IMPROVED DIFFERENTIAL PROTECTION FOR POWER TRANSFORMERS

Okan ÖZGÖNENEL Çağrı KOCAMAN
e-mail:okanoz@ieee.org *e-mail:ckocaman@omu.edu.tr*
Ondokuz Mayis University, Electrical & Electronics Engineering Faculty, Power Engineering Department, 55139, Kurupelit – SAMSUN - TURKEY

Key Words: Differential Protection, Discreet Wavelet Transform (DWT), Fast Fourier Transform (FFT), Discontinuity Analysis

ABSTRACT

This paper introduces a new approach for power transformer protection algorithm. Power system signals such as current and voltage are traditionally analyzed by Fast Fourier Transform. This paper examines the analysis these signals by using Wavelet Transform, which seems to provide a reliable and computationally efficient tool for distinguishing between inrush currents and fault currents.

I. INTRODUCTION

Transformers are essential and important elements of power systems. Due to their sizes and varieties, relaying for power transformers differs from situaiton to situation. For small distribution transformers of less then 1.5 MVA, a high rupturing capacity (HRC) fuse will suffice. Others use overcurrent relays. However, for the large power transformers, differential protection based on circulating current principle is usually adopted. The differential protection converts the primary and secondary currents to a common base and compares them. The difference between these currents is small during normal operating conditions. The difference is alse small for external faults, but is larger than the difference existed for normal operating conditions. However, during an internal fault in a transformer, the difference becomes significant. The differential protection then bases on matching the primary and secondary current of the trnasformer for ideal operation. When a transformer is switched off, its core generally retains some residual flux. Later, when the transformer is re-energized, the core is likely to saturate. If the transformer is saturated, the primary windings draw large magnetizing currents from the power system. This results in a large differential current while causes differential relay to operate.

In the view of numerious benefits of digital relaying in terms of economics, performance, reliability and flexibility, significiant efforts have been made in the development of digital relaying algorithms. Numerous algorithms for the differential protection of power transformers have been proposed [1], [2], [3]. Generally, an acceptable protection scheme consists of these features: reliability, cost, simple to use and fast. Traditional digital protective relays present several drawbacks; for instance, they are usually based on algorithms that estimate the fundamental component of the current and voltage signals neglecting higher frequency transient components. Moreover, phasor estimation requires a sliding-window of a cycle that may cause a significiant delay. Furthermore, accuracy is not assured. The Fourier integral transform is a very useful tool for analyzing the frequency content of a stationary processes, when dealing with non-stationary processes, however, other methods for determining the frequency content must be applied [4].

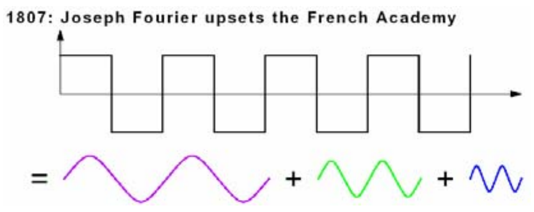
For this reason wavelet decomposition is ideal for studying transient signals and obtaining a much better current characterization and a more reliable discrimination. Wavelets allow the decomposition of a signal into different levels of resolution (frequency octaves). The basis function (Mother Wavelet) is dilated at low frequencies and compressed at high frequencies, so that large windows are used to obtain the low frequency components of the signal, while small windows reflect discontinuities [5].

Wavelet transform has a special feature of variable time – frequency localization which is very different from windowed Fourier transform.

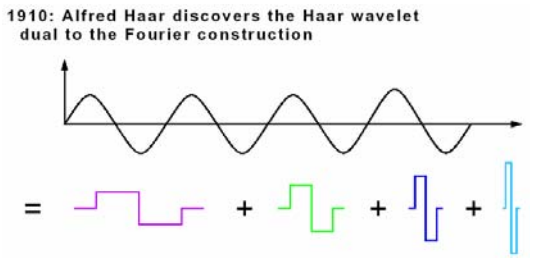
The main objectives of this paper are that discontinuities in current signals are analyzed during phase to ground faults and phase to phase faults.

