A Novel Inter-Turn Fault Detection in Power Transformers using Wavelets and Fuzzy Logic

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***Abstract*- In this research paper in order to detect incipient faults in a power transformer, a physical model of a 100MVA, 138/13.8 KV multiwinding power transformer is simulated in a power system using MATLAB/SIMULINK software. Different percentages of inter turns of power transformer are short-circuited and the resulting transformer terminals currents are measured. The changes in the terminals current are negligibly small. To experience significant changes in terminals current, negative sequence currents are extracted using symmetrical component approach. The changes that occur in both the magnitude and phase on both sides of the transformer during the incipient fault are estimated. It is observed that these changes are also not significant. So to improve the sensitivity of proposed scheme, wavelet transform is employed. Daubechies3 wavelet at level 4 is used to analyze the magnitude and phase varying signals on both sides of the power transformer. The absolute peaks of detailed1 (d1) coefficients on both sides of the power transformer are calculated. The ratios of d1 coefficients are taken as inputs to the fuzzy logic. Here fuzzy logic is implemented to monitor the severity of inter turn fault.**

***Keywords*- Inter-turn, Fault, Negative sequence current, Wavelet, Fuzzy logic, Membership function.**

I. INTRODUCTION

Power transformer is one of the critical elements in power system. Differential protection is generally employed to protect a power transformer. The traditional differential protection scheme is unable to detect incipient faults since the power transformer cannot draw sufficient current when such faults occur. As a result they develop in to major faults and finally lead to severe damage of considerable portion of the winding. In the literature it is reported that almost 70% of transformer failures are due to incipient faults. If these faults are not detected at an early stage, they result in severe hot spots on the windings, oil overheating, core damage, damage to the clamping structure, and sometimes explosion of the transformer may also take place. As a result there are adverse affects in power system such as voltage sag, interruption of power supply etc. So early detection of such faults is compulsory as economic and reliability issues are concerned.

Earlier these faults are used to detect by Buchhloz relay. But it is slow and it is able to detect only faults below oil level. DGA (Dissolved Gas Analysis) is prone to be one of the successful diagnostic technique. It identifies the incipient faults in an indirect way. Localized overheating of the transformer windings take place due to liberation of typical gas [1-2]. As other faults also have the same effect, DGA is declared to be an ineffective technique [3]. Also it has its own limitation of variability of gas data. There are some other techniques reported in the literature such as magnetic balance tests, ratio meter test etc. However they are not sensitive in determining such incipient faults. In [4], it is shown that no-load losses are high during inter-turn faults when compared with normal working condition. This feature is used to detect inter turn faults. But in this case the effect of core degradation will affect the no-load losses. Depending on the extent of heating up of the insulation, the quantity and types of dissolved gases will be evolved. The favorable reasons of overheating of the insulation are severe over loading, partial discharges, pump motor failures, low-energy sparking and arcing.

In recent years Artificial Intelligent (AI) techniques have been used for inter turn fault detection. In recent reports, a combination of neural network and extension theory is proposed. It is more accurate and able to detect incipient faults at an early stage, but it fails to detect a fault when three or more faults occur simultaneously. Fuzzy logic techniques have been developed for power transformer inter turn fault detection to enhance operational reliability, improve service to customers, and to reduce operating costs. A wavelet based fuzzy logic algorithm proposed in this paper is more sensitive and able to detect the incipient faults at an early stage.

In this article a multiwinding power transformer is simulated in the power system using MATLAB/SIMULINK software. Different percentages of inter turns of power transformer are short-circuited and the resulting transformer terminals currents are measured. The changes in the terminals current is negligibly small. To experience significant changes in terminals current, negative sequence currents are extracted using symmetrical component approach. The changes that occur in both the magnitude and phase on both sides of the transformer during the incidence of incipient fault is estimated. It is observed that these changes are also not significant. So to improve the sensitivity of proposed scheme, wavelet transform is used. Daubechies3 wavelet at level 4 is used to analyze the magnitude and phase varying signals on both sides of the power transformer. The absolute peaks of detailed1 (d1) coefficients on both sides of the power transformer are calculated. The ratios of d1 coefficients are taken as inputs to the fuzzy logic. Here fuzzy logic is implemented to monitor the severity of inter turn fault. There are two inputs employed in this system, such as ratio of d1 coefficients of magnitude varying signals (R1) and that of phase varying signals (R2). Then R1 and R2 are divided into three membership functions each. These membership functions are named as low, medium, and high depending on the ranges of data obtained for R1 and R2. The output of the fuzzy system gives the severity of inter turn fault. The output function is divided into three membership functions namely incipient fault (IF), minor fault (MF) and Severe fault (SF), which conveys the severity of fault.

