Power Transformer Protection Using Wavelet based Fuzzy Logic

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Abstract: *This paper presents a new approach for discriminating transient phenomena of power transformer, which may be implemented in digital relaying for transformer differential protection. Discrimination between internal faults and magnetizing inrush currents is achieved by combining wavelet transforms and fuzzy logic. The wavelet transform is applied to the analysis of the power transformer transient phenomena because of its ability to extract information from the transient signals in both time and frequency domain. Fuzzy logic is used because of the uncertainty in the differential current signals. The transient differential current arising in the differential relay is analyzed in its details and approximate waveforms using the Discrete Wavelet Transform (DWT). In the proposed work A 138/13.8 KV transformer is simulated using MATLAB/Simulink environment. The transient signals of differential currents are captured and analyzed using 'db6' wavelet transform at level 2 with a sampling frequency of 1600 Hz. The peak values of detailed1 coefficients (d1) are normalized and taken as inputs to fuzzy logic algorithm for building the membership functions. Trapezoidal membership functions are used for classifying the input variables. The input variable magnetizing inrush current is divided into three parts small, medium and large. Other input variable fault current is divided into two parts small and large. The output variable is divided into two partitions with triangular membership function representing trip or no trip.*

Key words: *Inrush current, fault current, wavelet Transform, differential current, detailed coefficient, fuzzy Logic, membership function, inter turn fault.*

1. Introduction

In power systems, transformer is one essential element and hence transformer protection is of critical importance. In general, differential relays are used to detect the internal faults of a transformer which involves converting the primary and secondary currents on a common base and comparing them. The magnetizing inrush current makes the transformer protection a challenge to the researchers. The magnetizing inrush current occurs during energizing of the transformer, which sometimes results in a high current in the order of ten times the full load current. This high current might cause the relay to mal-operate. To avoid mal-operation of the relay, distinguishing between the magnetizing inrush current and the fault current is required. There are many existing algorithms based on the second harmonic and sometimes also the fifth harmonic restraint concept [1, 2].

Among these algorithms Walsh functions, rectangular transform**,** Harr function, Fourier, least square algorithm, etc. are worth mentioning [2]. In reference [2], the authors experimentally compared six such existing methods to find out the best one in terms of speed and reliability. In all the algorithms described in reference [2], the second and the fifth harmonics have been chosen as the indication for determining whether the measured differential current is internal fault or inrush including over excitation.

A recent study reports show that in certain cases, the internal fault current might contain considerable second and fifth harmonics too [3]. Moreover, it has been also reported that the low loss amorphous core material in the modern transformer produces lower harmonic contents in magnetizing inrush current [4]. Considering these factors many researchers continued their work to develop new algorithms for transformer protection [3-5]. However, all these algorithms are either based on the transformer equivalent circuit model and/or require some transformer data and thus may become susceptible to parameter variations.

There are extensive research and applications of artificial neural networks over the last few years particularly in the field of pattern recognition. Recently to advance the conventional approaches, several new Artificial Intelligence features for protective relaying have been developed [6-9]. Luis proposed an algorithm based on artificial neural networks. Wiszniewski suggested a differential protective relay based on fuzzy logic. Wavelet based algorithms are also reported in the literature. Most of these approaches are liable to maloperate in the case of magnetizing inrush with low second harmonic component and internal faults with high second harmonic component.

In recent years, few works which investigate the feasibility of using intelligent techniques for transformer protection has also been reported [10-12]. Another recent work on wavelet entropy based approach for power system transient classification is presented in [13]. Here, [13] neural network is employed for automatic power system transient classification. Based on wavelet transform the idea of entropy and weight coefficient is introduced and the wavelet energy entropy and wavelet entropy weight are defined in [14]. A new algorithm for the classification of different transient phenomena in power transformers combining wavelet transforms and fuzzy logic is presented in [15]. In [16] a wavelet fuzzy expert technique for classification of power transformer transients is proposed. But in both the papers protection against inter turn faults are not addressed.

