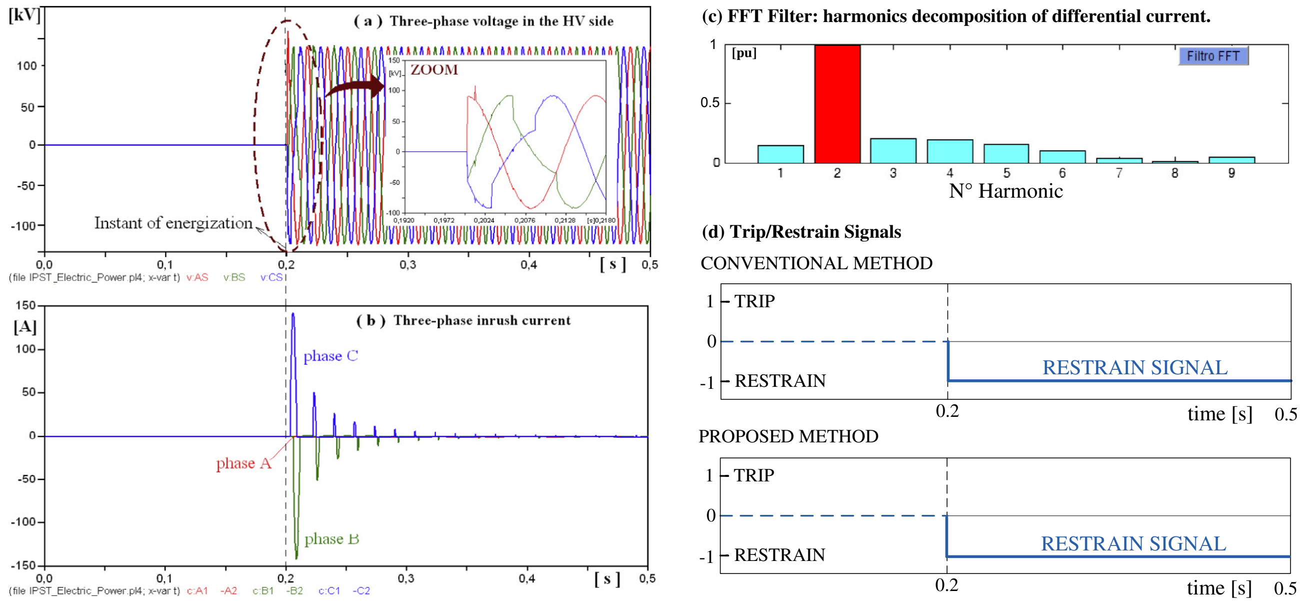

Fig. 9. Voltage and differential current caused by PT energization.

Table 1
Performance algorithm proposed in percentage of operation correct (OC) [%] to different switching instants [°].

Switch angle	Mother wavelet type					OC [%]
	Db	Hr	Sy	Coif	Mo	
0°	12	7	12	12	12	91.66
30°	12	2	12	12	12	83.33
60°	12	0	10	12	10	73.33
90°	11	0	9	8	6	56.66
OC [%]	97.11	18.75	89.58	91.66	85.41	

Table 2
Performance algorithm proposed in percentage [%] with load constant of 25 [MVA].

Test event	R_F [Ω]	Faults type			
		A–g	AB	AB–g	ABC
Set 2	0.01	100.0	100.0	100.0	100.0
	10	99.38	98.75	100.0	97.34
	50	98.75	91.25	97.50	92.81
	100	97.65	87.66	96.87	88.28
Set 3	0.01	100.0	100.0	100.0	100.0
	10	100.0	100.0	100.0	100.0
	50	99.22	98.28	100.0	100.0
	100	98.90	97.66	98.44	100.0
Set 4	0.01	99.38	100.0	100.0	100.0
	10	98.75	98.75	99.68	100.0
	50	97.81	97.65	98.75	98.75
	100	97.18	97.03	98.12	95.47

and AB–g showed little sensitivity to R_F variation in test set 2, 3, and 4.

6.3. Load variation effect

Internal short circuits are generally transformer windings turn–turn or turn-earth short circuits. Internal incipient faults usually develop slowly, often in the form of a gradual deterioration of insulation [17]. Different loads were switched at secondary side of PT at different switching times to investigate possible effects on the methods efficiency.

Table 3
Percentage of the trip correct [%] of the algorithm proposed to different load estate and faults type.

Load [MVA]	R_F [Ω]	Faults type			
		A–g	AB	AB–g	ABC
3	0.01	100.0	100.0	100.0	100.0
	10	99.21	98.75	100.0	97.34
	50	98.75	90.93	97.03	92.81
	100	97.65	87.66	96.87	88.28
5	0.01	100.0	100.0	100.0	100.0
	10	99.38	98.75	100.0	97.34
	50	98.75	91.25	97.50	92.81
	100	97.65	87.66	96.87	88.28
10	0.01	100.0	100.0	100.0	100.0
	10	99.38	98.75	100.0	97.34
	50	98.75	91.25	97.50	92.81
	100	97.65	87.66	96.87	88.28
25	0.01	100.0	100.0	100.0	100.0
	10	100.0	100.0	100.0	99.37
	50	98.75	91.25	97.50	98.90
	100	97.65	87.66	96.87	88.90

Table 3 presents the obtained results for different internal fault cases (Set 2) considering different load levels. As can be seen, the load level has small effect on the proposed protection methods efficiency.

