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Differential Protection for Unsymmetrical Phase Shift Transformers using Intelligent Tools

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***Abstract*: This abstract illustrates differential protection philosophy for indirect unsymmetrical phase shifting transformer (IUPST) by using combined wavelet transform and artificial neural network (ANN) methods. Discrimination between interval fault and magnetizing inrush condition is a very challenging task in IUPST differential protection scheme. Therefore, wavelet transform is used to extract the feature from the relaying signal (i.e. differential current) and the features of the relaying signal is used to train and test the ANN. The IUPST is modelled in PSCAD/EMTDC software to obtain the relaying under different operating conditions. The proposed algorithm is evaluated in MATLAB under forward and backward mode of PST operation and the tested data is simulated in PSCAD/EMTDC by varying inception angle, fault position, tap positions, loading conditions of IUPST. Genetic Algorithm (GA) is used to obtain the optimal structure of Multi-Layer Feed Forward Neural Network (MLFFNN). Results shows that the proposed algorithm is stable, reliable and selective under different operating conditions of IUPST.**

***Keywords*: Indirect unsymmetrical phase shifting transformer, Discrete wavelet transform, Genetic Algorithm, Multi-Layer Feed Forward Neural Network, Transformer Inrush MATLAB, PSCAD, SVM.**

1. Introduction

Day-by-day demand of electrical power is increasing due to development of new electrical and electronic equipment. Therefore, either expansion of transmission grid or optimal utilization of existing grid is required to fulfill the power demand. Expansion or development of new transmission grid depends on many factors like social, environmental, geographical and economical etc. On other hand, optimal utilization of existing grid is more convenient and rational solution. Moreover, the deregulation of electricity market lead major changes in utilization of existing transmission grid, which is used as a transport medium between producer and consumer. Special transformers are utilized to create a phase shift between the primary and secondary side of voltages, are known as Phase Shift Transformers (PSTs). PST has the ability to offer targeted active and/or reactive power control, is being deployed to reduce unplanned flows and optimal utilization of existing transmission grid. Indirect Unsymmetrical Phase Shift Transformers (IUPSTs) are very useful in the networks where intensive power wheeling takes places due the regulation. The apparent power transported over a transmission line is given by eq. (1).

$$S = P + jQ = \frac{|V_S||V_L|}{X_L}\sin\delta + j\frac{|V_S||V_L|}{X_L}\cos\delta \qquad (1)$$

Where,
V_S= Voltage of source side
V_L= Voltage of load side
X_L= Line reactance between source and load
δ= phase angle difference between V_S and V_L.

IUPSTs play key role in wide area monitoring and control system where the operator optimize the flow action of very large system. Its protection is a major concern. Repairing of IUPST is costly and time consuming affair. Therefore, monitoring the operating condition of an IUPST is very important issue in the protection of IUPST. Moreover, to save the repairing time the prior information about the type of internal fault occurred in an IUPST is required.

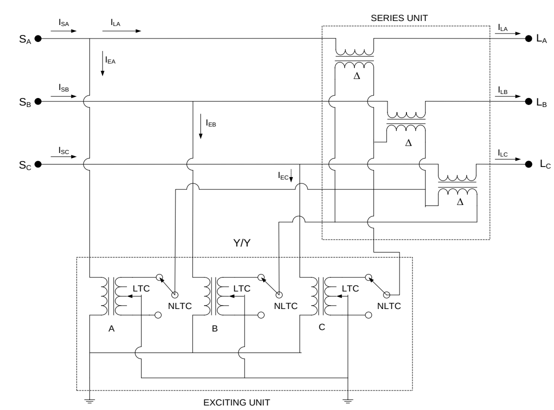

Fig. 1. Indirect unsymmetrical PST

Generally differential protection scheme is very popular for the internal fault detection of transformers. In the conventional differential protection scheme, the differential current is compared with a threshold but in case of nonstandard transformers like PST and IUPST, normal differential relay is unable to compensate the non-standard phase angle shift and that cause mal-operation. Moreover, in case of IUPST as shown in Fig.1, the magnitude of differential current also varies along with phase angle and this make it more challenging problem for

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protection engineer. There are paper that presents a compensation method that can calculate differential current for any power transformer if correct information about On-load Tap Changer (OLTC) position is known than total differential protection i.e 87T scheme can be used for PSTs. Like conventional harmonic restrained based differential protection approach for power transformer maloperate due to modern core material, these PST also suffers from the same problem.