This paper describes wavelet based fuzzy logic relaying for power transformer protection and includes clear fault discrimination between magnetizing inrush current, inter turn and internal faults. To enhance the fault detection sensitivity of traditional percentage differential current relaying algorithm, fuzzy logic approaches are used. In the proposed work A 138/13.8 kV, 30 MVA transformer is simulated using MATLAB/Simulink environment. The transient signals of differential currents are captured and analyzed using Daubechies6 (Db6) wavelet transform at level 2 with a sampling frequency of 1600 Hz. The peak values of detailed1 coefficients (d1) are normalized and taken as inputs to fuzzy logic to discriminate inrush currents with fault currents.To evaluate the performance of the proposed relaying, the transformer inrush currents, turn-turn faults, and internal fault signals have been used.

The organization of the paper is as follows: In section 2 a brief introduction to the wavelet transform is provided. Section 3 is an introduction to fuzzy logic. The power transformer under study and simulation results are presented in section 4. Design of wavelet based fuzzy logic protective relay is presented in section 5. The final section concludes the paper.

2. Discrete Wavelet Transform (DWT)

DWT is an ideal tool to capture the transient phenomena for a power transformer. The wavelet transform gives the frequency information of the signal and also the times at which these frequencies occur. Combining these two properties make the Fast Wavelet Transform (FWT), an alternative to the conventional Fast Fourier Transform (FFT). Wavelet is a waveform of limited duration whose average value is zero. Wavelets tend to be irregular, asymmetric, short, and oscillatory waveforms. To detect the transformer faults, only dominant transients within the certain bands play an important role. Therefore the wavelet filter banks are designed to extract the required transient currents. DWT is capable of extracting both fast and slow events in a desired resolution.

The DWT of a signal x is calculated by passing it through a series of filters. First the original signal x[n] is passed through a half band low pass filter with impulse response g[n]. Here x is the signal in discrete time function. The sequence is denoted by x[n], where n is an integer and g[n] is the impulse response of the low pass filter and y[n] is the output of the filter. The signal is also decomposed simultaneously using a half band high pass filter h[n]. The outputs from the high pass filter give the detailed coefficients and the outputs from the low pass filter give the approximate coefficients. It is important that the two filters are related to each other and they are known as a quadrature mirror filter. However, since half of the frequencies of the signal have now been removed, half the samples can be discarded according Nyquist's rule. The filter outputs are then down sampled by 2. Hence the resulting equations are

$$y[n] = (x * g)[n] = \sum_{k=-\infty}^{\infty} x[k].g[n-k] \quad (1)$$

$$y[n] = (x * g)[n] = \sum_{k=-\infty}^{\infty} x[k].g[2n-k] \quad (2)$$

This decomposition has halved the time resolution since only half the number of samples now characterizes the entire signal. However this operation doubles the frequency resolution since the frequency band of the signal spans only half the previous frequency band. The Block diagram of filter analysis is shown in Fig. 1.

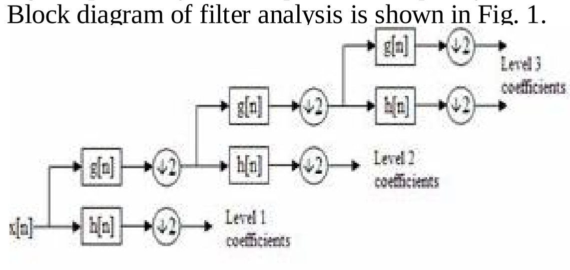

Fig. 1. Block Diagram of Filter Analysis

2.1. Selection of Wavelet Transform

Wavelet transforms are fast and efficient means of analyzing transient voltage and current signals. In this work, Db6 wavelet function has been used for the discontinuity analysis of the phase currents. Different kinds of wavelet families are derived. Db6 is simply chosen since it gives a more accurate solution and minimum reconstruction error during the magnetizing inrush condition and fault conditions.

3. FUZZY CONTROL

The operating principle of fuzzy logic controller is similar to the human operator. It performs the same actions as a human operator does by adjusting the input signal looking at only the system output. The fuzzy system is used to deal with the input without the data loss. Fuzzy logic has three steps as given below.