II. WHY WAVELETS

Differential protection algorithms based on FFT have lots of disadvantages such as neglecting high frequency harmonics. Furthermore, different windowing technics should be applied to calculate current and voltage phasor and this causes significant time delay for the protection relay. At this case, accuracy is not assured completely. Due to increased standarts of the delivered energy quality such as IEEE 519, high performance algorithms should be taken into account. The aim of the signal processing world is the FFT by a very wide margin. Despite volumes of advanced mathematics devoted to the subject ranging from signal processing to solution of difficult differential equations, the basic concept behind the FFT is actually remarkably straightforward.



Here it is: for any bounded stationary function, there is a set of sines and cosines that can be summed to reproduce the function *exactly*. In practice this is done by adding sines at differing frequencies and amounts of phase shift. The Fourier integral transform is a very useful tool for analyzing the frequency content of a stationary processes, when dealing with non-stationary processes, however, other methods for determining the frequency content must be applied.
The Wavelet Transform is well suited to our problem. It is similar to the Fourier transform, but uses a basis function that decays rapidly from a central feature rather than the infinite sine function. For this reason wavelet decomposition is ideal for studying transient signals and obtaining a much better current characterization and a more reliable discrimination.



Wavelets allow the decomposition of a signal into different levels of resolution (frequency octaves). The basis function (Mother Wavelet) is dilated at low frequencies and compressed at high frequencies, so that large windows are used to obtain the low frequency components of the signal, while small windows reflect discontinuities.

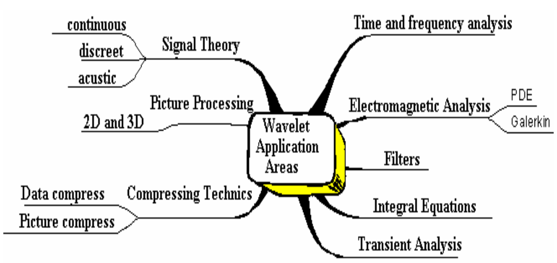


Figure 1. Application areas of wavelets

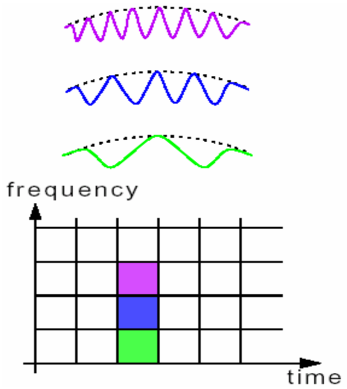


Figure 2. Gabor localizes the Fourier Transform (STFFT) in 1945.

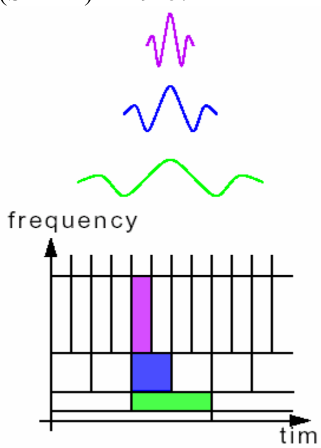


Figure 3. Morlet proposes the continuous wavelet transform in 1980.

III. SELECTION OF WAVELET FUNCTIONS

Wavelet transforms are fast and efficient means of analyzing transient voltage and current signals. In this work, Daubechies 4 wavelet function is used for discontinuity analysis of phase currents. Different kinds of Daubechies wavelets are derived. Daubechies 4 is simply chosen since it gives a more accurate solutions and minimum reconstruction error.
Daubechies wavelet transform is fundamentally same as Haar wavelet transform, however the only difference is in contents of wavelet and scale function. The following equations describe deriving Daubechies 4 (Daub 4) wavelet and scale functions step by step used in this paper.