On the other hand, the abrupt load level change connected on the power transformer may generate transients that the proposed algorithm should be able to distinguish from a fault situation [17]. Table 4 simulated test cases results through six switching sequences considering an initial load of 10 MVA. Thus, the cases tested are: load increasing 150%, load decreasing 50% and load decreasing 75% to four switching inception angles (0°, 30°, 60° and 90°).

6.4. Mother wavelet effect

Proper choice of the mother wavelet plays a significant role on the proposed methods performance. Therefore, careful consideration is required wavelet family selection.

Table 4
Decision algorithm for load abrupt changes in power transformer in four switching instant.

Load changes [%]	Load changes [MVA]	Switching sequence	Case tested	Decision algorithm
+150	25	A–B–C	4	Restrain
	↑	A–C–B	4	Restrain
	10	B–A–C	4	Restrain
		B–C–A	4	Restrain
		C–A–B	4	Restrain
		C–B–A	4	Restrain
−50	10	A–B–C	4	Restrain
	↓	A–C–B	4	Restrain
	5	B–A–C	4	Restrain
		B–C–A	4	Restrain
		C–A–B	4	Restrain
		C–B–A	4	Restrain
−75	10	A–B–C	4	Restrain
	↓	A–C–B	4	Restrain
	2.5	B–A–C	4	Restrain
		B–C–A	4	Restrain
		C–A–B	4	Restrain
		C–B–A	4	Restrain

In this work, the differential current change in spectral energy of the wavelet component is calculated and used to discriminate between internal faults and external faults or inrush currents. To verify the wavelet function type effect on the proposed formulation test results of set cases 1, 2, 3 and 5 were analyzed. The wavelet functions analyzed were: Daubechies (Db), Haar (Hr), Symlet (Sy), Coiflet (Coif) and Morlet (Mo). Table 5 presents the test results. As can be seen, it was found that the mother wavelet Daubechies showed the highest performance and efficiency in discrimination of simulated disturbances. The Symlet and Coiflet mother wavelets presented a satisfactory performance with greater efficient than the Morlet type. On the other hand, the wavelet Haar type did not achieved good performance for the simulated cases, presenting many inaccuracies in the discrimination of all test disturbances.

Table 5
Comparative performance of functions wavelets to test set different.

Mother wavelet	Test set	Correct operations [%] Proposed method [DWT]	Correct operations [%] Fourier analysis [FFT]
Daubechies (Db)	1	97.1	98.0
	2	99.2	85.5
	3	99.5	75.2
	5	97.8	81.3
Haar (Hr)	1	18.7	98.0
	2	18.2	85.5
	3	25.0	75.2
	5	14.5	81.3
Symlet (Sy)	1	89.6	98.0
	2	85.9	85.5
	3	84.5	75.2
	5	87.4	81.3
Coiflet (Coif)	1	91.7	98.0
	2	87.6	85.5
	3	85.9	75.2
	5	89.6	81.3
Morlet (Mo)	1	85.4	98.0
	2	80.5	85.5
	3	78.6	75.2
	5	75.2	81.3

6.5. Comparative analysis with Fourier analysis differential relay

Harmonic constraint is the most commonly used form to ensure correct discrimination on transformer energization. In this method, transformer inrush current due to energization is recognized on the basis of second harmonic components above 16% obtained by Fourier filters [1]. However, the filtering method can sometimes delay the trip decision. In addition to this, the advances in transformer construction and improvements in core materials has brought down the level generated second harmonics, whereas its level during an internal fault can be quite high in some situations [18,19].

In this sense, Table 5 presents comparative tests between the proposed algorithm and a Fourier based differential protection methodology. It can be observed that the Fourier Analysis (FFT) based technique obtained a lower efficiency on internal faults discrimination (set 1), external fault (set 3) and energization case with internal fault (set 5). On the other hand, the FFT methodology was more efficient in all tested cases when compared with Morlet and Haar wavelet based formulations.

6.6. Harmonic analysis of differential current

In the conventional differential protection method, the 2nd harmonic component level is used to discriminate internal faults from inrush currents. In this work, the time domain evolution of this harmonic component was studied using the FFT methodology. The harmonic analysis showed that, in some inrush case studies, during initial fault period, the 2nd harmonic increased up to 70% of the fundamental component value, decreasing to pre-fault values in about two cycles (0.33 s). Still, this behavior was not repeated for all simulated inrush cases.

7. Conclusion

In this paper a novel percentage differential relaying algorithm for three-phase power transformers protection is presented. The proposed formulation uses discrete wavelet transforms (DWT) to extract transitory features of the three-phase differential currents and to detect internal faults through the spectral energy change. Based on generated tests and after critical evaluation of the protection algorithm developed, some conclusions could be observed:

- The use of WT to analyze differential signals produced by transient phenomena showed to be an effective and robust tool. The spectral energy change of wavelet coefficients proved an effective measure for discrimination of the studied disturbances.
- The protection algorithm developed in this paper presents a perspective of practical application given the simplicity under which the methodology is based.
- Based on the tests results, it was noted that the fault resistance increase produced a slight decrease in efficiency of the algorithm and the load change showed no effect to the performance of the algorithm.
- The performance comparison between different mother wavelet types showed that the use of the Daubechies is the most appropriate for this study.
- The comparative study with the traditional differential protection algorithm showed that the proposed formulation presents greater performance.

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