This work presents a novel condition monitoring and differential protection scheme by cascading wavelet transform and optimal Feed Forward Back-propagation Neural Network (FFBNN), for detecting internal fault condition of IUPST which involves the discrimination from other healthy conditions followed by identification of the type of internal fault once the internal fault has identified in the IUPST whether the differential connection is either 87P and 87S or 87T type. As the 87P and 87S differential protection is not applicable for direct PSTs due to the locations of CT, 87T gives an extra advantage to protect direct PSTs. Because of that reason this paper will basically deal with the 87T differential protection for PSTs. As the selection of feature vector is very important for the classification of problems, therefore the detail coefficients of the differential signal is used as a feature vector in this work. Discrete Wavelet Transform (DWT) is applied to decompose the differential current of IUPST into a series of detailed components, each of which is a time domain signal that covers a specific frequency band. Thus, the time and frequency domain features of relaying signals are extracted and then these coefficients are employed to train an optimal FFBNN. Moreover, the interface between wavelet transform and optimal FFBNN is evaluated to ensure their effectiveness. In the study of IUPST condition monitoring and differential protection scheme external fault, internal fault of IUPST (including three phase faults, three phase-to-ground faults, phase-to ground faults, phase-to-phase faults, turn-to-turn fault), over-excitation and ultra-saturation phenomenon are considered. The load connected with IUPST is resistive and inductive. The proposed work is simulated and tested on PSCAD/EMTDC and MATLAB respectively.

2. Differential current in the power transformer

Differential current relay is mainly two types:

- Simple differential relay
- Percentage differential relay

Percentage differential relay without restraining coil is considered as a simple differential relay. Number of turns in restraining coil and operating coil decides the slope of the differential relay. Slope of the differential relay is in between differential current vs. restraining current (biased current). When compare restraining torque with operating torque the final equation will be.

$$I_1 - I_2 = T * \frac{I_1+I_2}{2} + T_0 \qquad (2)$$

Where,

$T = \frac{N_r}{N_o}$

N_r is the number of turns in restraining coil

N_o is the number of turns in operating coil

I_1 is the current obtained from one of the CT

I_2 is the current obtained from another one of the CT

T_o is the minimum pick up value of differential relay

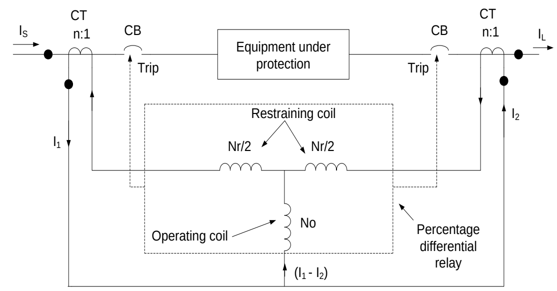


Fig. 2. 3-phase power transformer differential relay configuration

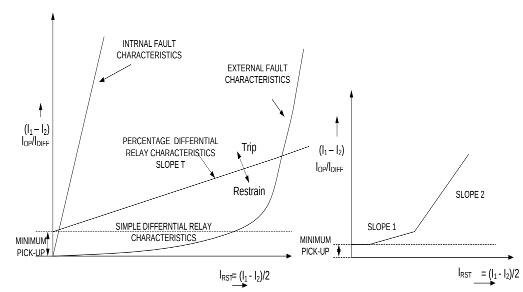


Fig. 3. (a) Percentage differential relay, (b) Dual slope percentage differential relay

The Fig. 3 (b), the percentage differential relay can be made more immune to mal-operation on 'external fault' by increasing the slope of the characteristic. That's why we go for dual slope percentage differential current slope1 gives high sensitivity for internal faults and slope 2 gives high security against external fault magnitude of slope 2 is greater than slope1 knee point of dual slope differential current is decided where saturation of CT is started. In the literature mainly, differential protection scheme is used for the protection of PST. Mainly two types of protection schemes have been discussed till now in the literatures for PST. Where primary differential relay (87P) is use to protect primary winding of the exciting and series unit and secondary differential relay (87S) is use to protect secondary winding of the exciting and series unit. These 87P and 87S combine protects the PST [5]. Other than this differential relay there exist overall differential relay (87T) to protect primary and secondary winding of the series and exciting unit combined [6].

