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Application of Discrete Wavelet Transform for Differential Protection of Power Transformers

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***Abstract*— This paper presents a novel formulation for differential protection of three-phase transformers. The Discrete Wavelet Transform (DWT) is employed to extract transitory features of transformer three-phase differential currents to detect internal faulty conditions. The performance of the proposed algorithm is evaluated through simulation of faulty and non-faulty test cases on a power transformer using ATP/EMTP software. The optimal mother wavelet selection includes performance analysis of different mother wavelets and resolution number of levels. In order to test the formulations performance, the proposed method was implemented on MatLab® environment. Simulated comparative test results with a percentage differential protection with harmonic restraint formulation shows that the proposed technique improves the discrimination performance. Simulated test cases of magnetizing inrush and close by external faults are also presented in order to test the performance of the proposed method in extreme conditions.**

***Index Terms*- *Index Terms*— Differential protection, discrete wavelet transform, high frequency details, inrush current, internal faults, power transformer.**

I. Introduction

ELECTRICAL Power Systems (EPS) are designed to provide reliable power quality for consumers. These characteristics of quality and reliability are related to strategy and the protection devices used by the utilities. In this context, Power Transformers (PT) are important elements. Power transformers protection is a task of technical and economic commitment that considers investments, operating costs and efficiency. Percentage differential protection schemes are a technically and economically feasible alternative for the Extra High Voltage (EHV) three-phase transformers protection [1]. However, under some conditions (e.g., transformer saturation, magnetizing inrush current, over excitation) significant differential currents can be induced causing incorrect operation of the protection relays based on the mentioned formulation. The correct and fast diagnosis of internal faults demands the construction of more robust and secure protection relaying algorithms.

To overcome such limitations some differential relays are equipped with harmonic restraint. In such formulations, relays are designed to restrain operation as long as the second harmonic exceeds 15% of the fundamental. For internals faults, the fundamental frequency component is large enough, in comparison to other harmonics, to cause a correct tripping [2]. However, Current Transformer (CT) saturation, transformer energization currents and high impedance faults still aren't correctly diagnosed. In order to overcome such limitations, a significant number of novel relaying formulations has been developed, based on finite elements, artificial neural networks (ANN), fuzzy logic and dynamical principal components analysis [3]-[6]. These formulations however, are applied on specific systems and have generalization difficulties. Recently, new protective schemes have also been proposed using Wavelet Transforms (WTs) [7]-[11] and the hybrid combinations [12]-[13]. However, all these proposed formulations have hard to design parameters, which make real life construction difficult.

In this paper, a differential protection scheme for three-phase transformers using Discrete Wavelet Transform (DWT) is proposed. The proposed technique uses wavelets decompositions and a logic decision algorithm, identifying and discriminating correctly external faults, inrush currents and incipient internal transformer faults. . In order to analyze the proposed formulations efficiency it was built in MATLAB® platform [14] and tested with simulated fault cases under BPA's ATP/EMTP [15]. Comparative test results with the differential protection formulation with harmonic restraint shows that the logic decision algorithm is not affected by CT saturation and is easy to construct, providing an efficient and reliable operation

II. Differential Protection

Differential protection is widely used by electric companies in order to avoid abnormal operating conditions of EPS equipments. This philosophy is applied on: power transformers protection, buses protection, large motors and generators protection and transmission lines protection, among others [16]. Considering power transformers above 10 MVA, the percentage differential relay with harmonic restraint is the most used protection scheme [2].

This transformer protection formulation uses a percentage differential relay as illustrated on Fig. 1. The operation (**o**) and restrictions (**r**) coils have an important role in the performance of the scheme (**R**).

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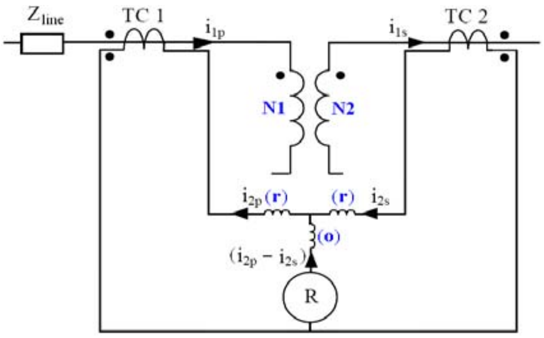

Fig. 1: Schemes of a differential protection relay.