1. Fuzzification (converting crisp values into fuzzy values).
2. Inference mechanism (Rule base and If-Then rules).
3. Defuzzification (converting fuzzy values into crisp values).

Fuzzification is the first step of fuzzy logic, where the actual measured input values are mapped into fuzzy values through membership functions. These membership functions could be defined by triangular, sigmoid, gauss, bell shaped, etc. In fuzzy logic, it is important for a variable to belong to a membership function with a relative membership degree. This gives the variables a “weighted” membership in a membership function. A variable can have a weighted membership in several membership functions at the same time.Secondly fuzzified values are processed in the fuzzy inference system to define the appropriate control action. Finally the resultant fuzzy numbers representing the controller output are converted into crisp values. This is the last step of the fuzzy control, which is called defuzzification.

The input to the defuzzification process is a fuzzy set (the aggregate output fuzzy set) and the output is a single number. As much as fuzziness helps the rule evaluation during the intermediate steps, the final desired output for each variable is generally a single number. However, the aggregate of a fuzzy set encompasses a range of output values and so must be defuzzified in order to resolve a single output value from the set. Perhaps the most popular defuzzification method is the centroid calculation, which returns the center of the area under the curve. There are five builtin methods supported: centroid, bisector, middle of maximum (the average of the maximum value of the output set), largest of maximum, and smallest of maximum.

4. SYSTEM UNDER STUDY

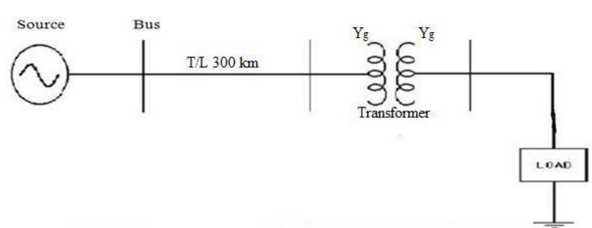

Fig. 2. One line diagram of power system model.

4.1. System Parameters

Table.1:

Three phase voltage source	
Voltage	138KV
Frequency	50Hz
Three phase transformer block parameters	
Nominal Power	1MV
Frequency	50 Hz
Transmission line parameters	
Resistance per unit length	0.02ohms/km
Inductance per unit length	0.506*10^4 H/km
Capacitance per unit length	1*10^-12 F/km
Number of pi sections	1
Length	300 km

The system under consideration is simulated at different switching instants from 0° to 315° at an interval of 45° and some of the plots for magnetizing inrush are plotted as shown below. During the energizing of the transformer the secondary side is kept open circuited.

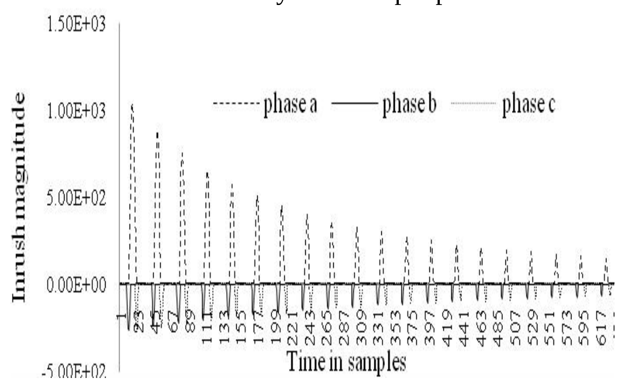

Fig. 3. Magnetizing inrush currents in phases a, b and c at switching instant of 0°.

Magnetizing inrush current signals are sampled at 1600 Hz and analyzed using db6 wavelet at level 2. The detailed coefficient d1 of phase A inrush current is as shown below.

