Chapter 1

Introduction

1.1 Outline

In the present chapter, the state-of-the-art of various methods of differential protection is given. From available literature, methods used for transformer protection can be categorized in six categories. These methods are based on harmonic restraint, wave shape, fuzzy logic, artificial neural network (ANN), decision tree, and wavelet analysis methods. The harmonic restraint method is the classical method and is still in use. However, due to dependency on the harmonic content of differential current, this method has shortcoming of mis-operation of relays during transformer energisation. To overcome this problem, use of harmonic sharing and blocking functions are suggested in literature. Also for better classification and intelligent trip decision, harmonic component details are used with fuzzy logic inference, and ANN based techniques. Due to advancements in the design of transformers, modern transformers have lower harmonic content and hence detection methods independent of harmonic content have been subject of research. Due to ability of wavelets to extract information from transient signals in both frequency and time domain, wavelet analysis has proved to be powerful tool in protection of power transformers.

Matched wavelets and its application for the protection purpose is discussed in this chapter. This chapter also presents the motivation, research gap, objectives and outline of the present thesis.

1.2 Literature Survey for Differential Protection of Transformer

Differential relays have been in protection of transformers in power systems since long. Differential protection for power transformers is recommended for 10 MVA and higher rating transformers which have self cooling ability [5]. The initial surge of current that occurs when a transformer is energized is called inrush current [6]. To the differential relay, the high magnitude of magnetizing inrush current may appear as in-zone (with in the protected zone) fault. However, the magnetizing inrush currents contain certain amount of higher harmonics which is used to discriminate between the magnetizing inrush currents and in-zone fault currents [7] [8]. The saturation of power transformer and current transformers add further complexity in the discrimination among in-zone faults, external faults and magnetizing inrush situations. The various detection methods observed in the literatures can be broadly categorized as follows.

(i) **Harmonic Restraint Method (HRM):** This method works on the principle that inrush and fault waveforms are different in shapes and therefore can be identified by analysis of their underlying harmonic content through Fourier analysis [9] [10]. This principle has led to several algorithms/methods. However, harmonic restraint methods may mal-operate in case of low harmonic contents in the inrush current in modern transformers. The low harmonic content is due to use of amorphous materials used for making magnetic core of transformers [11]. In order to provide secure, dependable differential protection, various harmonic restraint methods are discussed in literatures [12] [13] [14]. The variations are as follows.

- **Second harmonic restraint:** It involves per-phase calculation of ratio of second harmonic component to that of fundamental component in inrush current [15].

- **Shared second harmonic restraint:** The method is similar to simple second harmonic restraint method explained above with exception that the ratio of sum of second harmonics of all the three phases to fundamental component is taken here. This is done because in many cases second harmonic content is low in one phase while in other phase it may have considerably high value [16].

- **Cross Blocking:** Methods involving single-phase detection of inrush current can utilize the concept of cross blocking. Cross blocking is not a method of inrush detection, rather a choice is made to block tripping of relays in all the three phases if relay of any of the phase detects inrush [17].

Kalman filter is used for estimating the second harmonic content and fundamental component of the inrush current in [18]. The extension of inrush restraint method is used in [19] where instead of ratio of second harmonic to fundamental component, the ratio of phase angles of second harmonic and fundamental components of the differential waveform is taken. This implies that both, the amplitude and the phase angle are involved in the calculation. Also, Phase Angle Difference (PAD) among higher harmonics is used for discrimination [20]. Harmonic restraint technique utilizes microprocessor relays to capture actual inrush characteristics by capturing waveforms each time the transformer is energized, to determine the optimum set points for differential relays [19]. A technique to determine restraint function by computing flux and current relationship of the transformer is discussed in [21]. A scheme based on extraction of positive- and negative-sequence components of superimposed differential current is discussed in [22]. However, the estimation of harmonics in a differential waveform takes time and can be inaccurate depending upon the data window taken. Due to lower harmonics content, the threshold setting for declaring inrush current is to be set at a lower value. This may lead to restraining the relay during internal faults accompanied with the saturation of current transformers [23]. A thorough investigation into the performance of present state-of-the-art relays are conducted in [24]. The paper argues that present day relays normally utilize data samples of one cycle for detection and trip, may be restrained for several cycles due to CT saturation. CT saturation not only poses a problem of fault current flowing through the transformer for several cycles due to inrush restrains, but can also result in spurious trip in case of external faults. Fig. 1.1 shows a graphical overview of Harmonic Restraint Method (HRM) indicating the taxonomy of various literatures.