This protection philosophy is based on two currents. The first is named *restriction current* and defined as:

$$i_r = i_m = \frac{(i_{1S} + i_{2S})}{2} \quad (1)$$

The second is named the *operating current* and defined as:

$$i_{op} = i_{1S} - i_{2S} \quad (2)$$

Under normal operating conditions or external faults, the CT secondary currents have close absolute values. However, when transformer internal faults occur, the difference between these currents increase and the percentage relay operates. To include CTs transformation errors and power transformer variable taps, a threshold current is used so that a small differential current may appear without disconnecting the transformer. This threshold current is defined through of the index ***k***, and named *percentage differential characteristic*:

$$k_{[\%]} = \frac{i_{1S} - i_{2S}}{(i_{1S} + i_{2S})/2} = \frac{i_{op}}{i_r} \quad (3)$$

Thus, the relay disconnects the transformer when:

$$i_d \geq i_{op} = k \cdot i_r = k \cdot \frac{(i_{2p} + i_{2s})}{2} \quad (4)$$

where: i_d - Detection current.

In real life operation, some operating maneuvers may cause differential currents, even when of non-faulty conditions. Among these conditions, it can be highlighted [1]: Inrush Currents, CTs Saturation, transformer over-excitation, near by External Fault removal, CT secondary unbalance and load rejection. The traditional methods used to prevent tripping due to these conditions are [1]: Desensitize the relay during startup, Supervise the relay with voltage relays, Add time delay and Detect magnetizing inrush using the current harmonics.

III. Wavelet Transform

The Wavelet Transform (WT) use in the electric machines protection, especially in differential protection of power transformers, has managed to solve many of the problems mentioned previously. The frequency analysis of discrete signals is traditionally performed using Fourier Analysis based transformations, such as the Discrete Fourier Transform (DFT) and the Windowed Discrete Fourier Transform (WDFT).

The Discrete Wavelet Transform (DWT) is a frequency analysis tool for digital signals that works as the WDFT, using a data window to perform the transformation. However, the window used by the DWT is not static: it suffers dilation and translation during the transformation algorithm. This window is called the mother wavelet. There are several known mother wavelets that can be used. In this work, it is necessary to detect singularities (abnormal frequency changes) in the signals with the highest possible precision. In order to achieve this characteristic, the mother wavelet used should consider the number of vanishing moments [17]. With more vanishing moments, higher precision can be achieved in the singularities detection. However, with more vanishing moments, the mother wavelet has also more samples, limiting the number of details in which a specific signal could be analyzed, since the mother wavelet suffers dilation as the details increase [17].

The problem of time-frequency resolution is the result of the Heisenberg Principle of Uncertainty. However, you can analyze any signal using an alternative technique known as Multi-Resolution Analysis of Mallat (MRA) [18]. The implementation of the MRA is made by DWT, where the output is a set of details, each of one corresponding to a frequency bandwidth. The higher the detail number, the lower is the frequency bandwidth. The first detail has $n/2$ samples and the d^{th} 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 for the signal in the wavelet domain. The DWT can be implemented as a filter bank consisting of a series of high-pass and low-pass filter, as illustrated on Fig. 2, where x[n] is the input signal and the downsampling by 2 is represented by (↓2).

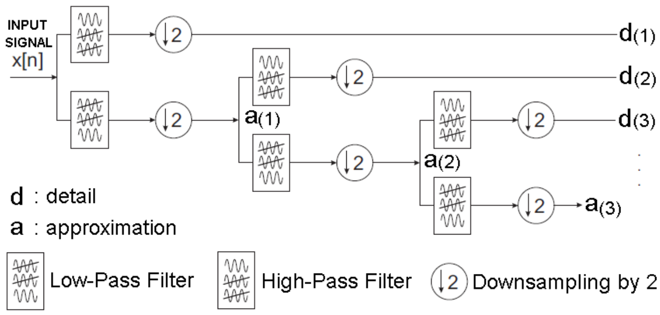

Fig. 2: DWT decomposition.

IV. Proposed Protection Algorithm

It is proposed in this work the development of a protection algorithm that can be used as a subroutine in an operating conventional differential relay.

The identification and discrimination between internal faults and inrush currents in the transformer is made from the analysis of the three-phase differential current signals, obtained through Current Transformers (CTs). The logical architecture of the proposed algorithm consists of two operational sub-routines (blocks): *Detection of Disturbance* and *Discrimination of Disturbance*. The flow chart of the proposed protection algorithm is presented on Fig. 3, which illustrates the decision logic diagram of the algorithm.

