Development of Wavelet Transform based numeric relay for differential protection of power transformer

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Abstract— This paper proposes the wavelet transform (WT) based algorithm useful in digital differential protection of transformer. It is shown that, the wavelet transform has more distinct feature extraction property, due to its ability to extract information from the transient signals, simultaneously both in time and frequency. A decision logic has been devised using extracted feature from differential current, so as to distinguish an internal fault from an inrush / over-excitation. The proposed algorithm is evaluated using simulated inrush, over-excitation and internal fault current signals. For this purpose a transient behavioral model of power transformer has been developed using MATLAB software. Results of evaluation study show that, proposed WT based differential protection scheme can over come the problem of false tripping due to inrush/over-excitation.

Key words: Wavelet Transforms, Differential protection, Transformer, Numeric relays

1. INTRODUCTION

Advancement in DSP Technology has helped us to have new look at the existing digital protection methods for power system components. The differential protection of transformer is one such area. Over the years there has been continuos effort from researchers to provide highly reliable and precise technique for differential protection of power transformer. But till now the question of best and ideal technique remain unanswered. This is mainly due to complexity in the behavior of transformer under inrush/over excitation conditions.

The transformer inrush current flows in one winding only. This results in large differential currents. Similarly over excitation causes highly distorted differential current. But above cases are not fault conditions, therefore the relay must be able to properly discriminate inrush/over excitation condition from internal fault condition. Several researchers have proposed discrimination techniques employed in digital protection schemes.

Earliest approach for digital protection was given by Rockefeller [1]. He proposed blocking of relay operation if successive peaks of the differential currents fail to occur at about 7.5-10ms. This was based on direct recognition of the wave shape distortion of the differential currents. J. S. Thorp and A.G. Phadke [2] proposed a method based on flux restraint principle. This method depends on magnetic characteristics of the core. But, here considering exact magnetic characteristics of the iron core is very essential. The method Proposed by Keizo Ingaki et al. [4] is based on equivalent circuit principle. Here it involves sensing the change of magnetic inductance.

Most widely accepted method is the harmonic restraint technique. This method relies on the presence of rich second and fifth harmonic components in the transformer differential current. Different digital filter algorithms were proposed to extract fundamental, second and fifth harmonic components of the differential current. The presence of predominant second harmonic component is distinguished as inrush, and used in restraining the relay operation. Similarly predominant fifth harmonic presence is distinguished as over-excitation condition and, an alarm signals. The digital algorithms proposed earlier are Kalman filtering algorithm[4], IIR filter algorithm [4] and Full cycle window Fourier algorithm [3] etc. But these techniques are slow in response. Further, the simulation test results reported by these method show appreciable restraint signal even during internal fault [4]. It is also reported that, for certain cases second harmonic content will be considerable in the internal fault current affecting the relay operation. Investigations show that, in modern power transformers, second harmonic content in magnetizing inrush currents tend to be relatively small due to improvement in the core material [4]

Recently, several schemes have been proposed based on the use of ANN in differentiating between inrush and internal fault conditions [5, 6]. However the use of ANN in such studies are specific to particular transformer systems and, would have to be re-trained to use in other power transformer of different capacity, voltage rating, type of core material, and winding connections. Moreover, in these methods the discriminant requires information from time domain and frequency domain for accurate discrimination between internal fault and inrush currents. In another approach, Kasztenny B. et al. proposed use of fuzzy logic [7]. But there is no standard set criteria for setting internal parameters of a relay. Moreover, since fuzzy logic is still rule-based and technique is not robust enough to cater for

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many commonly encountered transient conditions. The Wavelet Transform is relatively new analysis tool, which is widely being used for signal analysis. Recently several papers have been published on analysis of power system transient using wavelets. P.L.Mao et al.[8] have proposed a Wavelet Transform based discriminant to distinguish inrush condition from internal fault.

This paper proposes an improved scheme of Wavelet Transform based technique, for discriminating internal faults from inrush/over-excitation condition of transformer. The logic proposed is based on quantification of extracted features from wavelet transform. In order to evaluate the proposed scheme an improved digital model of power transformer is used [3], which properly addresses the complex behavior under, both inrush as well as internal fault condition of the transformer. Sections that follow explain the development of W.T. based numeric relay and, simulation studies carried out to evaluate the proposed relaying scheme.