The paper is systematically organized as follows: A brief introduction of wavelets is given in section 2. Section 3 describes the fundamentals of fuzzy logic. In section 4 the proposed algorithm is explained. Power transformer simulation and results are presented in section 5. Section 6 concludes the paper.

II. WAVELET TRANSFORMS

The power system disturbances are mainly due to non-periodic and transient components. The traditional Fourier transform is unable to detect any sudden change that takes place in a transient process. A wavelet based signal processing tool is able to overcome the drawback associated with Fourier transform. It is an effective tool for power system transient analysis and feature extraction. A wavelet with its inherent dilating and translating mechanisms, is able to analyze any waveform containing non-stationary events. By dilating a wavelet, the instant of fault occurrence can be known on the time scale.

In a pure frequency signal, a Fourier transform can isolate a peak only at that particular frequency. If a signal with two pure oscillations is analyzed using a Fourier transform, two peaks are obtained without localization in time. The solution for this is wavelet which would give local information in both time and frequency [5]. The most important property of wavelet transforms is that the individual wavelet functions are localized in space. This property of wavelets results in a wide variety of applications such as detecting features in images, de-noising, data compression, finger prints, and medicine [6].

To separate a signal discontinuities some short basis functions are required and to get a detailed frequency analysis very long basis functions are needed. It is achieved by having short high-frequency basis functions and long low-frequency ones. This is obtained using wavelets.There are an infinite set of possible basis functions. For a particular application, selection of a suitable wavelet is very important. In this paper Daubechies3 (db3) wavelet is used for its property of orthogonality. Various types of wavelets are tested, but Db3 is simply chosen since it results in an accurate solution and minimum reconstruction error. The wavelet transform has an advantage of varying window size unlike Fourier transform. It can able to analyze a signal in both time and frequency domains effectively. Wavelet Transform is nothing but a sequence of a function {h (n)}(low pass filter) and {g (n)}(high pass filter). The scaling function φ (t) and wavelet ψ (t) are defined by the equations1 and 2 given below.

$$\varphi(t) = \sqrt{2}\sum h(n)\, \varphi(2t-n) \quad (1)$$

$$\psi(t) = \sqrt{2}\sum g(n)\, \varphi(2t-n) \quad (2)$$

Where $g(n) = (-1)^n h(1-n)$

A sequence of {h (n)} defines a Wavelet Transform. There are many types of wavelets such asSymlet, Haar, and Daubachies etc. The selection of mother wavelet is based on the type of application.

III. FUZZY LOGIC APPROACH

Fuzzy sets were developed by Lotfi A. Zadeh and Dieter Klaua in the year 1965. These are expanded version of classical sets for dealing with uncertainty events. The application of fuzzy logic for power system problems was introduced in 1979 [7]. Fuzzy set theory is a nothing but a generalized classical set theory. In classical set theory each element of universe of discourse either belongs to the set or does not belong to it. So the degree of associated element is crisp. Fuzzy set is a mapping from the universe of discourse to the closed interval {0, 1}. In this theory the correlation of an element will be continuously varying.

As fuzzy logic uses expert knowledge and experience, it is very helpful while solving decision making problems. Fuzzy set is an effective tool to analyze uncertain events and relations between them. A fuzzy system is used to deal without data loss when there is vagueness in the input data. In this context fuzzy logic is employed to assess the severity of inter turn fault. Steps involved in fuzzy system are

A. Fuzzification
B. Inference mechanism
C. Defuzzification

A. Fuzzification

Fuzzy logic uses linguistic variables in place of numerical values. In other words Fuzzification is the method of converting real numbers into fuzzy numbers. In the proposed scheme the variables R1 and R2 are used as fuzzy inputs. Depending on the rage of data obtained for each variable these are divided into three membership functions each (low, medium, and high). The output variable (transformer condition) is also divided into three membership functions such as IF, MF, and SF.