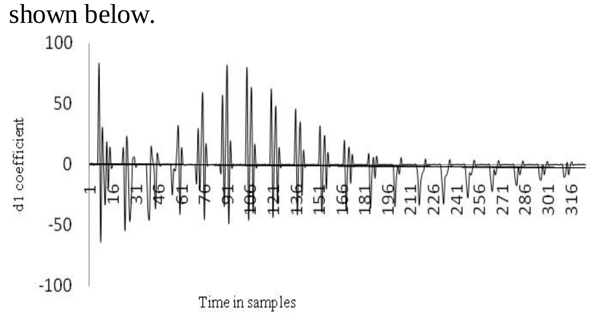

Fig. 4. d1 coefficient of inrush current in phase A.

Different fault cases such as L-G, L-L-G, L-L-L, and inter-turn faults are simulated at different fault incidence angles from 0° to 315° at an interval of 45° and some of the plots representing differential currents are plotted. The differential currents are analyzed using db6 wavelet at level 2. The detailed coefficient d1 of respective differential current signals in both time and frequency spectrum is as shown in Fig. 5. To Fig. 14.

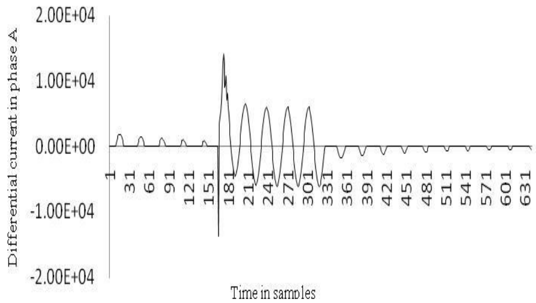

Fig. 5. Differential current in phase A at fault incident angle of 45°

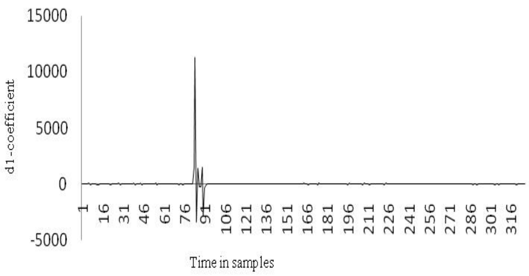

Fig. 6. d1 coefficient of Differential current in phase A at fault incident angle of 45° during A-G fault

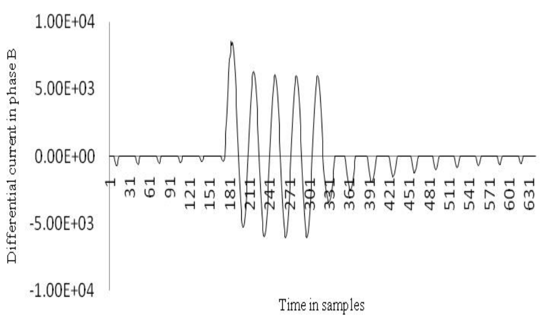

Fig. 7. Differential current in phase B at fault incident angle of 135°

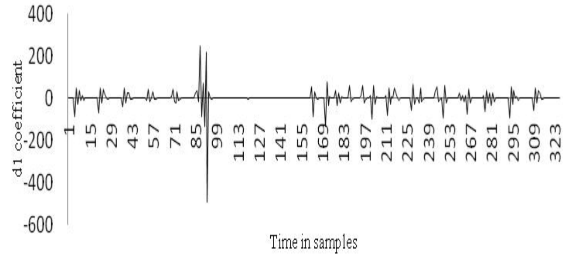

Fig. 8. d1 coefficient of Differential current in phase B at fault incident angle of 135° during B-G fault

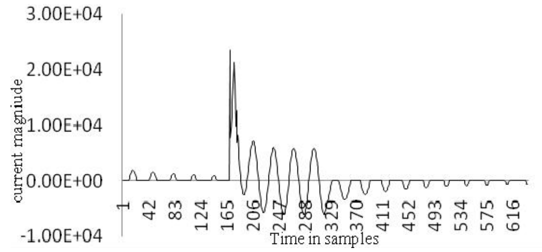

Fig. 9. Differential current in phase A at fault incident angle of 90° during A-B fault