A. Detection of Disturbance (BLOCK 1)

The first operation performed by the protection algorithm is the calculation of the three-phase average currents through equation (1). The proposed protection algorithm is activated when any of these differential currents satisfy equation (5), called *Activation Current*. This activation current is regulated in the differential percentage relay through the factor ***k***, known as percentage characteristic and it is expressed in values such as: 10%, 20% and 40% [2]. This regulation is used to avoid false operations due to CT saturation or abrupt tap changes. The following equation describes the algorithms activation signal:

$$|Ia| \geq |Id_{A,B,C}| = |k \cdot i_r| = \left| k \cdot \frac{(i_{2p} + i_{2s})^{A,B,C}}{2} \right| \quad (5)$$

where: I_a - Activation current;
$Id_{A,B,C}$ - Differential current on phases *A*, *B* and *C*;
k - Percentage differential characteristic;
i_r - Restriction current.

When the condition expressed on (5) is fulfilled by any of the three-phase differential currents calculated, the algorithm begins the discrimination analysis activating Block 2 in order to determine the fault type.

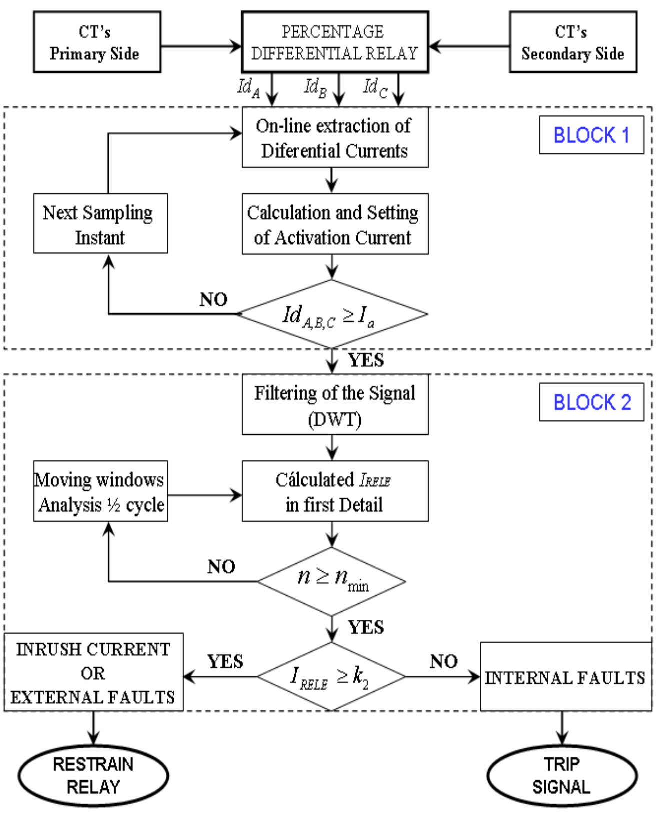

Fig. 3: Proposed Algorithm's Operation Scheme.

B. Discrimination of Disturbance (BLOCK 2)

Input signals are processed by a DWT extracting information from the transient signal in both time and frequency domains. After this procedure, approximations and details coefficients of the differential current are obtained through filter bank as illustrated on the Fig. 2. Under normal conditions, i.e., steady state operation, variations in the details coefficients values are very low. If abrupt changes (spikes) of the details coefficients in respect to time are observed, it is possible to conclude that the system is subjected to a fault.

After the DWT analysis, the proposed algorithm analyzes the first detail of the differential current. To verify if the system is subjected to an internal fault, the I_{RELE} index is calculated. This index quantifies the characteristic of the first detail of the differential signals. I_{RELE} is compared with a value k_2, which is the *Threshold*. The I_{RELE} value is defined as the relation between the maximum coefficient from the first detail (considering the differential signal previously analyzed with the DWT, $d_{max,D1}$) and the Spectral Energy (SE) of the other components present in the same detail [19]. I_{RELE} is given by:

$$I_{RELE} = \frac{I_{\max,D1}}{\sum_{n=1}^{M} |d_{(n)}|^2 \Delta t} \quad (6)$$

where: $d_{\max,D1}$ - Maximum coefficient from detail 1.
n - Coefficient *n* from detail 1.
M - Total number of coefficients of detail 1.
Δt - Sampling period.