B. Inference method

The proposed scheme makes use of vigorous rules to describe the operating condition of the transformer. In this article, to perform a mathematical operation, the Mamdani method is used from MATLAB software. In the proposed scheme 12 rules were used.

C. Defuzzification

The combination of a fuzzy set includes a range of output values and so it must be defuzzified in order to determine a single output from the set. The most accepted defuzzification method is the centroid method, which returns the centre of the area under the curve. There are other methods like centroid, middle of maximum, smallest of maximum, largest of maximum, bisector methods are also available. In this work centroid method is adopted.

IV. PROPOSED ALGORITHM

1. Three phase currents are measured.
2. Observe all the phase currents whether there is any deviation from steady state value. If there is no

significant deviation then, go for negative sequence currents measurement.

3. Obtain negative sequence currents by using symmetrical component approach on primary and secondary sides.
4. Find the magnitude and phase variations of negative sequence currents during fault incidence period.
5. Apply multiresolution analysis to obtain detailed1 coefficients on both sides.
6. Find the ratios (R1 and R2) of absolute peaks of d1 coefficients on faulted side (say secondary) to non-faulted (say primary) for both magnitude and phase varying signals for different percentages of shorted turns.
7. Apply R1 and R2 as inputs to fuzzy logic system.
8. Fuzzy system will give the output that corresponds to the severity of fault.

The block diagram of the proposed algorithm is shown in the appendix (Figure 12).

V. POWER TRANSFORMER SIMULATION AND RESULTS

A physical model of multiwinding transformer of 100 MVA, 138/13.8 KV, Y-Y shown in Figure1 is simulated using MATLAB/SIMULINK software. Different percentages of inter turns of power transformer are short-circuited and it is observed that the changes in transformer terminals current is very small.

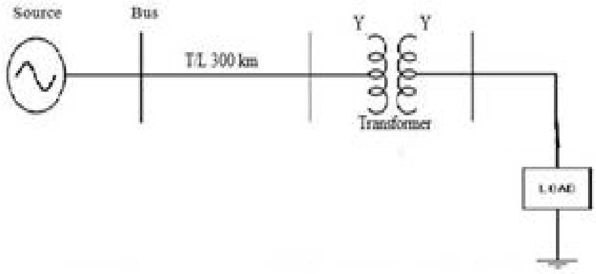

Fig. 1. One line diagram of power system model.

The changes in the transformer terminals current when different percentages of turns are shorted are measured and shown in Table I. When 1% of turns are shorted, the changes in transformer currents are shown in Figures 2 and 3.

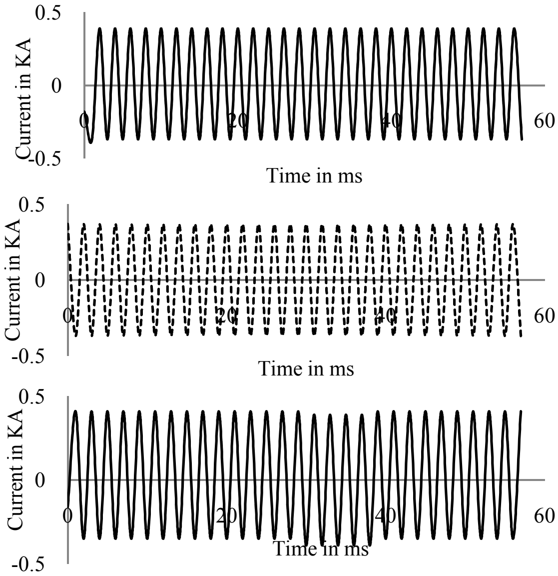

Fig. 2. Three Phase currents on primary side when 1% of turns are shorted in phase C.

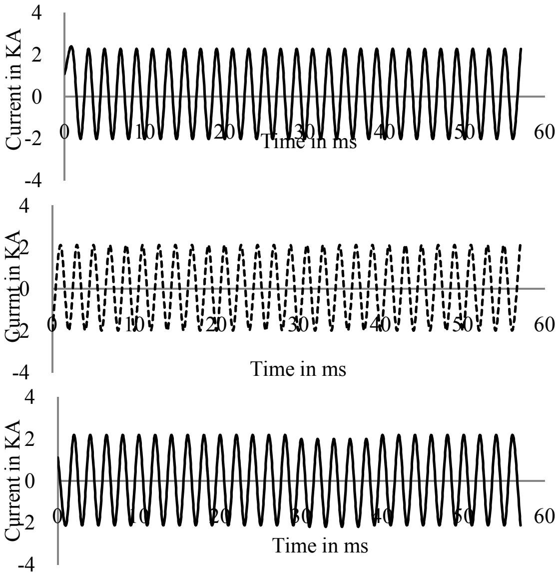

Fig. 3. Three Phase currents on secondary side when 1% of turns are shorted in phase C.