3. Discrete wavelet transform

Whenever fault occurs there are always transients present. This transient contains different frequency component of current at different time. The strength of different frequency depends on different operating current. Like in case of inrush 2nd harmonic current is higher than the fundamental current [14]. Different signal processing technique are available to study the different frequency component present in the differential current. One of the techniques is Discrete Fourier Transform DFT. It is used only for stationary signal and it gives only about frequency information and it losses about time information. So, this technique is not suitable for this purpose because differential current contains transients. Another technique is the discrete time Short Time Fourier Transform STFT. It gives information about both frequency as well as time but limited precision. It increases the frequency information by varying window then time information is reducing. So, to overcome the above problem DWT is introduced, it gives information about frequency as well as time at very high precision and it gives information like at what time what frequency component is present which is very useful for analysis of transient in fault current [10].

$$x[n] = \frac{1}{\sqrt{M}}\sum_k U_\Omega[l_0,k]\Omega_{l_0,k}[n] + \frac{1}{\sqrt{M}}\sum_{l=l_0}^{\infty}\sum_k U_\beta[\,l,k]\beta_{l,k}[n] \tag{3}$$

Discrete signal is comprising by using scaling and wavelet function is:

Where,

$\Omega_{l_0,k}[n]$ is scaling function
$\beta_{l,k}[n]$ is wavelet function
$U_\Omega[l_0,k]$ is approximate coefficient
$U_\beta[\,l,k]$ is detailed coefficient
l_0 is shifting parameter
k is shifting parameter

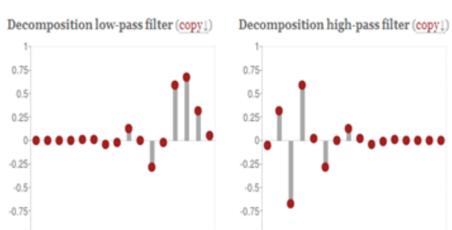


Fig. 4. DWT decomposition LPF and HPF

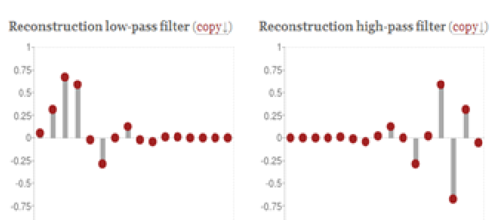


Fig. 5. Reconstruction LPF and HPF

Approximate (2) and detailed (3) coefficient are:

$$U_\Omega[l_0,k] = \frac{1}{\sqrt{M}}\sum_k x[n]\Omega_{l_0,k}[n] \tag{4}$$

$$U_\beta[\,l,k] = \frac{1}{\sqrt{M}}\sum_k x[n]\beta_{l,k}[n] \quad l \geq l_0 \tag{5}$$

There are many kinds of mother wavelets, like Harr, Daubichies, Coiflet and Symmlet wavelets. Smoothness of db8 (Daubichies) wavelet is same like power signal (differential current). So, it gives vary good result to extract higher harmonics present in differential current. Discrete db8 filter is shown in Fig. 4.

The differential current is first sampled with sampling frequency f_s($f_s \geq 2f, f$ = fundamental frequency) then passes through LPF and HPF parallel. half of lower frequency band is passed through LPF and half of higher frequency band is pass through HPF, the total number of sample after filtering is+l,-1, here L is length of input signal, l is length of FIR of filter, it means number of sample is getting increased after passing again output of LPF through HPF and LPH, so that to make less calculation and memory efficient, number of sample stored by reduce to half of the total sample by taking only even number of sample. This process is called down sampling. Output of LPF is called approximate coefficient and output of HPF is called detailed coefficient. Reconstruction of signal is done by first padding zero in odd places of signal (up sampling) and then pass through opposite of the filter that is used before for filtering purposes.

