Chapter 4

Application of Matched Wavelets in Transformer Protection

4.1 Transformer Protection

The Power Transformer is a major equipment in power systems. It requires highly reliable protective devices. Due to their sizes and varieties, protection approaches of power transformers differ depending on the situation. While for the small distribution transformers, high rupturing capacity (HRC) fuse will suffice, differential protection is recommended for the larger power transformers.

Inrush and Fault: Any device based on electromagnetic induction like motor or transformer balance the induced magnetic field and back e.m.f which is present in the device. When the device is started this previously back e.m.f is zero. So in absence of back e.m.f. the device takes large amount of current which is 10-20 times greater than the nominal value of the current through the device. This high value of current flows for a small time and reduces gradually to normal value as back e.m.f. is produced. This flow of large current is called Inrush current. And once the back e.m.f. is created the stable condition is reached the only nominal value of current flows through it. But since the current value is very large as compare to the normal value it seems that a fault has occurred. Thus, the protective devices have a tendency to mal-operate assuming that a fault has occurred.

When Power Transformer internal faults occur, immediate disconnection of the faulted transformer is necessary to avoid extensive damage and/or preserve power system stability. For many years, differential protection has been used as the primary protection of power systems. It contains the differential relay, which operates for all internal fault types of power transformer and block when inrush current is present. The major drawback of the differential protection relays stem from its potential for mal-operation caused by the transient inrush current, which flow when the transformer is energized. Thus, a mechanism is embedded in the system to detect that the large current flow is due to fault or due to inrush.

Most of the methods for digital differential protection of transformers are based on harmonic content of differential current. These methods are based on this fact that the ratio of the second harmonics to the fundamental component of differential current in inrush current condition is greater than the ratio in the fault condition. However, the second harmonic may also be generated during faults on the transformers. It might be due to saturation of CTs, parallel capacitances or disconnected transformers. The second harmonic in these situations might be greater than the second harmonic in inrush currents (see Moravej *et al.* (2000)). Thus, the commonly employed conventional differential protection based on second harmonic restraint will face difficulty in distinguishing inrush current and internal faults. Therefore, an accurate and rapid algorithm is required for discrimination of magnetizing inrush current from internal fault current.

To overcome this difficulty stated above and prevent the mal-function of differential relay, many methods have been presented to analyse and recognize inrush current and internal fault currents. Traditional tool for signal analysis, the Fourier transform, is not an efficient tool for detection of inrush currents, because it assumes the signal to be periodic. Moreover, it provides only the frequency information and lacks time localization. To overcome this difficulty, some previous researchers used the windowed Fourier transform or the short-time Fourier transform (STFT), where the signal is windowed by a windowing function of fixed width to analyse its frequency components (see Lin *et al.* (1988)). This approach also was not adequate because the resultant transform had prior fixed frequency and time resolution.

The need of varying width windows was provided by the wavelets, which are obtained by the translations and dilations of a single function, called *mother wavelet*. 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 (see Vetterli (1992)). The ability of the Wavelet Transform to focus on short time intervals for high-frequency components and long intervals for low-frequency components improves the analysis of signals with localized impulses and oscillations. For this reason, wavelet transform is an efficient tool for studying transient signals and obtaining a much better current characterization and a more reliable discrimination (see Moises *et al.* (1999); Youssef (2003)).

4.2 The Proposed Methodology

Since both inrush current and internal faults are non-stationary signals, wavelet based signal processing technique is an effective tool for transformer protection. The performance of any such method depends on the wavelet function chosen. The researchers in past have used the family of Daubechies wavelets in their methods of transformer protection (Youssef (2003); Ozgonenel *et al.* (2004)). For easy and efficient detection of some specified (desired) pattern in a signal at hand, the peak values of the transform is to be maximized. If the analysing wavelet matches the shape of signal well at specific scale and location, then large value of transform is obtained. If they are not correlated, a low value of transform is obtained. The application of the wavelet matched to the signal at hand for signal analysis provides better results compared to other wavelets. Hence we have used the concepts of *matched wavelets* for the detection of inrush and fault waveforms in output of a transformer.