TABLE I

Sl. no	% of shorted turns in secondary of phase C	Magnitude of steady state current	Magnitude of fault current	% change
1	1	2.15	2.2	2.27
2	3	2.13	2.2	3.286
3	5	2.06	2.13	3.39
4	10	1.92	2	4.16
5	15	2.21	2.284	3.34
6	25	2.41	2.53	4.97

Table I shows percentage changes in the transformer terminals current in secondary, phase C for different percentages of shorted turns.

Table II shows percentage changes in the transformer terminals currents in primary, phase C for different number of shorted turns.

TABLE II

Sl. no	% of shorted turns in secondary of phase C	Magnitude of steady state current in primary	Magnitude of fault current in primary	% change
1	1	0.41	0.415	1.21
2	3	o.34	0.364	1.62
3	5	0.38	0.384	1.05
4	10	0.36	0.367	1.944
5	15	0.37	0.377	2.652
6	25	0.375	0.392	4.53

These changes in the transformer terminals currents are very small during incipient faults. So a new protection principle based on the theory of symmetrical components or more exactly, on the negative-sequence currents is proposed. The negative sequence currents are extracted using MATLAB/SIMULINK.

Figure.4 shows the magnitudes of the negative sequence current on the primary side (Inscp) and the magnitude of the negative sequence current on the secondary side (Inscs) in phase C for 1% of shorted turns. The magnitude of the negative sequence current on the faulty side (Inscs) is greater than the magnitude of the negative sequence current on the other side (Inscp) as expected.

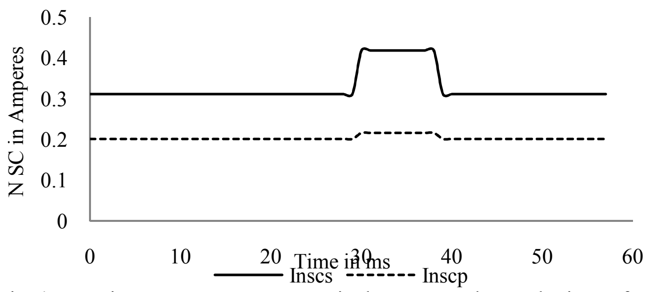

Fig. 4. Negative sequence current magnitudes on secondary and primary for 1% shorted turns on secondary in phase C.

Table III shows percentage changes in the negative sequence currents in secondary, phase C for different number of shorted turns.

TABLE III

Sl. no	% of shorted turns in secondary of phase C	Magnitude of steady state current	Magnitude of negative sequence current	% change
1	1	0.3115	0.321	3.04
2	3	0.4013	0.4145	3.289
3	5	0.4085	o.4264	4.38
4	10	0.6839	0.725	6.839
5	15	0.8773	0.941	7.26
6	25	1.5346	1.682	9.605

Table IV shows percentage changes in the negative sequence currents in primary, phase C for different number of shorted turns.

TABLE IV

Sl. no	% of shorted turns in secondary of phase C	Magnitude of steady state current in primary	Magnitude of negative sequence current in primary	% change
1	1	0.1287	0.1316	2.276
2	3	0.251	0.264	5.17
3	5	0.2018	0.2066	7.33
4	10	0.264	0.293	10.98
5	15	0.354	0.388	9.604
6	25	0.614	0.6645	8.224

Even though the percentages of negative sequence currents are relatively higher than the normal fault currents, the variation during incipient faults is very low. Hence, they cannot detect the incipient faults with more sensitivity. So to improve the sensitivity of the proposed scheme wavelet transform has been employed.

Fig.5 shows the d1 coefficients obtained when Inscp and Inscs signals are analyzed using multiresolution analysis.