Scale vectors for Daub 4 at level 1.

$$V_1^1 = (\alpha_1, \alpha_2, \alpha_3, \alpha_4, 0,0,0,....)$$
$$V_2^1 = (0,0,\alpha_1, \alpha_2, \alpha_3, \alpha_4, 0,0,0,....)$$
$$V_3^1 = (0,0,0,0,\alpha_1, \alpha_2, \alpha_3, \alpha_4, 0,0,0,....)$$
$$.. \qquad (1)$$
$$..$$
$$V_{\frac{N}{2}-1}^1 = (0,0,0,....\alpha_1, \alpha_2, \alpha_3, \alpha_4)$$
$$V_{\frac{N}{2}}^1 = (\alpha_1, \alpha_2, 0,0,0,....0,0,\alpha_3, \alpha_4)$$

where

$$\alpha_1 = \frac{1+\sqrt{3}}{4\sqrt{2}}, \alpha_2 = \frac{3+\sqrt{3}}{4\sqrt{2}}, \alpha_3 = \frac{3-\sqrt{3}}{4\sqrt{2}}, \alpha_4 = \frac{1-\sqrt{3}}{4\sqrt{2}}$$

and N is number of samples.

As a generalized expression, equation (1) can be re-written as below.

$$V_m^1 = \alpha_1 V_{2m-1}^0 + \alpha_2 V_{2m}^0 + \alpha_3 V_{2m+1}^0 + \alpha_4 V_{2m+2}^0 \quad (2)$$

Scale vector for Daub 4 at level 2 is expressed below.

$$V_m^2 = \alpha_1 V_{2m-1}^1 + \alpha_2 V_{2m}^1 + \alpha_3 V_{2m+1}^1 + \alpha_4 V_{2m+2}^1 \quad (3)$$

Wavelet vectors for Daub 4 at level 1.

$$W_1^1 = (\beta_1, \beta_2, \beta_3, \beta_4, 0,0,0,....)$$
$$W_2^1 = (0,0,\beta_1, \beta_2, \beta_3, \beta_4, 0,0,0,....)$$
$$W_3^1 = (0,0,0,0,\beta_1, \beta_2, \beta_3, \beta_4, 0,0,0,....)$$
$$.. \quad (4)$$
$$..$$
$$W_{\frac{N}{2}-1}^1 = (0,0,0,....\beta_1, \beta_2, \beta_3, \beta_4)$$
$$W_{\frac{N}{2}}^1 = (\beta_1, \beta_2, 0,0,0,....0,0,\beta_3, \beta_4)$$

where

$$\beta_1 = \frac{1-\sqrt{3}}{4\sqrt{2}}, \beta_2 = \frac{\sqrt{3}-3}{4\sqrt{2}}, \beta_3 = \frac{3+\sqrt{3}}{4\sqrt{2}}, \beta_4 = \frac{-1-\sqrt{3}}{4\sqrt{2}}$$

and N is number of samples.

The relationship between β and α is $\beta_1 = \alpha_4$, $\beta_2 = -\alpha_3$, $\beta_3 = \alpha_2$ and $\beta_4 = -\alpha_1$.
As a generalized expression, equation (4) can be re-written as below.

$$W_m^1 = \beta_1 V_{2m-1}^0 + \beta_2 V_{2m}^0 + \beta_3 V_{2m+1}^0 + \beta_4 V_{2m+2}^0 \quad (5)$$

Wavelet vector for Daub 4 at level 2 is expressed below.

$$W_m^2 = \beta_1 V_{2m-1}^1 + \beta_2 V_{2m}^1 + \beta_3 V_{2m+1}^1 + \beta_4 V_{2m+2}^1 \quad (6)$$

Inverse wavelet transform for Daub 4 is expressed in Equation (7).

$$F = A^1 + D^1 \quad (7)$$

In Equation (7), A is called *approximation* and D is called *detail* signal where F is synthesized signal.