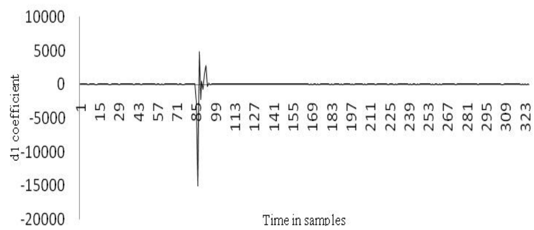

Fig. 10. d1 coefficient of Differential current in phase A at fault incident angle of 90° during A-B fault

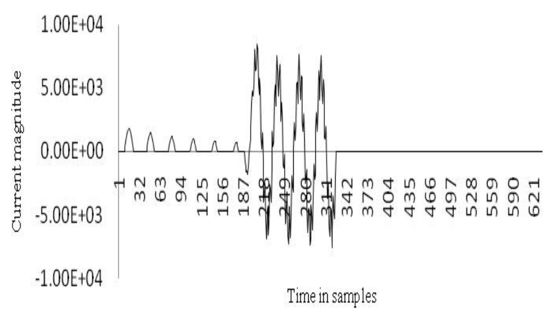

Fig. 11. Differential current in phase A at fault incident angle of 315° during A-B-C fault

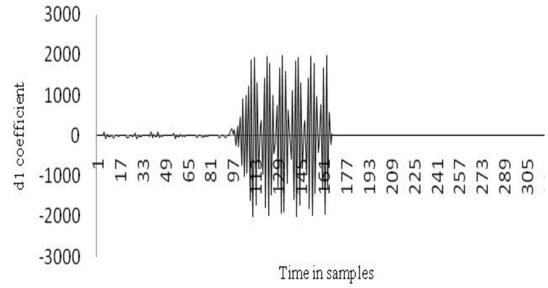

Fig. 12 d1 coefficient of Differential current in phase A at fault incident angle of 315° during A-B-C fault

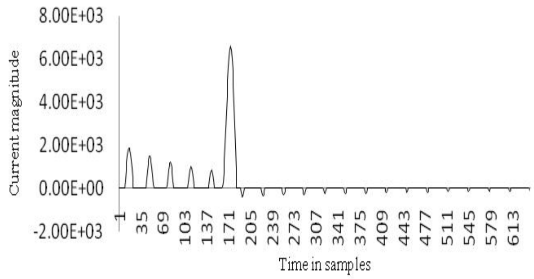

Fig. 13. Differential current in phase A during 20% of phase A is shorted

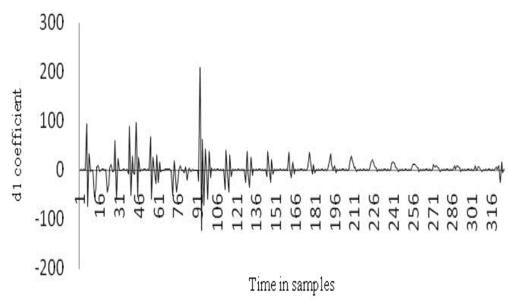

Fig. 14. d1 coefficient of Differential current in phase A during 20%

The peak values of detailed1 coefficients (d1) are normalized and taken as inputs to fuzzy logic to discriminate inrush currents with fault currents.

5. Design of Wavelet based Fuzzy Logic Protective Relay

Fuzzy inference is a process that makes a decision in parallel. Because of this property, there is no data loss during the process and so final fault detection will be far more precise than that of conventional relaying techniques. A membership function is a function that defines how each point in the input space (universe of discourse) is mapped to a membership value varies between 0 and 1. The section of membership function type depends upon the designer experience and the problem under consideration. Fuzzification gives the following results such as uncertainty of input relaying signals is quantified and all data contained in input relaying signals are acquired without loss. The rationality of quantified uncertainty and quality of acquired data depends on input and output fuzzy sets.

Here, the proposed fuzzy based relaying uses two fuzzy inputs defined as Magnetizing Inrush Current (MIC) and Fault Current (FC). The input variable MIC is divided into three parts small, medium and large. Other input variable FC is divided into two parts small and large. The output variable is divided into two partitions with triangular membership function representing trip or no trip. The graphical representation of the input and output variables are shown in Fig.15. To Fig.17.