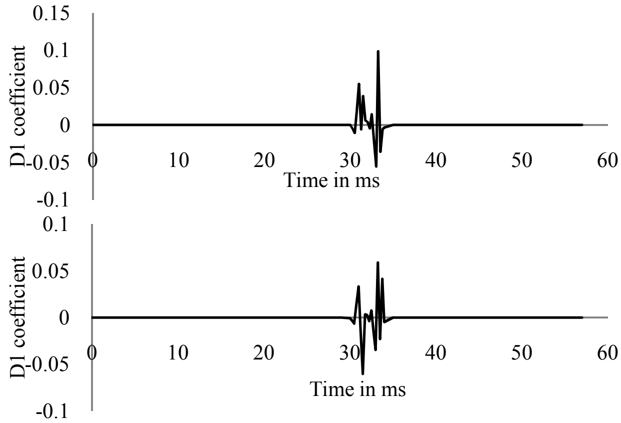

Fig. 5. d1 coefficients of Inscs and Inscp for 1% shorted turns.

The phase angle variations of negative sequence currents on both sides of the power transformer during different percentages of shorted turns are measured and the phase variations during 1% shorted turns are shown in Fig. 6.

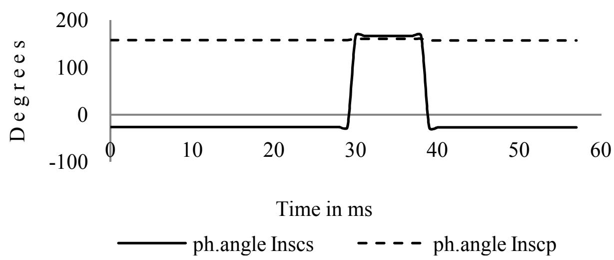

Fig. 6. Phase shift between Inscs to Inscp when 1% turns are shorted

Theoretically, the phase angle between two phasors of negative sequence currents has to be 0 degrees during internal short-circuit. But in reality there are some other arbitrary phase angle shift caused by the quite high current in the shorted turns as shown in figures. The phase shift during different percentages of shorted turns on primary and secondary sides of power transformer is shown in the Table V.

TABLE V.

Sl. No.	% of shorted turns	Phase angle of Inscs	Phase angle of Inscp	Phase shift
1	1	166.84	160.27	6.57
2	3	162.33	156.11	6.21
3	5	156.64	151.12	5.51

4	10	160.63	152.40	7.80
5	15	159.11	152.83	6.28
6	25	160.19	154.63	5.55

Fig. 7 shows the d1 coefficients obtained when two waveforms in figure 6 are analyzed using using multiresolution analysis.

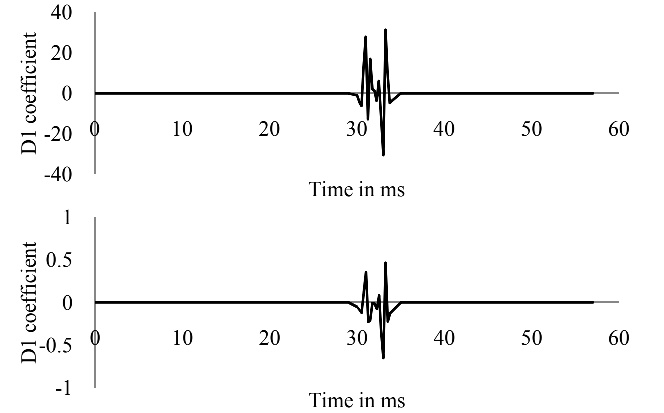

Fig. 7. d1 coefficient of phase varying signals when 1% turns are shorted.

The ratio of absolute peaks of d1 coefficients on faulted side (secondary) to that on non-faulted side (primary) at different percentages of shorted turns is calculated for magnitude variations and for phase angle variations and the results are given in Tables VI & VII respectively.

TABLE. VI

Sl. No.	% of shorted turns	Absolute peak of d1 coefficient on secondary (a)	Absolute peak of d1 coefficient on primary (b)	Ratio (a/b) (R1)
1	1	0.1137	0.05883	1.9327
2	3	0.1309	0.05875	2.228
3	5	0.1554	0.06817	2.279
4	10	0.214	0.08746	2.4468
5	15	0.2852	0.1114	2.56
6	25	0.5116	0.1951	2.622

TABLE VII

Sl. No.	% of shorted turns	Absolute peak of d1 coefficient on secondary (a)	Absolute peak of d1 coefficient on primary (b)	Ratio (a/b) (R2)
1	1	31.4178	0.65169	48.20
2	3	48.1615	0.9805	49.14
3	5	27.0606	0.5426	49.87
4	10	49.8699	0.9626	51.8
5	15	50.1187	0.9268	54.07
6	25	50.7503	0.8982	57.02

R1 and R2 are fed as inputs to the fuzzy logic .For building membership functions R1and R2 are divided into three parts each namely low, medium, and high. The three membership functions of R1 and R2 are represented by trapezoidal membership functions with their respective ranges as shown in figures 8 and 9.