After calculating the spectral energy components of the 1st detail, the index I_{RELE} is used to discriminate against disturbances. Under normal operation conditions the variation of the spectral energy observed in the coefficients of the wavelet detail is very low. The same happens when an external fault occurs, for example, on the transmission line. It should be noted that the spectral energy variation is greater for internal faults, in comparison with inrush currents and external faults. The proposed methodology makes the comparison of the index I_{RELE} with the threshold value (k_2) after a pre-defined number of consecutive windows. This is necessary because some of the simulations showed the occurrence of some disturbances (internal faults and energization of the power transformer going in the same time) could cause an incorrect discrimination by the algorithm. It should be noted that the index I_{RELE} is calculated on a window of pre-defined length, which was considered in this work, 1/4 cycle (0.005 ms at 50 Hz). The minimum number of windows necessary to calculate the index I_{RELE} can be chosen by the protection engineer. In some cases simulated the use of two windows of calculation was sufficient to correctly discriminate the disturbance. Fig. 4 illustrates in graphical form the procedure of calculating index I_{RELE}.

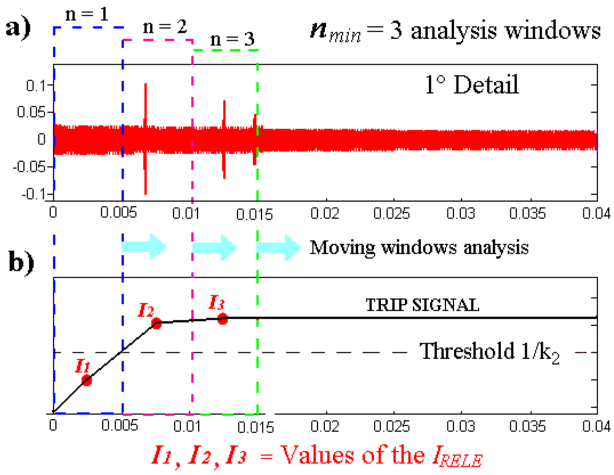

Fig. 4: Graphic examples of the calculation of index I_{RELE}.

The calculation window moves from 1/4 of cycle as the number of windows does not reach the minimum number ($n > n_{min} = 3$), when then a new index I_{RELE} is calculated. After this step, as shown in Fig. 4, three values of the I_{RELE} are calculated. The algorithm then compares the values of the indices I_{RELE} calculated in the previous step with a pre-defined threshold, called $\boldsymbol{k_2}$. Hence, a trip decision can be made, as presented in Fig. 3. In this sense, at least two of the three values calculated I_{RELE} should be larger than the threshold, for the relay to identify an *External Fault* or *Inrush Current*. For an *Internal Fault* identification, at least two of the three indexes I_{RELE} calculated should be smaller than the threshold value.

V. Case Study

The proposed protection scheme was tested using simulated test data obtained with BPA's ATP/EMTP software.

A. *Power System Simulation*

In Fig. 5 the studied electrical power system is illustrated and consists of:

A) Generator: 138 kV, 30 MVA, 50 Hz;
B) Power Transformer (PT): 35 MVA, 13,8/138 kV, Yg–Δ ;
C) Current Transformers (TC) with the 1200/5 and 200/5 characteristic;
D) Transmission line: divided in two J. Marti line sections with a total length of 100 km;
E) Load of 3, 10, 25 MVA with a power factor of 0,92.

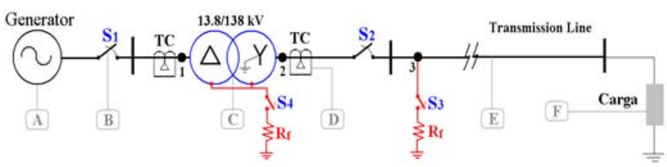

Fig. 5: Simulated electric power system.

The switches shown in Fig. 5, S_1 and S_2, are used to simulate the energization operation of the Power Transformer. In this phenomenon the PT is connected without load. The switch S_3 simulates external faults through a fault resistor R_f. The closing of the switch S_4 simulates an internal fault to the PT in both the primary and secondary windings.