(ii) **Wave-Shape (WS) Methods:** This detection method is based on direct shape analysis of inrush and fault waveforms. In general, the fault waveform is characterized by non-decaying nature with alternating peaks. The inrush waveform is characterized by having flat period of approximately 1/4 cycle having peaks of same polarity and also having a decaying nature [25]. Thus, if shape of a waveform is not flat and close to zero for

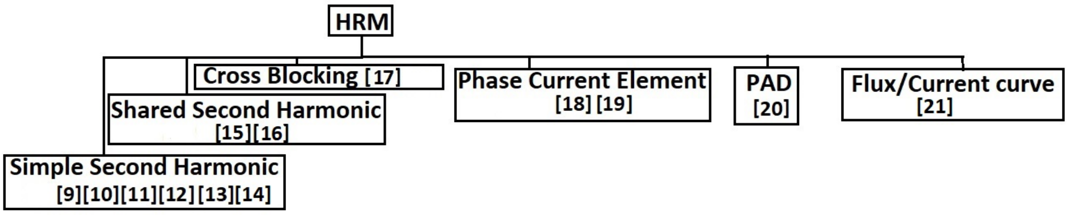

Figure 1.1: Taxonomy of literatures on Harmonic Restraint methods.

more than 1/4 of a cycle then it is not an inrush. Rectifier relay is also used for transformer protection. The working principle of the rectifier relay is based on the fact that the inrush current waveform is unipolar [26]. Wave-shape recognition based discriminating criteria of the instantaneous differential current is proposed in [27]. However, the three phases may not show typical unipolar inrush waveform and hence the main disadvantage of this algorithm is the need of cross polarization between the phases [28]. Furthermore, during smooth energisation this criteria may fail. Fig. 1.2 shows the graphical overview of literature for wave shape based methods.

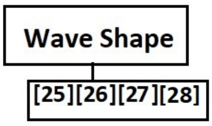

Figure 1.2: Taxonomy of literatures on Wave shape methods.

(iii) **Fuzzy Logic Methods (FLM):** Fuzzy logic methods of inrush detection are also proposed in literature. These methods are based on harmonic restraint method and use harmonic content of the inrush for detection [29]. The wave shape and terminal voltage based technique using fuzzy logic to distinguish internal fault from inrush current is discussed in [30]. In order to get un-conflicting and correct decision, a relay working on multi-criteria algorithm using fuzzy logic based approach for making final trip decision is proposed in [31] [32] and [33]. A method using morphological gradient approach is suggested in [34]. The method shows promising results, however, this method fails where internal fault and inrush occurs simultaneously and for the case of sympathetic inrush. To improve the performance of differential protection, a scheme using Clarke‘s transform and fuzzy logic is discussed in [35]. Fuzzy-neuro technique for higher sensitivity and for improved learning capability of neural network is discussed in [36]. The algorithm applied for detecting the inrush and fault uses fuzzy logic based inference rather than a simple threshold. Source of input information for fuzzy logic based methods is similar to that for HRM and WS based method. However, intelligent decision making helps up-to some extent. Fig. 1.3 shows the graphical overview of Fuzzy Logic Methods(FLM) for differential protection.

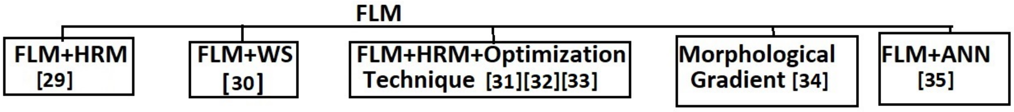

Figure 1.3: Taxonomy of literatures on Fuzzy Logic Methods.