2. WAVELET TRANSFORM BASED NUMERIC RELAYING SCHEME

Fig.1 shows the typical differential relaying scheme for 3 phase, two winding delta/ star power transformer, supported with numeric relay. Fig.2 shows the functional blocks of a microprocessor based numeric relay. The three phase currents at the primary and secondary sides are first scaled down using current transformer of suitable ratio, then connected to the microprocessor based data acquisition system. The currents are then sampled by sample and holder (S/H) circuits and digitized by analog to digital converter (ADC) before being presented to the microprocessor. At the microprocessor, the data is processed using the wavelet transform based algorithm. Further, the relay logic program uses output of this wavelet process block to discriminate internal fault from other conditions.

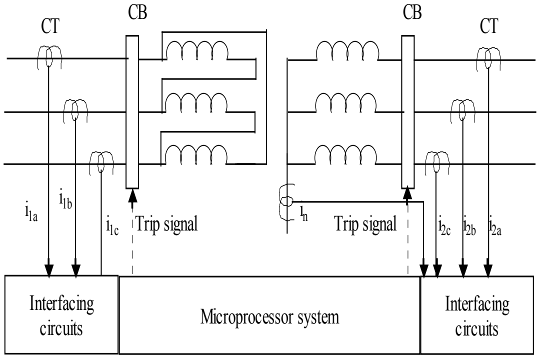


Fig.1. Differential relay connection for 3 phase Transformer

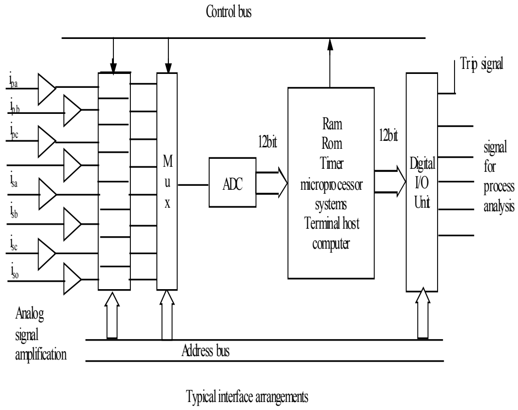


Fig . 2 Microprocessor Based Differential Relay

3. WAVELET ANALYSIS

In the *L_2 ($\Re$),* space of continuous- time energy functions, let a scalar product be defined as

$$\langle f(t),\varphi(t)\rangle = \int_{-\infty}^{\infty} f(t)\,.\,\varphi^{*}(t)dt,\ f(t)\in L_2(R). \tag{1}$$

Using this scalar product, signals $f(t) \in L_2(\Re)$ are mapped from the original domain into the transform domain, in order to obtain and make use of further information about them. Here $\varphi(t)$ is called basis function. If $\varphi(t) = e^{-j\omega t}$, then we have well-known Fourier transform:

$$F(\omega) = \int_{-\infty}^{+\infty} f(t)\, e^{-j\omega t} dt \tag{2}$$

The Fourier transform of a signal f (t) depends on the parameter ω, and is usually called spectrum. Time-dependency is lost in the transform. It cannot be seen when exactly the spectral components of the signal appear, and this is unsatisfactory for non–stationary signals. The short time Fourier transform (STFT), offers a remedy.

$$G\, f(\omega,t) = \int_{-\infty}^{+\infty} e^{-j\omega t} g(t-\tau)\, f(t)\, dt \tag{3}$$

The STFT contains time parameter τ as well as the frequency parameter ω. The basis function $g(x-t)$ is used to window the signal. Therefore, short time Fourier transforms is not only frequency based but, also time based. In the case of STFT, the division of the time –bandwidth product into time duration and bandwidth is the same for all values of ω and τ : the STFT achieves constant resolution.

In many applications it is desirable to divide the time-bandwidth product differently at different frequencies and / or at different times. This is attained by wavelet transform, and exactly this justifies its special significance. The wavelet transform is given by

$$wT(a,b)=\frac{1}{\sqrt{a}}\int_{-\infty}^{+\infty}\psi\left(\frac{t-b}{a}\right)f(t)\,dt \qquad (4)$$

Here $\psi(t)$ is called mother wavelet that must satisfy certain requirements. There are many such mother wavelets, and with them many systems of wavelet functions and wavelet transform too, which have different characteristics. The parameter b is time shift, (position) and the parameter a, a scaling (frequency) of the time variable t. With continuous parameters a and b, the wavelet transform becomes highly redundant, and associated inverse transform is not unique. In this form the wavelet transform has minor practical importance. Significant step towards a practically manageable wavelet transform is the introduction of concept of multiresolution [9,10] and dyadic wavelets[11]. Dyadic wavelets help in removing redundancy problem of CWT and, parameter 'a' and 'b' are discretized.