B. *Types of Analyzed Events*

The proposed algorithm operates through three-phase differential currents. The simulations performed are presented on Table I:

TABLE I
Simulated Events

Nº	Type Event
1	Different energization cases, comprising different switching inception angles (0°, 30°, 60° and 90°) by closing the switch S_3 in the Low Voltage (LV) side.
2	Internal faults in both primary and secondary sides of the transformer. These faults were simulated with a fault resistance R_f of 0 Ω, 0,01 Ω, 10 Ω, and 100 Ω.
3	Several cases of external faults with fault resistances R_f values: 0 Ω, 0,01 Ω, 10 Ω, and 100 Ω.
4	Faults applied between the PT and the TC's.
5	Energizing the PT with the presence of internal faults.
6	Energizing the PT with the presence of external faults.

VI. Proposed Method Implementation

The proposed algorithm was implemented in MatLab® platform [15]. Fig. 6 presents the graphical interface developed.

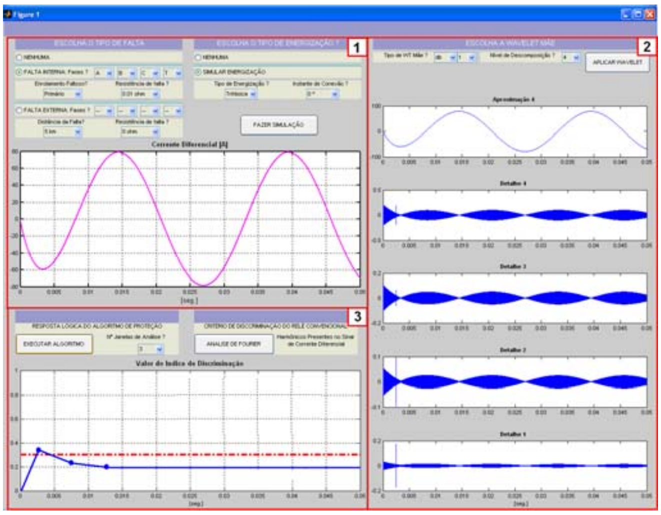

Fig. 6: Graphical implementation in MatLab environment.

As illustrated in Fig. 6, the architecture of the graphical interface can be divided into three functional blocks, namely:

1) Selecting the disturbance type;
2) Selecting of the characteristics of the Wavelet Analysis;
3) Visualization of the analyzed results.

The simulations outputs were used as inputs in the proposed algorithm, which was implemented in MatLab®. The summary of the simulated test cases in BPA's ATP/EMTP are detailed in the following.

VII. Simulations And Result

A. Simulated Cases

The simulations performed under the electrical system represented in Fig. 5 are concentrated in the following situations:

- The Fig. 7 presents an energization case. In part (a) is illustrated the voltages in the secondary of the PT. In part (b) the differential currents.
- Fig. 8 illustrates a case of energization with internal fault. The internal fault was simulated in the A phase with a faults resistance R_f of the 10 Ω.
- Fig. 9 illustrates a case of the internal fault occurring between A-B-G. The faults resistances are: R_{fA} = 10 Ω and R_{fB} = 100 Ω.
- Fig. 10 shows an external fault occurring on the transmission line at 30 km of the PT. The external fault was simulated with R_f = 0.1 Ω.
- Fig. 11 illustrates a case of external fault removal. The faults occurring at 3 km to the PT.

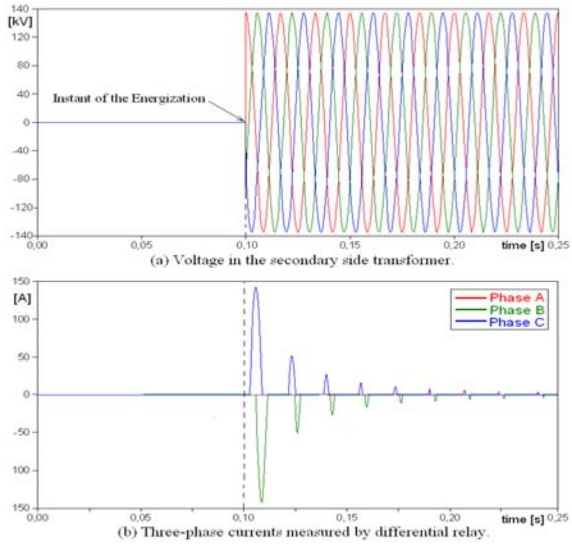

Fig. 7: Energization simulation on power transformer (PT).