(iv) **Artificial Neural Network (ANN):** Artificial Neural Network (ANN) based methods utilize wave-shape analysis through pattern recognition [37]. These methods have ability to learn from the waveform samples (training patterns). ANNs are first trained with different types of inrush and fault waveform patterns along with the desired classification and once the ANN has learned then it can be used for prediction [38]. ANN based scheme utilizing ANN structure with Feed Forward Backward Propagation (FFBP) learning with training data obtained from MATLAB simulations is proposed in [39] and [40]. Use of Multilayer Feed Forward Neural Network (MFFNN) for classification of magnetizing inrush and in-zone fault is proposed in [41] [42] [43]. The shortcomings of MFFNN for having long training time is also discussed in ref [41]. Radial Basis Probabilistic Neural Network (RBPNN) is used for classification of differential current waveforms which is based on the difference in wave shape of inrush and fault waveforms [44]. ANN based protection algorithm for power transformers proposed in [45] is different from classical approach, as it is independent of harmonic components in differential current and the trip decision is made on the basis of current signatures. Combined approach based on ANN and wavelet transform is used for detection and classification of disturbance in transformers is proposed in [46] and [47]. The technique proposed in [46] and [47] use wavelet based disturbance detector and neural network for classification purposes. For better training of

ANNs, Genetic Algorithm (GA) based ANNs are proposed in [48] for obtaining accurate discrimination of inrush and in-zone fault. ANNs are elaborate mathematical models of network of neurons and therefore, are difficult to put into a hardware. Also, it is not known for which particular patterns, it may predict the classification satisfactorily and for which it may not [49]. Fig. 1.4 depicts the graphical overview of ANN based methods for differential protection of transformers.

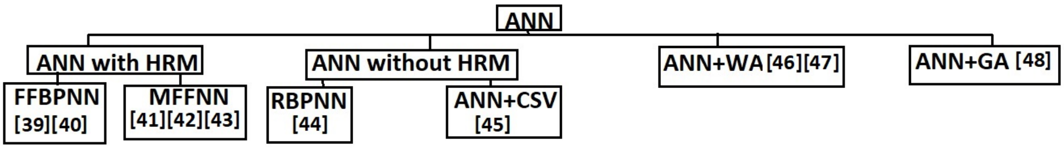

Figure 1.4: Taxonomy of literatures on ANN methods.

(v) **Decision Tree (DT) Methods:** A concept based on Decision Trees is presented in [50] and [51] for differential protection of transformer. The DTs learn on the basis of data presented along with the given class label. The performance of the approach is compared with Support Vector Machine. The Decision Tree based method is independent of selection of threshold. Fig. 1.5 shows the graphical overview of DT based methods.

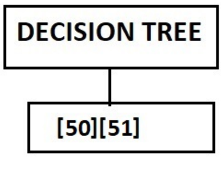

Figure 1.5: Taxonomy of literatures on DT based method.

(vi) **Wavelet Analysis (WA) Methods:** Wavelet based method is similar to Fourier analysis of waveforms for harmonic determination. However, instead of sine or cosine bases, the wavelet bases (mother wavelets) are used which support time-scale analysis and are more appropriate for applications such as differential protection . Wavelet analysis allows choice of different mother wavelets for analysis as opposed to only sine/cosine bases in Fourier analysis. Sine wave curve fitting method is used in [52], wherein a sine wave is fitted to the normalized differential current, employing least square technique. However requirement of high sampling rate is prime disadvantage of this algorithm [22]. Wavelet analysis of differential current waveforms on different scales is proposed in literatures where wavelet coefficients are used to find its energy distribution. Using the information of energy distribution, inference mechanisms are developed to differentiate inrush from fault. So far, wavelet analysis is performed using known mother wavelets such as Daubechies, Haar, Meyer, and Bi-orthogonal wavelets [53] [54] [55]. A method based on the polarity comparison of wavelet coefficients for differentiating inrush and fault is proposed in [56]. Similarly, another transform, Chirplet Transform (ChT) utilizes the mean and standard deviation of normalized energy for classification of transformer operating conditions [57]. A Time-time transform is also proposed for fault diagnosis in [58]. The author uses the energy distribution of S-matrix for diagnosis of faults. The analogy of time-time transform is drawn from Short-Time Fourier Transform (STFT) and wavelet based methods. Differential protection using Boundary Wavelet Transform (BWT) is proposed in [59]. The negative-sequence differential current and phase current differential element is recreated using boundary wavelet coefficient energy. Detection of in-zone fault, external fault and inrush in the presence of CT saturation using energy distribution of wavelet coefficients is proposed in [60]. Extraction of high frequency sub-band contents of differential current using wavelet packet transform for detecting and classifying differential current in power transformer is proposed in [61]. A method based on combined DT and WA for protection of large transformers is proposed in [62]. The method uses DT analysis of the wavelet coefficients and harmonic components of differential current. Wavelet transform combined with neural network for better detection and classification of in-zone fault and inrush current is also proposed in [63] and [64]. This technique uses the spectral energies of wavelet components for training the neural network. Use of wavelet correlation matrix for protection purpose is presented in [65].