The DWT is defined as

$$DWT\,[m,n]=2^{-m/2}\int f(t)\psi\left(2^{-m}t-n\right)dt \qquad (5)$$

In the above $\psi(t)$ is the mother wavelet. The scaling and translation parameters 'a' and 'b' of equation (4) are functions of Integer parameter m, $a=2^{m}$ and $b=n2^{m}$. The result is geometric scaling, that is 1,1/2, ¼----- and translation by 0, n, 2n. Observation of the structure of equation (5) shows that, there is a close relationship between DWT and, perfectly reconstructing filter banks. This leads to computationally efficient and, establishes the practical significance of this transform.

In practice, DWT is implemented by using high pass and low pass qudrature mirror filter banks. In order to extract the signal features by using DWT, first it is required to decompose the signal (known as forward wavelet transform). This is done by using analysis filter bank. Fig. 3 shows 2 level decomposition. After the signal decomposition, inverse DWT (IDWT) can be obtained by using synthesis filter banks. This process is called signal reconstruction and it is reverse process of decomposition.

There are different wavelet families with various characteristics[12]. Some prominent ones are Bi-orthogonal, Daubechies, Morelets, etc. One of the most popular and widely known orthonormal wavelet is Daubechies wavelet. In our work, Daubechies family wavelet is selected as mother wavelet, this is because the decomposition solutions using Daubechies wavelet are orthogonal, compactly supported, and no marginal overlaps will happen during the signal reconstruction. The Daubechies wavlets further categorized in to Db1, Db2 etc. for the purpose of frequency range discretion. Db4 wavelet is used in this study. For applications where, the information at a specific instance of time or for a very short period of time is to be retrieved, then lower than Db4 wavelets with less number of coefficient is a better option to use than wavelets with more number of coefficients such as db20. Fig.4 shows the Db4 wavelet pattern.