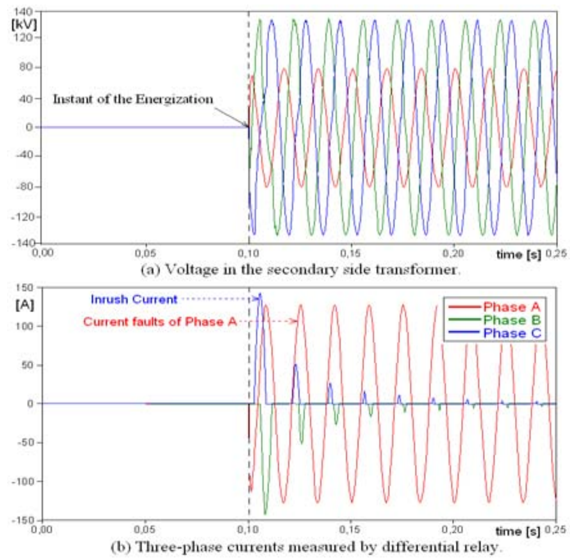

Fig. 8: Energization and internal faults simulation on PT.

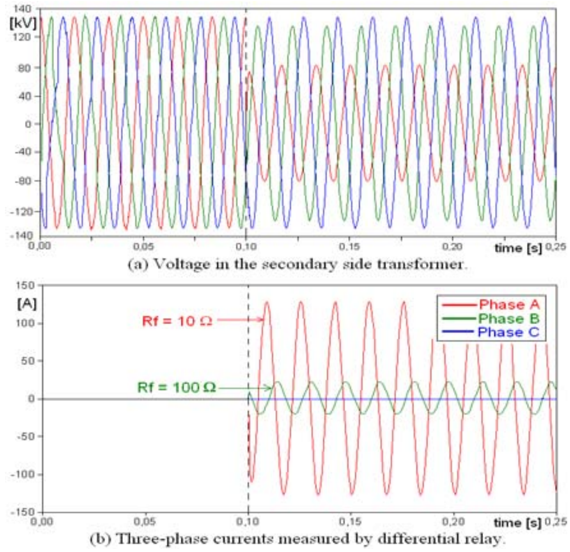

Fig. 9: Internal faults simulation on PT.

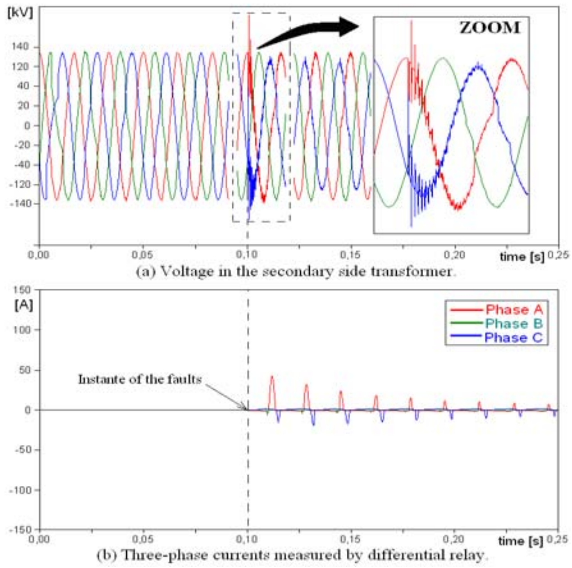

Fig. 10: External faults simulation on PT.

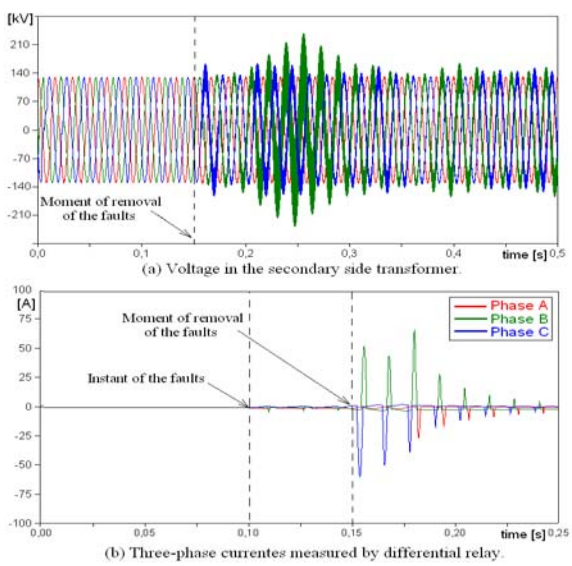

Fig. 11: External faults removal simulation.