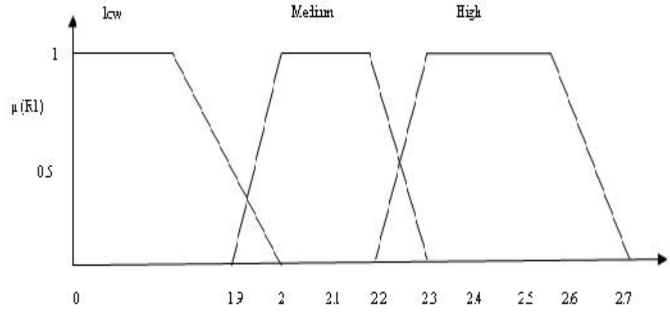

Fig. 8 Membership functions of R1

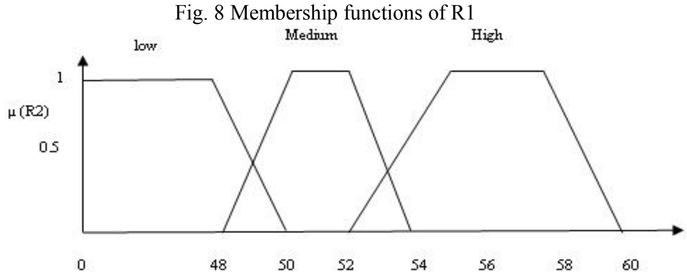

Fig. 9 Membership functions of R2

The fuzzy inference is build by framing the following rules

Rule 1: If R1 is LOW and R2 is LOW then the fault is IF
Rule 2: If R1 is LOW and R2 is MEDIUM then the fault is IF
Rule 3: If R1 is LOW and R2 is HIGH then the fault is IF
Rule 4: If R1 is MEDIUM and R2 is LOW then the fault is IF
Rule 5: If R1 is MEDIUM and R2 is MEDIUM then the fault is MF
Rule 6: If R1 is MEDIUM and R2 is HIGH then the fault is MF
Rule 7: If R1 is HIGH and R2 is LOW then the fault is IF
Rule 8: If R1 is HIGH and R2 is MEDIUM then the fault is MF
Rule 9: If R1 is HIGH and R2 is HIGH then the fault is SF

As described in the rules the output function is also divided into three parts, which represent the severity of fault associated with the transformer winding. The three embership functions concerned with the output are named as IF, MF, and SF as shown in figure 10.

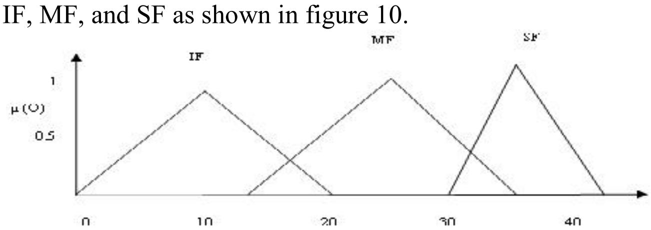

Fig. 10 Membership functions of Outfunction

By using a Fuzzy Logic tool box in the MATLAB environment the rule viewer at an instant is obtained as shown in Figure 11.