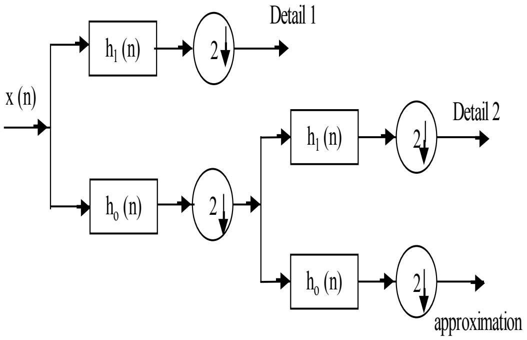


Fig.3. Two level analysis filter bank

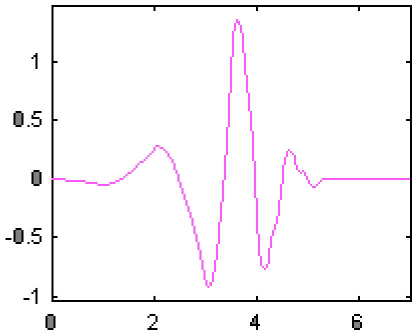


Fig.4 Db4 Wavelet

4. DETECTION SCHEME

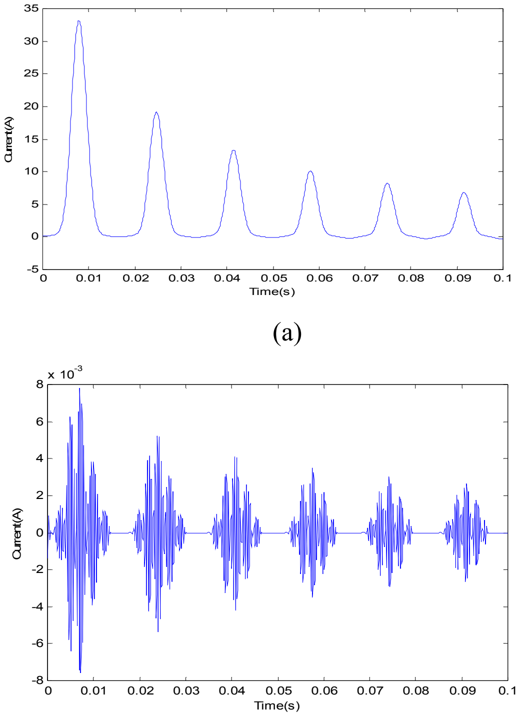
For a differential protection to be operate properly, the accurate discrimination between inrush/over-excitation and internal fault is needed. Scheme used here is based on the quantification of extracted features of DWT by the use of suitable discriminant for differential current under inrush, over-excitation and internal fault conditions. The transient behavioral model of transformer [3] is used for simulating these abnormal conditions. The specifications of transformer modeled is given in the appendix. MATLAB software is used for transient simulation. The wavelet analysis of differential current signal under following conditions are carried out:

i. Inrush condition at various switching point on voltage, different levels of residual flux.
ii. Over excitation at various percentage of rated terminal voltage.
iii. Internal fault at,
    a. various fault inception angles,
    b. various percentage of turn to ground,
    c. various number of turn-to-turn faults.

A 10 level dyadic wavelet decomposition structure is utilized. The sampling frequency used in the study is 10240 Hz. Here for clarity level 2 detail are used for quantification and for Taking decision. The wavelet analysis program is compiled under wavelet toolbox of the MATLAB, and coefficients are obtained for programming numeric relay.

Differential current obtained from the transformer for inrush conditions of zero degree switching angle and zero residual flux is shown in Fig.5. As can be seen from the Fig. 5a , null periods appear in the inrush current waveforms. Null period is the very small, later immediately the current magnitude changes from near zero to a significant value or significant value to near zero, covering most of fundamental cycle period. But this can be discerned using discrete wavelet transform. As shown in Fig.5 b, bursts appear in the null periods. These bursts will be present throughout inrush period.

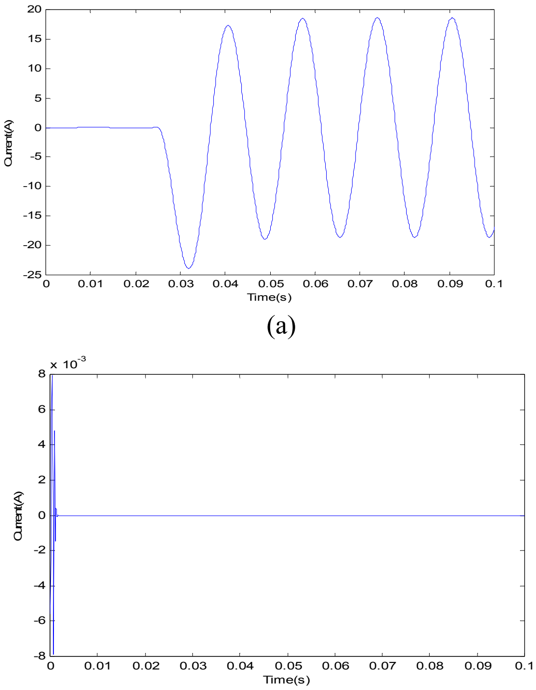
Fig.6a shows the differential current obtained during typical turn to earth on the primary winding of the transformer at the fault inception angle of 0 degree. It evident from the figure 6.a. that, at the instant of fault, high frequency transient will set up, and decays with respect to time. This feature is common to most of the faults. The feature extracted using wavelet transform for this condition is shown in Fig.6b. The wavelet transformed output for this condition shows, the short interval of bursts, and it settles to zero during rest of the interval. This forms a major distinguishing feature and well exploited in discrimination logic. Fig.7.a. shows differential current during 150% over-excitation of low voltage winding. In this, case, Fig.7.b. shows wavelet transform output with bursts occurring throughout span of observation, similar to that of inrush condition. However, distinction is, there is almost continuous burst, and little null (no burst) interval, as against the no burst interval seen in case of inrush condition.