B. Result Obtained

The following tables present the obtained test results. The results obtained were divided into two groups and are analyzed in the following:

1) Performance of the algorithm due to the value change of R_f

TABLE II
FAULT RESISTANCE (R_f) OF 0.00 Ω

Events	Nº of Cases	Correct Operation	Incorrect Operation
1	64	64	0
2	33	33	0
3	33	30	3
4	63	63	2
5	288	288	6
6	48	46	2
TOTAL	**529**	**516**	**13**
TOTAL (%)	**100**	**97.54**	**2.5**

TABLE III
FAULT RESISTANCE (R_f) OF 0.01 Ω

Events	Nº of Cases	Correct Operation	Incorrect Operation
1	64	64	0
2	33	33	0
3	33	31	2
4	63	60	3
5	288	280	8
6	48	46	2
TOTAL	**529**	**514**	**15**
TOTAL (%)	**100**	**97.16**	**2.84**

TABLE IV
FAULT RESISTANCE (R_f) OF 10 Ω

Events	Nº of Cases	Correct Operation	Incorrect Operation
1	64	60	4
2	33	33	0
3	33	28	5
4	63	60	3
5	288	260	28
6	48	40	8
TOTAL	**529**	**481**	**48**
TOTAL (%)	**100**	**90.92**	**9.08**

TABLE V
FAULT RESISTANCE (R_f) OF 100 Ω

Events	Nº of Cases	Correct Operation	Incorrect Operation
1	64	55	9
2	33	32	1
3	33	28	5
4	63	58	5
5	288	250	38
6	48	38	10
TOTAL	**529**	**461**	**68**
TOTAL (%)	**100**	**87.14**	**12.86**

There was a slight drop in accuracy of the protection algorithm with the fault resistance increase. High-impedance faults could produce a variation of spectral energy very similar to the variation produced by the energization phenomenon, that would produce a poor discrimination of the protection algorithm. Fig. 12 illustrates the decrease of accuracy in terms of faults resistance.

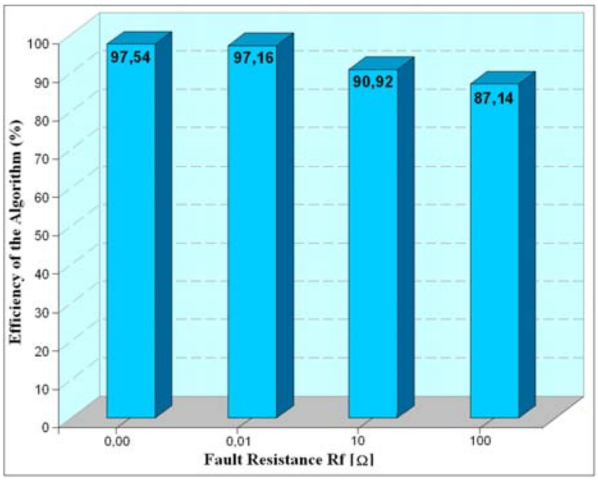

Fig. 12: Efficiency of the algorithm for different R_f.

2) Performance of the algorithm due to changes in the load

TABLE VI
LOAD OF 3 MVA

Events	Nº of Cases	Correct Operation	Incorrect Operation
1	64	64	0
2	33	32	1
3	33	31	2
4	33	33	0
5	288	287	1
6	48	47	1
TOTAL	**499**	**494**	**5**
TOTAL (%)	**100**	**98.99**	**1**

TABLE VII
LOAD OF 10 MVA

Events	Nº of Cases	Correct Operation	Incorrect Operation
1	64	62	2
2	33	32	1
3	33	31	2
4	33	33	0
5	288	285	3
6	48	45	3
TOTAL	**499**	**488**	**11**
TOTAL (%)	**100**	**97.79**	**2.21**

TABLE VIII
LOAD OF 25 MVA

Events	Nº of Cases	Correct Operation	Incorrect Operation
1	64	62	2
2	33	32	1
3	33	30	3
4	33	32	1
5	288	285	3
6	48	45	4
TOTAL	**529**	**485**	**14**
TOTAL (%)	**100**	**97.19**	**2.81**

The accuracy of the algorithm due to changes in load presented no significant variation, as summarized on Fig. 13.