Frequency band of detailed and approximate coefficient after m-level of decomposition are:

$$f_{approximate_{c]}} = [0, \quad \frac{f_s}{2^{m+1}}]$$

$$f_{detail_c} = [\frac{f_s}{2^{m+1}}, \quad \frac{f_s}{2^m}]$$

In this process decompose the signal into 5 level means get detailed coefficient from d1 to d5 and approximate coefficient A5, and waveform of d4 is clearly different for inrush and all types of internal faults so that coefficient of d4 component is use for classification purpose. To obtain waveform of different level of decomposition coefficient reconstruction filter is used which is mentioned in Fig. 6.

The Fig. 4, shows the decomposition LPF and HPF of Daubichies8 (db8) mother wavelet family, where 8 represents the order of the filter.

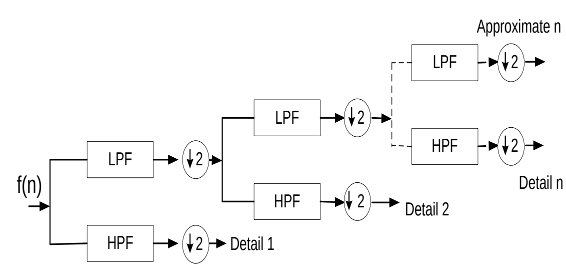


Fig. 6. DWT decomposition filtering block diagram

4. Multi-layer feed forward neural network (MLFFNN)

Classification is a most frequently observed phenomenon of human activities and it is characterized by training learning and adaptive capabilities of brain. The artificial neural network (ANN) can successfully use for classifying real time problem like speech recognition, medical diagnosis, fault detection etc.

Here Multi-Layer Feed Forward Neural Network (MLFFNN) is use for classification purpose, inputs of MLFFNN are wavelet coefficient of differential current and output which shows what type of fault is occurs or inrush condition. The number of hidden layers used here is two for this purpose. MLFFNN is a black box approach to generalize network by learning its weights by using various learning algorithm such as TRAINLIM, TRAINBFG and TRAINRP. Out of this learning algorithms levenberg-marqurdt (trainlim) learning algorithm (back propagation) is faster as suited for MLFFNN with large number of input patterns. MLFFNN used for classification can uses various type of activation function (Table 1). The architecture used for classification is shown in Fig. 7. For a particular application of neural network, it is very difficult to decide number of neurons in hidden layer and which activation function will be suitable for particular problem. One of the solutions for that is to optimize it with different evolutionary technique like PSO, Genetic Algorithm (GA), etc.

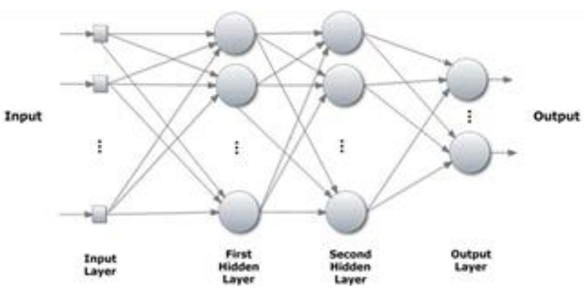


Fig. 7. Structure of MLFFNN

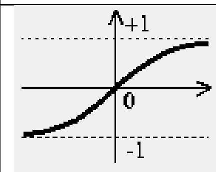
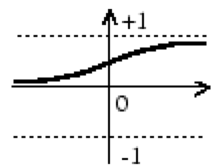
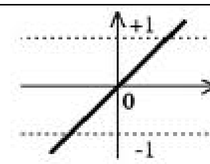
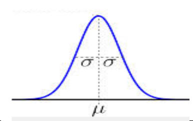
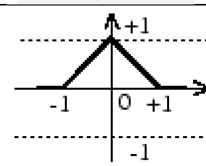
5. Genetic algorithm (GA)

GA is a search machine which follows natural selection. This is use for getting optimum value in search algorithm. It uses-

- *Inheritance:* acquiring parental characteristic
- *Crossover:* acquiring some characteristics of both parents.
- *Mutation:* developing new characteristic with course of time.
- *Selection:* evolution of the best individual among a set of competitors who is superior from every one.