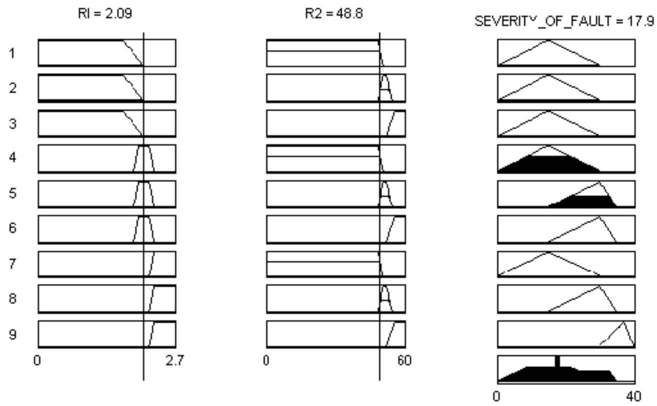

Fig. 11 Rule viewer of proposed Fuzzy Inference Scheme

VI. CONCLUSION

In this research article a novel algorithm combining wavelet transforms and fuzzy logic is employed. Wavelet is a powerful tool in analyzing a signal in both time and frequency domains, and hence it can able to extract the information of a signal in depth. Fuzzy logic is employed to judge the severity of fault. The combined wavelet and fuzzy approach is more effective in dealing with incipient faults. This approach is found to be more robust and computationally much simpler when compared with other methods reported earlier.

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NOMENCLATURE

NSC: Negative Sequence Current.
Inscs: Magnitude of negative sequence current on secondary side.
Inscp: Magnitude of negative sequence current on primary side.
Ph.angle Inscs: Phase angle variation of negative sequence current on secondary side.
Ph.angleInscp: phase angle variation of negative sequence current on primary side.
DWT: Discrete Fourier Transform
WT: Wavelet Transform
Db3: Daubechies3
D1: detailed1 coefficient
μ (R1) : Degree of membership functions of input R1
μ (R2): Degree of membership functions of input R2
μ (o) : Degree of output membership function.

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APPENDEX

Three phase voltage source

Voltage: 138KV

Frequency :50Hz

Three phase transformer block parameters

Nominal Power: 100MVA

Voltage:138/13.8 KV

Transmission line parameters

Resistance per unit length: 0.02ohms/km

Inductance per unit length :0.506*10^2 H/km

Capacitance per unit length :1*10^-12 F/km

Line length: 300 km

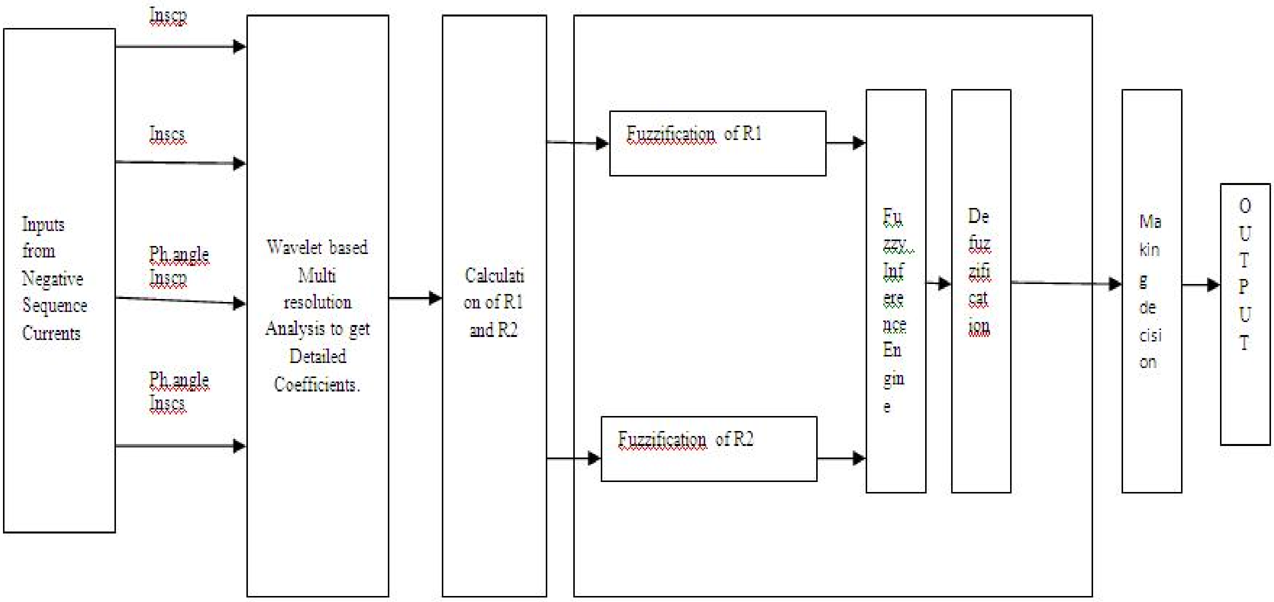

Fig. 12. Block diagram of the proposed algorithm