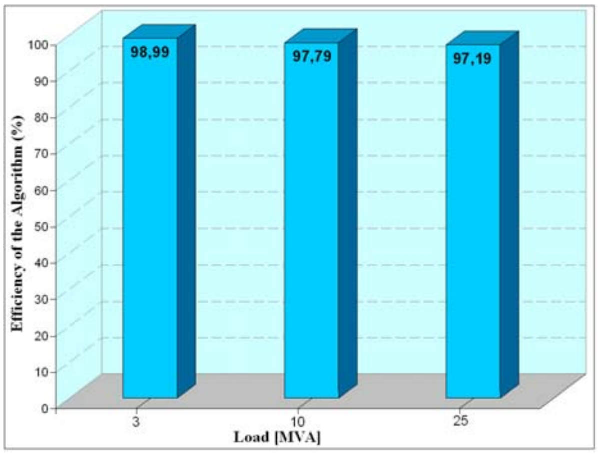

Fig. 13: Efficiency of the algorithm for different loads.

VIII. Comparison With The Conventional Relay

Another variable capable of affecting the efficiency of the proposed algorithm is the wavelet function chosen for the analysis. Also, for comparative efficiency analysis a differential protection scheme based on (5) was also implemented.

This study compared the accuracy of three different types of mother wavelet with the differential protection scheme. The mother wavelets tested were: Daubechies, Haar and Symlet. The table IX presents the comparative study results, where: EF: External Faults, IF: internal faults, and E: Energization.

TABLE IX
Comparative Performance of the Functions Wavelet Tested

Mother Wavelet	Type of Disturbance	Correct Operations (%)	
		Proposed Methodology	Conventional Methodology
Daubechies (Db)	EF	98.43	98.00
	IF	97.73	85.50
	E	98.43	75.21
	FI + E	91.14	81.32
Haar (Hr)	EF	25.00	98.00
	IF	18.18	85.50
	E	17.18	75.21
	FI + E	14.32	81.32
Symlet (Sy)	EF	84.84	98.00
	IF	85.94	85.50
	E	90.62	75.21
	FI + E	87.50	81.32

From the simulated tests it was found that the mother wavelet Daubechies type showed an excellent performance and high efficiency in discrimination of simulated disturbances. The mother wavelet Symlet presented a satisfactory performance with a smaller efficient than the Daubechies wavelet. The mother wavelet Haar type did not achieved a good performance, presenting many inaccuracies in the discrimination of simulated disturbances.

Fig. 14 shows a comparison between different types of wavelet functions used in this work. It can be observed that the traditional technique differential protection based on Fourier Analysis (FTT) obtained a lower efficiency than the proposed methodology developed in this work when using a Daubechies wavelet function.

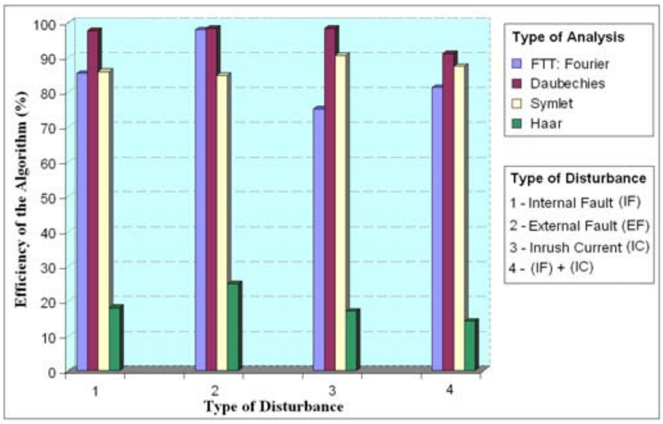

Fig. 14: Comparison between different types wavelet functions.

IX. Conclusions

The proposed method has been implemented through a graphical interface built in MATLAB ® environment and tested through computer simulations using the software ATP / EMTP. A test system of 138 kV, with a 35 MVA transformer, was used to simulated several disturbances including: normal operation conditions, internal faults, energization with internal faults, external faults and removal of external faults.

Based on these tests and after critical evaluation of the protection algorithm developed in this work, several conclusions could be observed:

- The use of Wavelet Transforms to analyze differential signals produced by transient phenomenon proved to be an effective and robust tool.
- The variation of spectral energy coefficients of wavelets proved to be an effective measure of discrimination.
- 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.
- The load variation showed no effect to the performance of the algorithm.
- The performance comparison made between the wavelet types: Daubechies, Haar and Symlet, showed that the use of the wavelet of 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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XI. Biographies

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