Here GA is use for optimize crucial parameter of MLFFNN which largely affects the classification accuracy. In this case number of optimization parameter are five. First 2 are number of neurons in 1st & 2nd hidden layer and remaining 3 is activation function of hidden & output layer. GA creates a random population and find their fitness value. A new population is generated from the existing population. Then crossover between parents is done. Mutation takes place. The whole procedure is repeated until the stopping criteria is satisfied.

Table 1
List of different activation function used in MLFFNN

S. No.	Activation function	Waveform	Equation
1	Tansig		$O_i = \frac{2}{1+e^{(-2*WI_i)}} - 1$ O_i is output of i^{th} neuron WI_i is sum of weighted input with bias of i^{th} neuron
2	Logsig		$O_i = \frac{1}{1+e^{(-WI_i)}}$
3	Purelin		$O_i = WI_i$
4	Radial basis		$O_i = e^{-(\frac{WI_i-\mu}{2\sigma^2})}$ μ is center & σ is variance
5	Triangular basis		$O_i = \begin{cases} 1-\lvert WI_i \rvert & for \\ -1 < WI_i < 1 \\ 0 & else\ where \end{cases}$

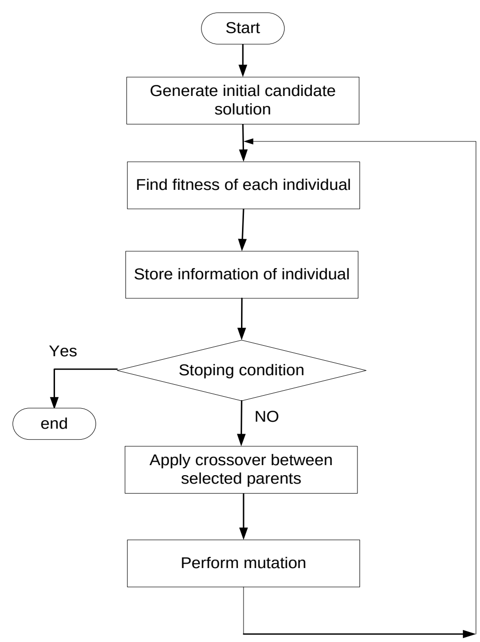


Fig. 8. Flow chart of GA

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6. Modelling, simulation and results

A. Modelling of IUPST in PSCAD:

The rating of IUPST for overall and based on exciting and secondary unit and current transformer are listed below [5], [3].
Rating of PST: Voltage- 132kV / 150kV

Rating of PST: Voltage- 132kV / 150kV
Current- 1015A / 1154A
Phase shift- ±28.4°
Frequency- 50 Hz
Exciting unit:
Voltage: 76.21/kV / 35.34kV (at full tap position) taping present in lower voltage side
MVA- 125.562 MVA (3Ph)
Leakage reactance- 0.0438 pu
Series unit:
Voltage: 41.2kV / 61.2kV
MVA- 142.713 MVA (3Ph)
Leakage reactance- 0.0801 pu
Transmission line parameter: line1-
+ve sequence R= 0.00945 ohm
+ve sequence XL= 0.0302 ohm
+ve sequence XC= 1.435 Mohm
Transmission line parameter: line2-
+ve sequence R= 0.00203 ohm
+ve sequence XL= 0.0065 ohm
+ve sequence XC= 6.6966 Mohm
CT rating of source side, load side and primary side of exciting unit is [8]:
Current ratio- 2400A / 5A
Burden- R=1.0 ohm

Simulation of PST is done in PSCAD/EMTDC and all the operating signals are generated. When generating internal fault current three things are considered. First is fault percentage of winding, at what phase angle fault (time of fault) occurs and tap position of exciting unit. In case of Ph-G percentage of fault winding is 20%, 40%, 60% and 80% from the neutral point, and fault time is also changing from 0.1sec to 0.12sec in 24 interval and tap of exciting unit is also varied from 0.179 to 0.9 (-5° to+24°) of full tap position in 6 intervals. Same is done for Ph-G fault in exciting primary series primary and secondary winding and also for turn to turn fault. For finding operating signal for remaining fault percentage of winding is different and other things are same as Ph-G fault condition. Model of IUPST for above condition is shown in Fig. 14. In case of inrush four things are considered first is the residual flux, second is the switching angle and third is the tap position of exciting unit and last is the load condition. In this case switching angle is varied from 30° to 330° in the interval of 30° and residual flux is varied from 10% to 80% of rated flux in the interval of 10%. The total number of 30720 testing and training signal are generated. Model of IUPST for above condition is shown in Fig. 13.