For this purpose we have constructed wavelets matched to the inrush and fault parts of the waveform obtained from a power transformer. Such an output obtained from Simulink is shown in Figure 4.1. This waveform contains three types of waveforms, namely-inrush, normal and fault waveforms. Their respective regions have been highlighted in the Figure 4.1. The sections of inrush and fault waveforms are shown in Figures 4.2 and 4.3, respectively.

We name the constructed matched wavelets as *inrush matched wavelet* and *fault matched wavelet*, respectively. In our method, these designed wavelets are used as analysing function (mother wavelet). The wavelet transform coefficients are calculated

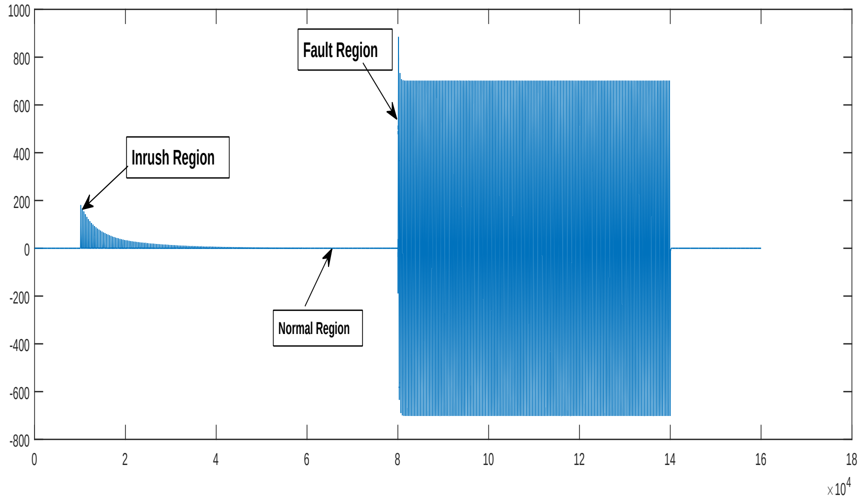

Figure 4.1: Output from Power Transformer

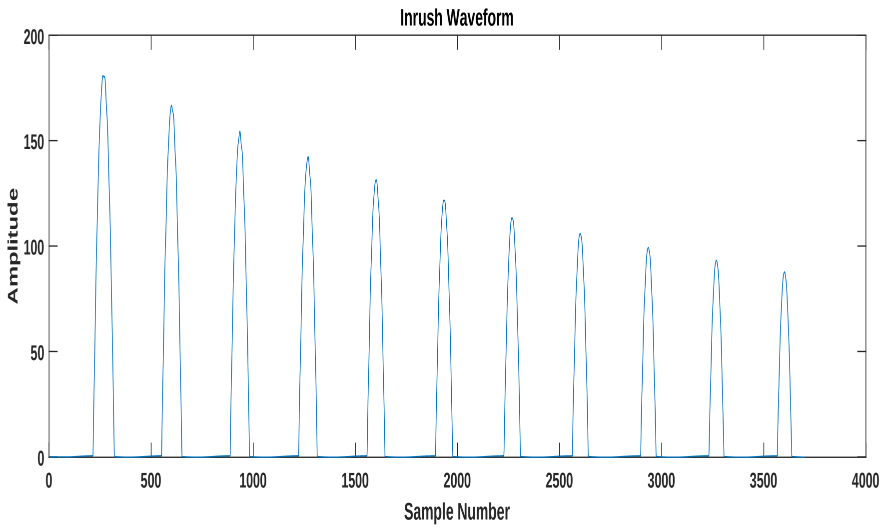

Figure 4.2: Inrush waveform

using the following equation:

$$W_{j,k} = \int_{-\infty}^{\infty} f(t)\psi_{j,k}(t)\,dt \tag{4.2.1}$$

where ψ is matched wavelet function and $\psi_{j,k}(t) = 2^{j/2}\psi(2^j t - k)$.

We have used wavelet coefficients as a discriminating function in our approach to differentiate the inrush, fault and normal waveforms at the output of power transformer.