(a)

(b)

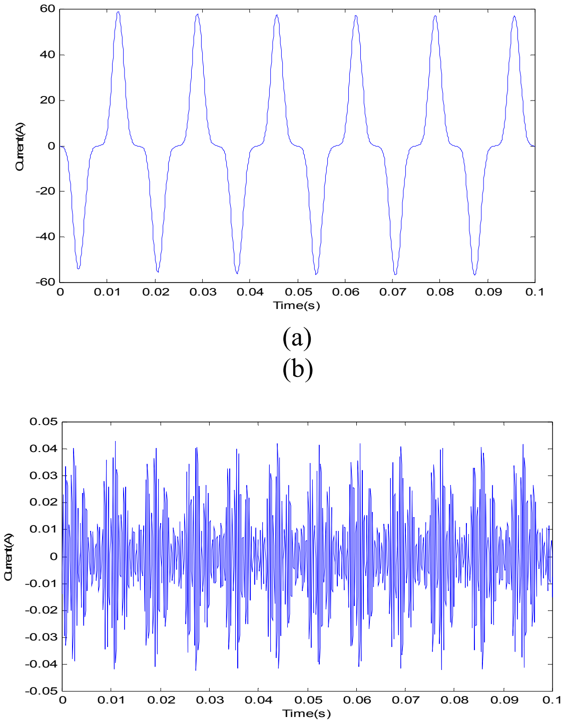
Fig 5. a) inrush current under zero flux density and zero switching angle. b) DWT at detail 2.



(a)

(b)

Fig 6. a)internal fault current when 25% primary turns are grounded with inception angle of 90 degree. b) DWT at detail 2.



(a)

(b)

Fig 7 a) current under 150% over-excitation
b) DWT at detail 2

5. W.T. BASED RESTRAINT LOGIC

Decision for restraining the relay operation under inrush and over-excitation is devised using the moving window method. In this method the extracted features are quantified by taking ratio of maximum peak of transformed current in i^{th} moving window to the maximum peak of transformed current in the fist window.

That is,

$$I_{ratio} = \frac{\text{Max. Peak current in } i^{th} \text{ window}}{\text{Max peak current in the first window}}$$

Ratio will be taken at the end of each window. Decision can be taken if this ratio is greater than certain threshold value at the end i^{th} window, then that particular transient can be classified as inrush / overexcitation. If this ratio is less than threshold value at the end of i^{th} window, transient can be classified as internal fault signal.

Window width is ½ cycle and window is moved by $\frac{1}{4}^{th}$ of a cycle each time. Threshold value selected in this study is 0.1. Based on the restraint logic explained above the ratio of W.T. transformed current will be taken at the end of each window and used in the relay logic program.

Discriminant behavior:

Fig. 9 shows the response of the relay under typical inrush, internal fault and over excitation condition shown in the figures 6,7 and 8 respectively. Referring to Fig. 9 it can be seen that, the current ratio taken at the end of the third window is greater for inrush and over excitation cases, but less incase of internal fault case. This is true for all the case of inrush, overexcitation and internal faults studied. The distinction in ratio shows that, the distinction between inrush and other conditions can be obtained by half cycle. Thus proving the efficacy of fast detection using Wavelet Transform method.

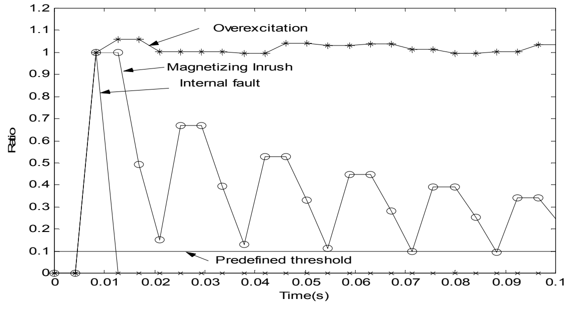


Fig 9 Discriminant behavior under inrush, internal fault and over excitation cases.

6. CONCLUSION

The basic idea of using discrete wavelet transform approach for the differential protection of transformer has been presented. The analyzing functions of wavelet offers important advantages over Fourier methods, in which former gives discrimination by the end of half cycle. Further, the discrimination logic presented is reliably showing the discrimination under all simulated conditions of inrush, over excitation and internal fault.

Appendix.

Transformer data:

5KVA, 230/115 v, 60Hz

N_1 = 36 turns, N_2 = 18 turns , A = 0.02 m^2 , l = 0.58 m

L_1 = 0.24 mH, R_1 = 1.5 m ohm

L_2 = 0.06 mH, R_2 = 0.38 m ohm

Source data**: L_s=.7 mH, R_s=115 m ohm**

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