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|| *Hare Ram Hare Ram Ram Ram Hare Hare*||

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DECLARATION

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Abstract

Power transformers face various transient disturbances like internal faults, external faults, and inrush current. Differential relays are used for protection of power transformers to detect these disturbances. When the transformer is switched on, there occurs an abrupt rise in current level which is termed as magnetizing inrush and can be falsely interpreted as fault by differential relay. In order to avoid false tripping of protected transformers, various methods have evolved based on harmonics present in differential current. The conventional differential relays employ harmonic analysis approach to determine the type of current flowing through the transformer. The feasibility of conventional methods is subject to the value of second and higher harmonics present in the differential current. However, in modern transformers the value of second harmonic is comparatively very low due to improved core materials. The ratio of dominant harmonics to fundamental component of differential current is used along with Phase Angle Difference (PAD) of higher harmonics for better discrimination. However, the estimation of harmonics in a differential waveform takes time and can be inaccurate depending upon the data window taken. A large data window can give an accurate estimate of harmonics but consumes large time for detection. A small time window may take small detection period but suffer from inaccuracies in harmonic estimates. This may lead to restraining the relay during internal faults accompanying the saturation of current transformers. A thorough investigation into the performance of present state of the art relays is conducted in literature, which shows that the present relays normally utilize data samples of one cycle for detection and trip may be restrained for several cycle due to CT saturation. Wave-shape based detection is based on direct analysis of inrush and fault waveforms. In general, the fault waveform is characterized by non-decaying nature with alternating peaks and the inrush waveform having 1/4 cycle flat period of same polarity and also decaying peaks. 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. Furthermore, during smooth energisation this criteria may fail. Fuzzy logic methods of inrush detection are based on harmonic restraint method and use harmonic content of the inrush for identification. In order to get non-conflicting and correct decision, a relay working on multi-criteria algorithm using fuzzy logic approach is used for making final trip decision. In Artificial neural network based approaches, patterns are first trained with inrush and fault waveforms. 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.

In 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. 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 wavelets were developed for specific type of analysis in a domain. However, these mother wavelets were adopted in various other type of analysis without establishing its theoretical suitability for such analysis. Thus, we come across literature using these wavelets for analysis, without commenting on their suitability for the given purpose. 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 new 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.

0.1 Motivation, Research Gap and Objectives of the Thesis

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.

0.2 Contributions and Outline of the Thesis

The current work 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.

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Nomenclature

List of Symbols and Acronyms

$f(t)$	Signal
$w(t)$	Window function
τ	Length of window function / Translation parameter
ω	Frequency
$F(\omega)$	Fourier transform of $f(t)$
$\psi(t)$	Wavelet function
$\phi(t)$	Scaling function
C_ψ	Continuous wavelet transform
s	Scaling parameter
Z	Set of integers
i, j, k	Integer constants
V_j	Dyadic space
$L^2(\Re)$	An array of closed subspaces
U	Union
H_s	Hilbert Space
M_1, M_2	Constant

δ	Dirac-delta function
p_k	Bi-orthonormal Riesz basis
H_s	Hilbert Space
c_k	k^{th} finitely supported sequences
d_k^j	Detailed coefficients for j^{th} scaling and k^{th} translation
$h(k)$	Scaling function coefficients
$g(k)$	Wavelet function coefficients
$X^\star$	Parameter vector
$f(X)$	Objective function
ζ	Non-empty search domain
NP	Population of parameter vectors
G_{max}	Maximum number of generation
D	Dimension of parameter vector; Number of wavelet coefficients
G	Generation Count
X_i^G	i^{th} target vector at G^{th} generation
V_i^{G+1}	i^{th} mutant vector at $(G+1)^{th}$ generation
F	Mutation constant
U_i^G	i^{th} crossover vector at G^{th} generation
CR	Crossover constant
$\nabla_x V$	Gradient of V w.r.t. x
ϕ	Flux
ϕ_m	Maximum flux

ϕ_r	Residual flux
ANN	Artificial Neural Network
ADC	Analog-to-Digital Converter
BWT	Boundary Wavelet Transform
ChT	Chirplet Transform
CWT	Continuous Wavelet Transform
CT	Current Transformer
DT	Decision Tree
db	Daubechies wavelet/signal
DE	Differential Evolution
DSP	Digital Signal Processor
DWT	Discrete Wavelet Transform
DAC	Digital-to-Analog Converter
DSO	Digital Storage Oscilloscope
FLM	Fuzzy Logic Method
$FFBP$	Feed Forward Backward Propagation
FTR	Fault Transient Recognition
$FPGA$	Field Programmable Gate Array
GA	Genetic Algorithm
GRM	Gradient Repair Method
HDL	Hardware Description Language
HRM	Harmonic Restraint Method

HT	High Tension
LT	Low Tension
MFFNN	Multilayer Feed Forward Neural Network
MRA	Multi-Resolution Analysis
MRA	Multiply-Add-Accumulate
PAD	Phase Angle Difference
RBPNN	Radial Basis Probabilistic Neural Network
STFT	Short Term Fourier Transform
WS	Wave-Shape
WT	Wavelet Transform
WPT	Wavelet Packet Transform
WA	Wavelet Analysis (FPGA) (MAA) (DSO)