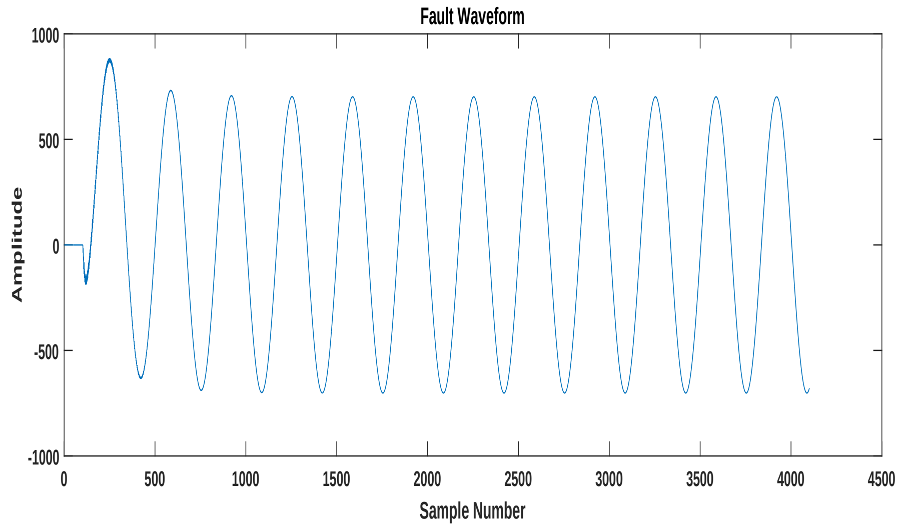

Figure 4.3: Fault waveform

4.2.1 Construction of Wavelet Matched to inrush waveform

We have followed the algorithm proposed by Chapa *et al.* (2000) (discussed in Chapter 3) for designing the wavelets matched to inrush and fault currents. We have taken two peaks from the inrush region and three peaks from fault regions of the output of transformer, as the desired signals for which the matching wavelet is to be constructed. The first step of the matching algorithm is to dilate the signal such that there is a maximum amount of energy in the wavelet passband. We have also used suitable zero-padding to the signal to get its spectrum in the passband. The wavelet passband taken in this construction was $2\pi/3 \leq |\omega| \leq 8\pi/3$ for getting orthonormal wavelets.

We have taken $N = 512$ and $\triangle\omega = 2\pi/16$ so that $l = 4$. With this value of l and bandlimits as above, the non-zero frequency indices in eq. (3.2.18) are $k = \{6, 7, \cdots, 21\}$.

The desired signal power spectrum, $W(n) : n = -256, \cdots, 255$, is given as

$$W(n) = \begin{cases} |F(n \triangle \omega)|^2 & \text{for } |n| = \{6, 7, \cdots, 21\} \\ 0 & \text{otherwise} \end{cases}$$

where $F(n\triangle\omega)$ is the Fourier transform of f. The equality constraints in eq. (3.2.16) and (3.2.17) in Theorem 3.2.4 generate $L = 11$ in 16 unknowns. The spectrum of wavelet function, $Y(k)$, is found using eq. (3.2.20) and (3.2.21) where $W = \{W(k) : k = 6, 7, \cdots, 21\}$. The full matched wavelet spectrum is constructed by reflecting $Y(k)$ onto the negative axis, and taking its square root.

For finding the matched phase the first step is to find the group delay of the desired signal,Γ_F, which is done using the following process:

1. Calculate $F_D^\theta(n \triangle \omega) = F_D(n \triangle \omega)/|F_D(n \triangle \omega)|$.
2. Interpolate across samples of $F_D^\theta(n \triangle \omega)$ where $|F_D(n \triangle \omega)| = 0$.
3. $\Lambda_F = | \triangle^1 F_D^\theta(n \triangle \omega)|$ where $\triangle^1$ is the first difference operator.
4. Take the average values of the adjacent samples across samples of Λ_F, when there is a sudden change in the value, to make it smoother.

This procedure in (4) above was done to eliminate the 2π phase jumps.