At level 1, A is defined as:

$$A^1 = (F.V_1^1)V_1^1 + (F.V_2^1)V_2^1 + ... + (F.V_{N/2}^1)V_{N/2}^1$$
(8)

At level 1, D is defined as:

$$D^1 = (\mathrm{F.W}_1^1)W_1^1 + (\mathrm{F.W}_2^1)W_2^1 + ... + (\mathrm{F.W}_{N/2}^1)W_{N/2}^1$$
(9)

Inverse wavelet transform for Daub 4 at level 2 is expressed in Equation (10).

$$F = A^2 + D^2 + D^1 \quad (10)$$

At level 2, A is defined as:

$$A^2 = (F.V_1^2)V_1^2 + ... + (F.V_{N/4}^2)V_{N/4}^2 \quad (11)$$

At level 2, D is defined as:

$$D^2 = (F.W_1^2)W_1^2 + ... + (F.W_{N/4}^2)W_{N/4}^2 \quad (12)$$

Figure (4) shows schematic representation of the mathematical procedure summarized above.

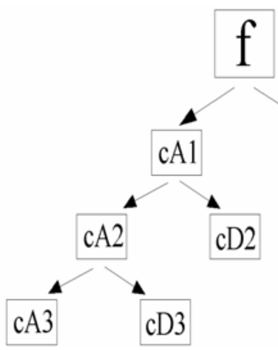


Figure 4. Signal decomposition (Mallat's wavelet tree). F is discreet signal, c is coefficient, A is approximation and D is detail.

IV. SIMULATION AND APPLICATION

A system with a generator, a three phase transformer and a load has been simulated (see Figure 5) using the ATP-EMTP software. Extensive series of simulation studies have been carried out to obtain fault transient signals for subsequence analysis.
Simulations include:

- 150 different type of energizing situations with different source triggering angles,
- 80 different type of faults either primary side or secondary side of the transformer such as phase to phase and phase to ground faults with different source triggering angles.

To simulate high impedance fault identification, all faults are generated with a fault resistance.
The fundamental frequency is 50Hz and the sampling frequency 2000Hz. This corresponds to 40 samples per cycle. 2000 Hz is chosen in order to catch the high frequency components of the signals and seemed to be adequate for our research.

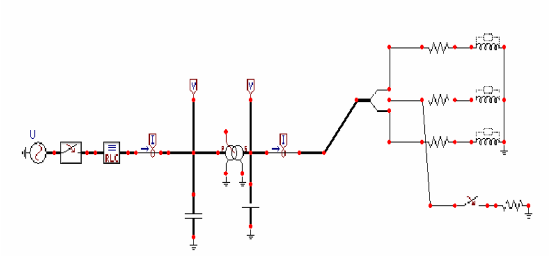


Figure 5. Simulated system. Phase to ground faults are generated at secondary side.

Similarly, phase to phase faults are also generated in both side of the transformer. A three phase – three windings laboratory transformer is used and modelled in ATP-EMTP with a saturation curve (see Figure 6).

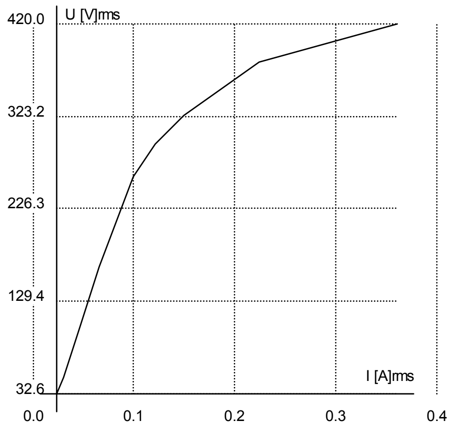


Figure 6. Saturation curve of the transformer (220V/55V/55V, 50Hz, B=1Tesla, N_1=253 turns, N_2=53 turns, S=2100VA, S=30cm^2).

The proposed fault detection scheme is as follows: Input signals are preprocessed by a discreet wavelet transform (using Daub. 4) extracting information from the transient signals simultaneously in both time and frequency domains. After this procedure, approximation and detail coefficients of the faulted current are obtained. Since approximation coefficients are the low frequency components, they are out of our scope. Variations of the detail coefficients are *distinctive* samples. Under normal conditions for steady state operation, variation of detail coefficients is very low level. If the detail coefficients have some spikes with respect to time, we can conclude that the faults that are developing or have developed.