It is known that the energy distribution characteristics of an inrush waveform is different from that of an in-zone fault waveform. The wavelet method has a drawback that several coefficients are to be calculated at different scales for distinguishing the energy distribution which can be time consuming. Also, as we go for higher scales, the wavelet analysis becomes prone to noise. Thus, a special mother wavelet would be needed to have most of the energy concentrated in the first scale. This is only possible if a wavelet is specifically designed to have a shape similar to the waveforms to be identified namely; *inrush* and *fault* waveforms. For designing a wavelet directly from the signal of interest, an algorithm was developed by Chapa [2] for detection of moving objects. Such a wavelet matches the signal in shape and hence is called a matched wavelet. Thus, deriving matched wavelet directly from signal of interest has specific advantages in signal detection/discrimination applications as discussed above. A graphical representation of wavelet based methods in the literature is shown in Fig. 1.6.

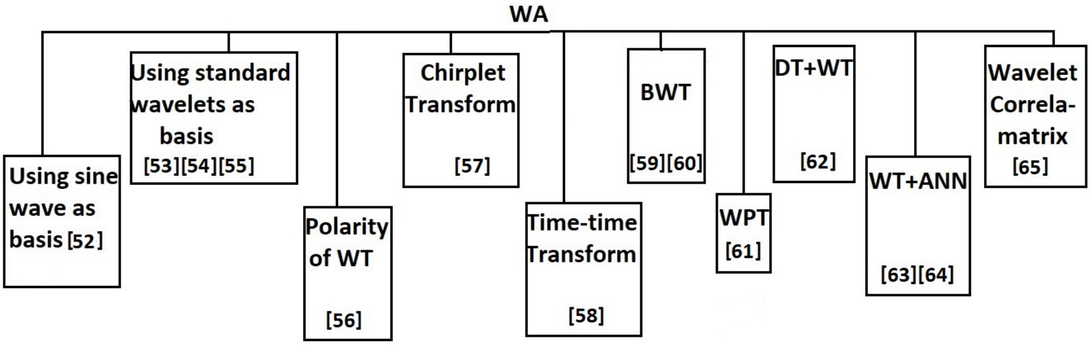

Figure 1.6: Taxonomy of literatures on Wavelet Analysis (WA) based method.

(vii) **Hardware Implementations:** We have already discussed that there are several approaches for detection of in-zone faults and its differentiation from inrush current based on current signal, flux/current curve characteristics, voltage signal, harmonic component, wave-shape of differential current and its phasor element. Also, there are literatures based on hardware implementation of protection algorithms. ANN based relaying scheme implemented on DS-1102 Digital Signal Processor (DSP) is presented in [45]. Another algorithm based on dq-axis wavelet packet transform is implemented on DS-1102 DSP and is discussed in [61]. Fault Transient Recognition (FTR) system is developed on DSP platform using Texas instrument floating point TMS320C6713 DSP board in [66]. The system implements Hidden Markov model based classifier for fault and inrush detection. Hardware implementation of differential relays on micro-controller platform is discussed in [67], [68], [69], and [70]. Micro-controller based relays are designed with three functional blocks, viz. isolation and analog scaling block, data acquisition block and microcomputer block. DSP-16 microcomputer board has also been used in the literature [67]. This DSP-16 board is based on TMS32025 DSP board. A Kalman filter for estimating fundamental and higher harmonics is implemented on TMS320 DSP board [18]. Wavelet Packet Transform (WPT) is implemented using Butterworth filter to extract high frequency components from differential current is presented in [71]. Real time testing and implementation of WPT on DS-1102 DSP for power transformer protection is presented in [72].

1.3 Motivation, Research Gap, Objectives and scope of the Thesis

In conventional wavelet based approaches, a mother wavelet is chosen from previously designed libraries such as Daubechies, Haar, Symlets, Coiflets and bi-orthogonal wavelets, to analyze differential current [53] [54]. Wavelet is a mathematical tool capable of analysing a given signal into varied scale components, having its own frequency range at each scale. The so called standard mother wavelets were developed for specific domain of analysis. However, these mother wavelets were adopted in other domains without validating its theoretical suitability for such analysis. Thus, we come across literature using such mother wavelets for analysis, where their suitability for the given purpose has not been verified. The wavelet transform of signal results in decomposition of signal into set of frequency channels of same bandwidth on logarithmic scale. Obtaining a wavelet which produces the best interpretation of given signal is topic of wide research. A concept of matched wavelet which matches in shape to the signal to be analyzed is introduced in literature. In the present work, matched wavelet is designed for the inrush and fault waveforms of power transformer. This goal of getting an optimal matched wavelet is achieved through differential evolution algorithm.