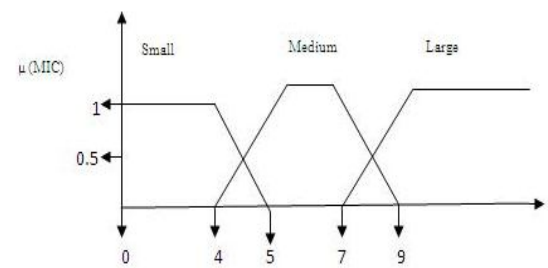

Fig. 15. MIC Fuzzy Membership functions

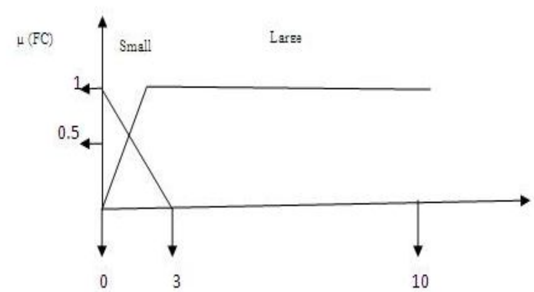

Fig. 16. FC Membership functions

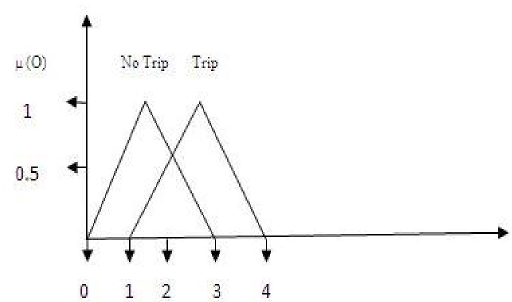

Fig. 17. output Membership functions

Fig. 18. shows the block diagram of the proposed relaying technique.

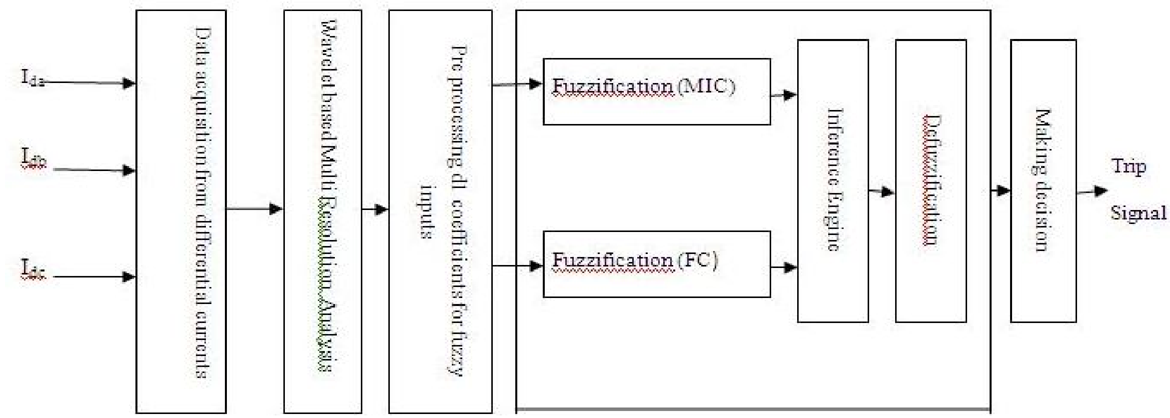

Fig. 18. Block diagram of proposed relay

5.1. Proposed algorithm

The wavelet transform is applied for extracting several features from the differential current signal. Fuzzy logic is used for distinguishing inrush current from the fault current. The proposed algorithm can be explained as follows:

1. Differential currents from the three phases are extracted.
2. These currents are analyzed by using DWT.
3. The first level detailed coefficients are calculated.
4. The peak values of d1 coefficients are normalized.
5. The normalized values are fed to the fuzzy logic system to carry on the discrimination between inrush current and fault current.
6. The decision is made by the fuzzy system whether the transient is an internal fault or inrush current.