A. The Case of Magnetizing Inrush

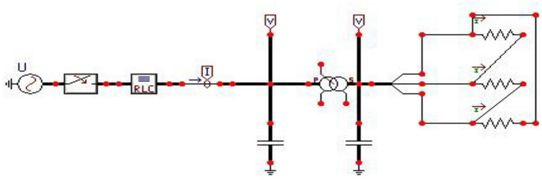


Figure 7. Simulating of magmetizing inrush current.

In Figure (7), transformer is connected YY0 and load resistances are chosen 500 Ω. Switching time is 5ms and phase angle of the supply is chosen $\delta = 0^o$ in order to simulate large magnetizing inrush current.

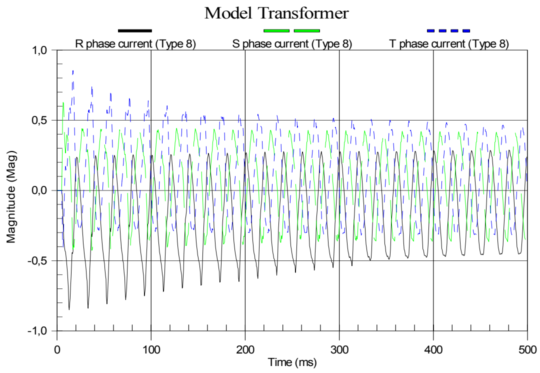


Figure 8. Typical inrush current of the model transformer.

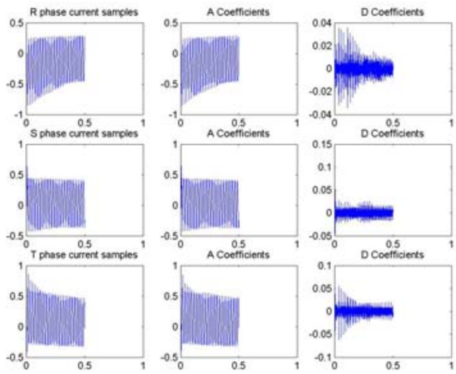


Figure 9. Decomposition of magnetizing inrush currents.

As seen from Figure 9, variation of detail (D) coefficients is quite significant and shows the ability of detection inrush currents. At this case, inrush currents have large value till 0.3s and then are in tendency of normal operation.

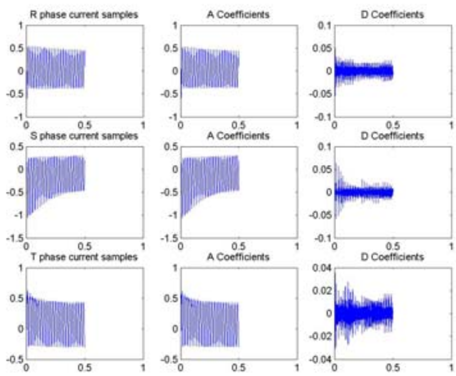


Figure 10. Inrush current in case of $\delta = 90^o$.

B. The Case of Single Phase to Ground Fault

To obtain the simulation data, the test system seen on Figure 5 is used. The resistance at the fault location is chosen $1\,\Omega$ and transformer is assumed on rated load $(5 + j6)\Omega)$. The decomposition of the voltage samples of the secondary side is seen in Figure 11. Fault time begins at 0.2s and cleared at 0.25s. Total fault time is 5ms.

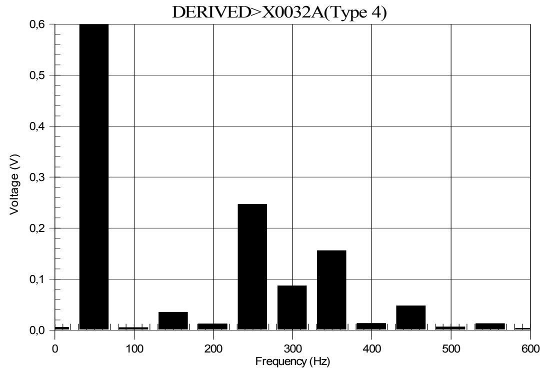


Figure 11. FFT solution of faulted voltage with rectangular window.