Extended basis of standard wavelets were used depending upon the better results of detection. The present work is motivated to design specific wavelet for specific pattern (inrush or fault). The frequency response of matched filter has the same shape as the frequency spectrum of the signal. When wavelet transform is applied to multi-resolution analyses of signals, theoretically, it produces the similar output to those of matched filters. Hence matched wavelet for inrush and fault waveform have been attempted in this work. In the literature, the detection of fault and inrush has not been treated as independent of each other. In other words, it is assumed that if inrush has been detected then it indicates absence of fault. And this approach fails to capture simultaneous occurrence of inrush and fault. In view of this, it is desirable that inrush and fault are detected independent of each other. The basic philosophy used in this thesis, is to find matched wavelet for inrush waveforms and fault waveforms independently. This approach provides fast discriminating ability (nearly half cycle). This approach also improves the detection ability and provides ease in studying relay mal-operations. Getting an optimal matched inrush wavelet and fault wavelet by the use of differential evolution algorithm is attempted in the present approach.

The major objectives of the present thesis are as follows:-

- To theoretically and practically establish the efficacy of matched wavelets for inrush and fault detection.
- To develop set of matched wavelets in optimal sense through optimization process to maximize wavelet coefficients obtained for inrush and fault waveforms.
- To test the obtained wavelets under various operating conditions of transformers.
- To implement the wavelet based differential protection in hardware to obtain a proof of concept that such a ”real-time” implementation is possible in the present state-of-the-art.

1.4 Outline of The Thesis

The thesis has following major contributions.

1. A modified scheme for differential protection of transformer using independent detection of the fault and the inrush current is developed.
2. Optimal matched wavelets are developed to implement the scheme proposed in (1), and
3. Proposed scheme has been implemented in hardware and verification with simulation results has been performed in real-time.

4. Real-time testing of the algorithm on the waveforms of a physical transformer is performed to establish the efficacy of the proposed matched wavelet method, in practical environment.

The first chapter covers the literature survey. This chapter also present the motivation, objectives, and scope of the work embodied in this thesis. The details of the mathematical background of the wavelets and wavelet transforms are discussed in second chapter. Also, the concept of matched wavelet and designing of matched wavelets are described in this chapter. Matched wavelets for known standard wavelets have been obtained to validate the proposed algorithm for designing matched wavelets. The matched wavelets for inrush and fault waveforms are synthesized in Chapter 2. The efficacy of the designed wavelets is compared with that of existing wavelets and is presented in Chapter 2.

In third chapter, various operating conditions of power transformers are discussed. Also the effect of CT saturation is taken into consideration. Designed matched inrush and fault wavelets are implemented for differential protection of power transformers. The detection scheme using designed matched wavelets is applied for various test cases and some scenarios are discussed in detail.

The hardware implementation of the proposed methods is addressed in Chapter 4. Chapter 4 contains the details of the steps involved in hardware implementation of the proposed scheme. The hardware implementation is done in two major steps. The first step is to create desired input signal to be given to the filter unit, and second step is the design of filter unit itself. The results obtained in simulation are verified for the hardware. This chapter addresses the real-time testing of the proposed scheme. In Chapter 4, the real-time testing of the proposed algorithm is implemented for the waveforms of a physical transformer. The "real" waveforms are obtained from an actual transformer and the real-time testing of the algorithm is performed in actual scenario for several cases. The conclusion and the future scope of the the work in the thesis are presented in Chapter 5.

1.5 Summary

Literature survey on differential protection of power transformer and matched wavelets has been discussed in this chapter. The chapter discusses about various detection methods based on Harmonic Restraint, Wave shape, Fuzzy logic, ANN, Decision Tree, and Wavelet Analysis. Apart from the above approaches, few researchers have also worked on current and voltage ratios based power transformer differential protection [88][89]. Literatures based on hardware implementations of differential protection techniques were also discussed. The motivation, research gap, objectives, outline and major contributions of the thesis are described in this chapter.