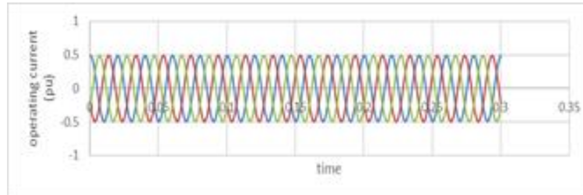

Fig. 9. Overall differential current for normal condition

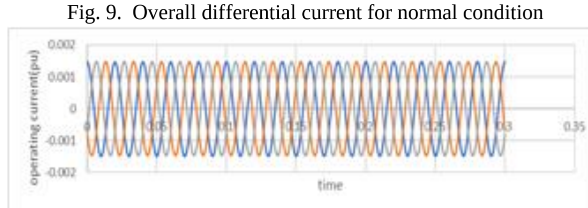

Fig. 10. Primary differential current at normal condition

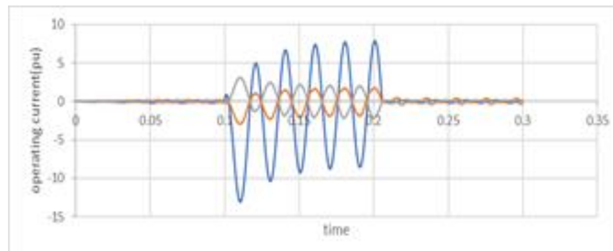

Fig. 11. Differential current during Ph-G fault

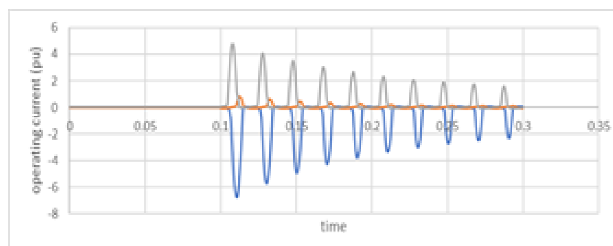

Fig. 12. Magnetizing inrush at no load

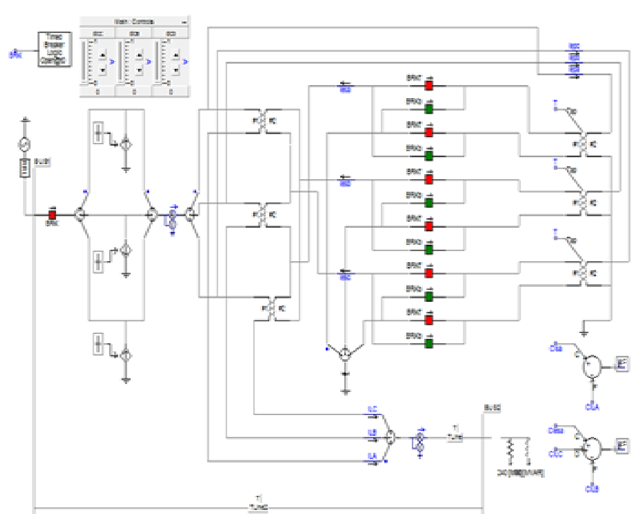

Fig. 13. Model for inrush when residual flux is present

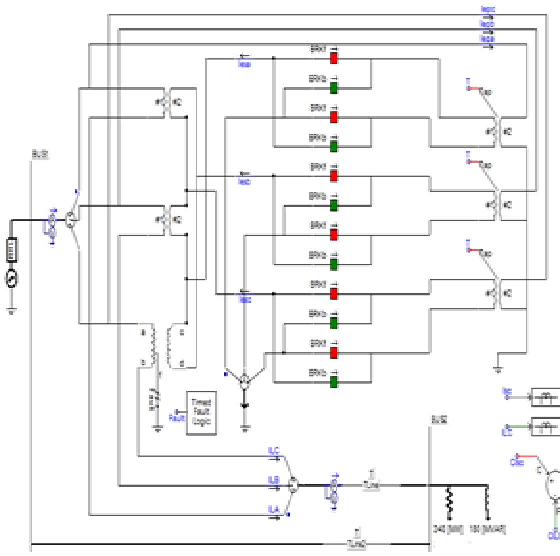

Fig. 14. Model of IUPST in PSCAD for internal fault

After modelling and generation of differential current for different operating conditions of IUPST. The following algorithm is simulated in the MATLAB environment for the protection of IUPST:

B. Implementation of Algorithm for Overall Differential Protection (87T)

CT connection for overall differential protection is shown in the figure 16 In this case overall differential current is use for detecting the internal fault and inrush, in this case over excitation is simply detected by v/f ratio, after this discrete wavelet transform is apply to the differential current of 100 samples/cycle/phase (300 for 3Ph/cycle) and coefficient of d4 (20 samples in each phase) is use for classification purpose by MLFFNN. Before this in case of normal condition coefficient of d4 are all zero because no transient present in normal differential current. All the steps are clearly shown in Fig. 16.

After applying GA for five better combination, MLFFNN is trained and tested.

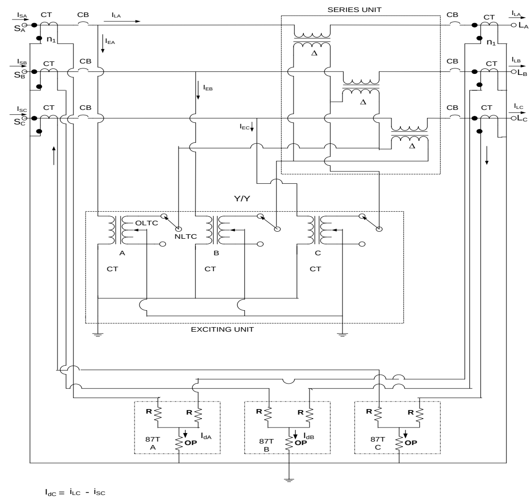

Fig. 15. CT connections for overall differential protection

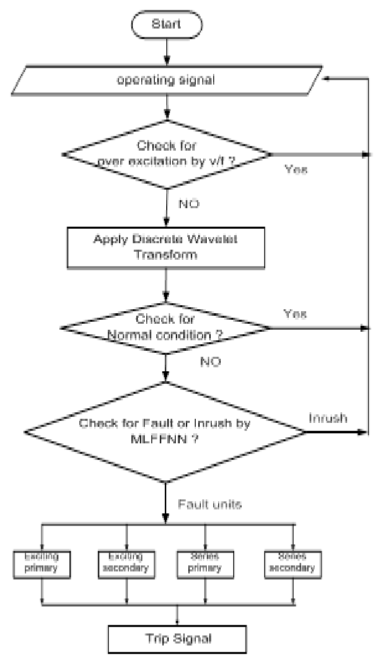

Fig. 16. Algorithm for 87T

Table 2
Five better results for 87T

Hidden layer I		Hidden layer II		Output layer		Training accuracy %	Testing accuracy %
Activation function	No. of neuron	Activation function	No. of neuron	Activation function	No. of neuron		
logsig	95	tansig	15	pureline	5	90.12	89.88
radbas	90	tansig	10	logsig	5	91.54	92.86
logsig	120	radbas	12	pureline	5	92.99	90.56
tansig	110	tansig	11	logsig	5	93.5	93.12
tansig	100	tansig	9	pureline	5	94.01	94.86

Table 3
Best result of 87T

Fault Unit and Inrush	Training Sample	Tested Sample	False Detection
exciting primary	1400	1288	93
exciting secondary	1800	1320	63
series primary	1720	1064	73
series secondary	1720	1064	16
inrush current	300	32	0

$$\text{fault detection accuracy} = \frac{4768-245}{4768} = 94.86\%$$

7. Conclusion

The proposed protection i.e. 87T based on combine wavelet and neural network algorithm provides an overall differential protection of IUPST. ANN has been taken as classification tool and DWT as a feature extractor. The training and testing accuracy are reasonably high. The testing accuracy achieved in this technique is 94.06%. Which is far better than the conventional differential relay. This approach is also applicable on direct PSTs, which removes the limitations of 87P and 87S for PST protection. Here Genetic Algorithm was used to get the optimum hidden layer neurons, activation function etc.

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