If an internal fault is detected a tripping signal is issued; otherwise, the relay restrains and goes on to the next window.

5.2. Control Rule Base of the Proposed Approach

The control rule base content is a linguistic description of how the expert will behave to achieve the control function. This linguistic based description takes the form If primes Then consequent rule. Number of fuzzy inference rules for the proposed relaying for transformer protection are six. All rules consist of two antecedents for input and one consequent for the output. In this work, the compositional fuzzy inference matrix is used, where Max-Min method is chosen to perform a mathematical operation. The rules are shown below.

If MIC is small and FC is small Then No-Trip.
If MIC is small and FC is large Then Trip.
If MIC is medium and FC is small Then No-Trip.
If MIC is medium and FC is large Then Trip.
If MIC is large and FC is small Then No-Trip.
If MIC is large and FC is large Then Trip.

By using a Fuzzy Logic tool box in the MATLAB environment the rule viewer and the surface viewer are obtained as shown in Fig. 19 and Fig. 20.

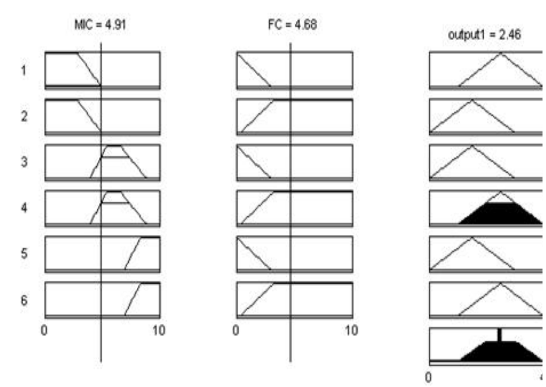

Fig. 19. Rule viewer

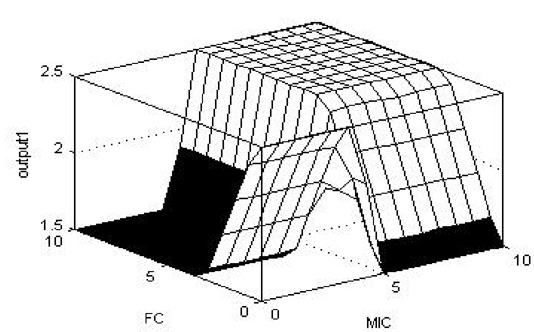

Fig. 20. Surface viewer

6. CONCLUSION

The integrated proposed technique is tested using different transient conditions obtained from a simulation of a real power transformer. The proposed algorithm combines the use of the wavelet transforms and fuzzy logic. Wavelets break up the time domain into long time intervals at high frequencies, and hence allows for an efficient description of the signal. The wavelet transforms are used for extracting different features of the differential currents. Fuzzy logic is applied to overcome the uncertainty in the differential current signals. Simulation is performed applying the MATLAB tools. The simulation results obtained demonstrate the success of the proposed algorithm, as it operates only in case of internal faults, and blocking magnetizing inrush current.

ABOUT THE AUTHORS

K. RAMESH received the B. Tech degree in Electrical & Electronics Engineering from JNTU KAKINADA in 2001 and M. Tech degree in 2008 from the same university. Currently he is working as Assistant Professor in Bapatla Engineering College, Bapatla. His research interests include digital protection of Electrical Power Systems and Electrical Machines.

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Nomenclature

db6	:	daubechies6 wavelet
d1	:	detailed1 coefficient
L-G	:	Line-Ground fault
L-L-G	:	Double line-Ground fault
L-L-L	:	Triple Line fault
I_{da}	:	Differential current in phase A.
I_{db}	:	Differential current in phase B.
I_{dc}	:	Differential current in phase C.
MIC	:	Magnetizing Inrush Current.
FC	:	Fault Current.
μ (MIC)	:	Degree of membership function MIC.
μ (FC)	:	Degree of membership function FC.
μ (O)	:	Degree of membership function output.

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