Next, the matrix D_Ψ is calculated from eq. (3.2.37). We have taken $N = 512$ and $R = 16$ for this example. Therefore, D_Ψ is a 512×9 matrix. The polynomial coefficient vector, $\hat{c}$, is calculated using eq. (3.2.42) where $\overline{D_\Psi}$ and $\overline{\Lambda_F}$ are weighted by the normalized matched spectrum, Y, calculated above. The group delay of matched wavelet function are calculated from eq. (3.2.45). The matched wavelet phase is found by integrating (or summing) $\Lambda_\Psi(n)$. The matched wavelet function is found by taking the inverse Fourier Transform of their complex spectra. The matched wavelet function for the inrush current is shown in Figure 4.4:

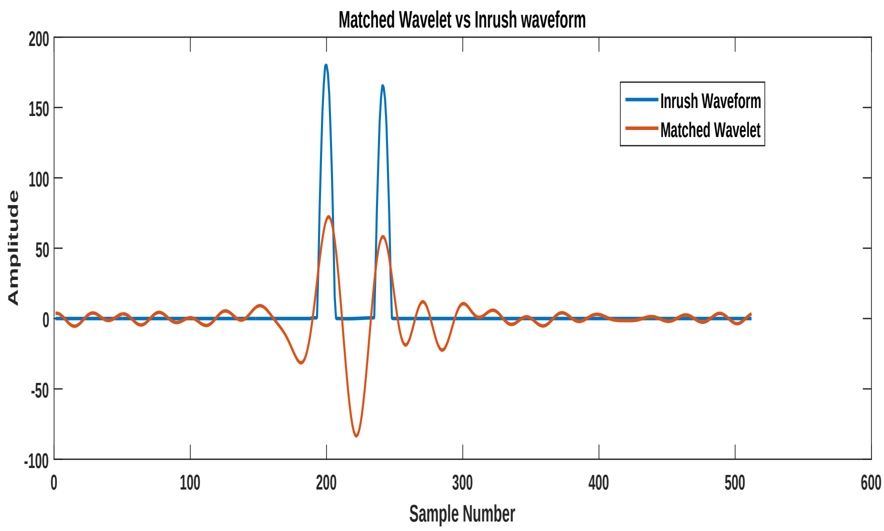

Figure 4.4: Wavelet Matched to inrush waveform

The matched wavelet function for the fault current is shown in Figure 4.5:

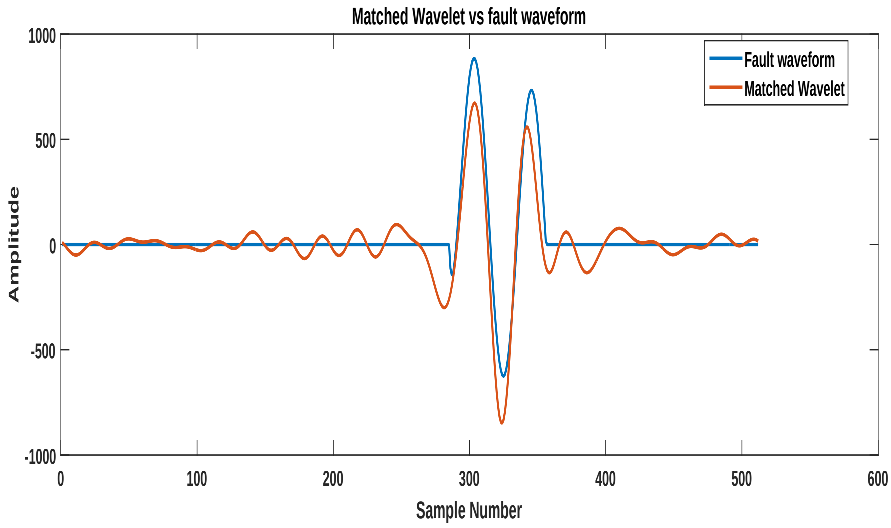

Figure 4.5: Wavelet Matched to fault waveform

4.3 Results

Power transformer waveform was obtained from Simulink. The generated data were used by the MATLAB to test the performance of the technique. Noting that wavelets were constructed using only a section of inrush and fault region, we used the constructed matched wavelets as sliding window to analyse the output from power transformer. We analysed the output period by period and calculated the wavelet coefficients using eq. (4.2.1). When we used matched wavelet for the inrush part of waveform for analysing the output from power transformer, the wavelet coefficients obtained corresponding to the inrush part were found to be much higher in magnitude compared to that of fault part of the waveform. Figure 4.6 shows the coefficients obtained when the inrush matched wavelet was used to analyse the waveform of Figure 4.1. It is observed that inrush part of the waveform is characterized by the consistently high values of coefficients compared to the fault part of the waveform. However, at discontinuity of fault waveform a high value of coefficients was observed. Figure 4.7 shows the coefficients obtained when the fault matched wavelet was used to analyse the waveform of Figure 4.1. It is observed that fault part of the waveform is characterized by the consistently high values of coefficients compared to the inrush part of the waveform.

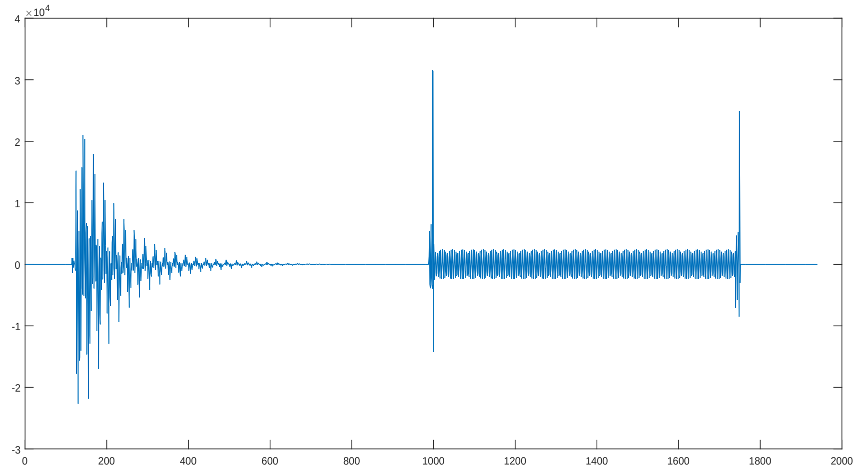

Figure 4.6: Wavelet Coefficients when inrush matched wavelet was used

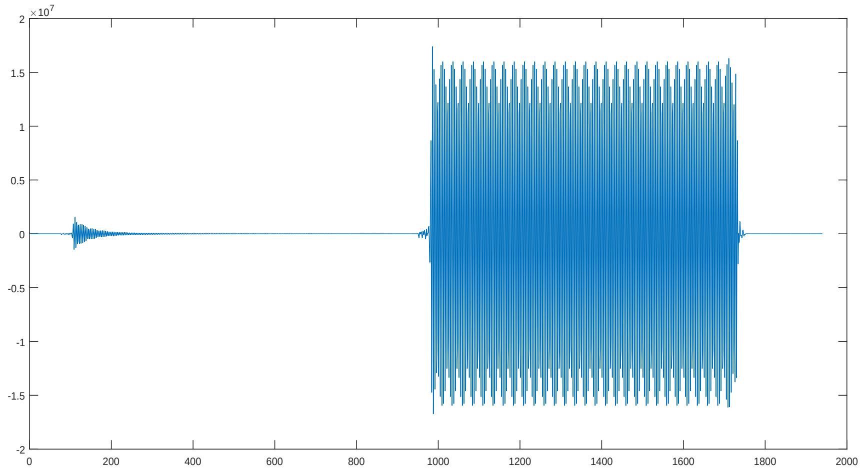

Figure 4.7: Wavelet Coefficients when fault matched wavelet was used

4.4 Conclusions

The method of matched wavelets is used for discriminating the inrush waveform from the fault waveform in differential protection scheme of power transformer. Matched wavelets for inrush waveform and fault waveforms are developed in this chapter and tested for their applicability. It was observed that concept of matched wavelet can be used for differential protection purposes.