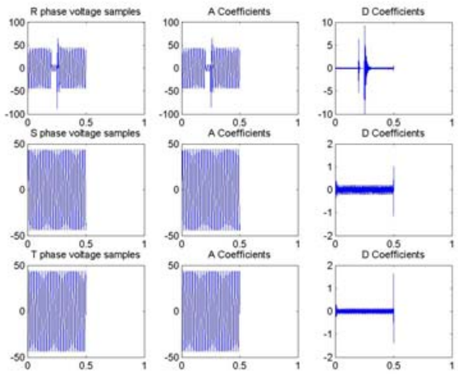


Figure 12. The case of single phase to ground fault.

As seen from Figure 12, D coefficients gives very distinctive solution for faulted current. By the similar way, phase to phase currents can also be analyzed.

V. INTERPRETATION OF WAVELET COEFFICIENTS

Recently, there are many ways of interpreting detail coefficients. In this work, maximum likelihood estimation is chosen for interpreting D coefficients. This method gives very sensitive estimations of faulted current or voltage.

A. Magnetizing Inrush Condition

For $\delta = 0^o$, the value of D coefficients are calculated as below:

R phase = 0.0355
S phase = 0.0514
T phase = 0.0548

For $\delta = 0^o$, the value of D coefficient for a pure sine signal is calculated as 0.0056.

For $\delta = 90^o$, the value of D coefficients are calculated as below:

R phase = 0.0480
S phase = 0.0637
T phase = 0.0349

According to the rated values of the transformer, these values can vary. The proposed relay software blocks the relay to send a needless trip during inrush condition with the above D coefficients.

B. Faulted Transformer Condition

The value of D coefficients are calculated as below:

R phase = 9.2616 (faulted phase)
S phase = 1.0119
T phase = 1.6242

As it is seen from the calculated D coefficients for R phase, relay can easily conclude that there is a fault and sends a trip signal.

VI. CONCLUSIONS

Very accurate and satisfactory results obtained with Daub. 4 wavelet transform are due to the following factors:

- The wavelet decomposition breaks up the signals into both time and frequency, allowing for a more complete and efficient description of each phase currents and accurate fault detection.
- Since this method is used for discontinuity analysis of the signals, even if the fault occurs at the lowest time space with a high impedance at the fault location, detail coefficients of the signal gives us faulty condition.
- The required calculations are very simple, it is only necessary to perform a wavelet decomposition at level 1 for Daub. 4.

For a novel approach, artificial neural network can be used for classification of faults in addition to detection scheme.

SUGGESTIONS

This work is based on recorded data, which is obtained from ATP-EMTP. For a future work, a real time digital signal processor can be used for analyzing current and voltage samples.

REFERENCES

1 M. A. Rahman, B. Jeyasurya, A State-of-The-Art Review of Transformer Protection Algorithms, IEEE Transactions on Power Delivery, Vol. 3, No. 2, April 1988.

2 M. A. Rahman, B. So, M. R. Zaman, M. A. Hoque, Testing of Algorithms for A Stand-Alone Digital Relay for Power Transformers, IEEE Transactions on Power Delivery, Vol. 13, No. 2, April 1998.

3 M. Habib, M.A. Marin, A Comparative Analysis of Digital Relaying Algorithms for Differential Protection of Three Phase Transformers, IEEE Transactions on Power Systems, Vol. 3. No. 3, August 1988.

4 Fancisco Martin, Jose A. Aguado, Wavelet Based ANN Approach For Transmission Line Protection, IEEE Power Engineering Review,

5 Moises Gomez-Morante, Denise W. Nicoletti, A Wavelet-Based Differential Transformer Protection, IEEE Transactions on Power Delivery, Vol. 14, No. 4, October 1999.