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Locating Earth Fault of Synchronous Generator using Wavelet Transform and ANFIS

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ABSTRACT

Synchronous generators are considered the most important part in power generation equipment, hence protecting them is a high priority issue. This paper introduces a technique to detect and locate synchronous generators' earth fault using wavelet transform (WT) as a tool of features extraction and classification by Adaptive Neuro Fuzzy Inference System ANFIS. WT and ANFIS approaches have been illustrated using Simulink/Matlab for validation and proof of the concept.

1. Introduction

Synchronous generators are considered as the most important part of power generation industry for both fossil and renewable energy units, hence protecting them is the high priority concern for both vendors and operators. Generators are susceptible to many types of faults such as over/under voltage, abnormal frequencies deviations, over/under excitation, earth faults...etc. Earth faults may cause a severe damage to the windings and also may lead to possible damage to the core. Since the setting of the protective relays is normally designed to trip the generator when the neutral voltage is higher than 5% of the phase to ground nominal voltage and this means that the rest 95% of the stator winding is protected, hence it is essential to find a way to protect 100% of the windings. There are two existing methods to do this presented in [1] and [2] by measuring the 3rd harmonic voltage of the generator or by the sub harmonic injection. Both ways detect the earth fault along the 100% of the windings. It has been noticed that using 3rd harmonics and sub harmonic injection techniques have some disadvantages such as the practical difficulties in setting the protection in the 3rd harmonic voltage protection, or the higher cost associated with providing and maintaining reliable sub harmonic source.

This paper aims to develop a method to detect and locate synchronous generator earth fault using Wavelet Transform (WT) as a feature extraction tool and Adaptive Neuro Fuzzy Inference

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System (ANFIS) as an artificial intelligent technique that will utilize the features extracted by the wavelet transform by monitoring the phase current. Merging those techniques has been introduced before for detecting and locating faults in transmission lines [3] also used in induction motors for fault classification [4]; but the applications on generators is limited to using only one of them or using both on monitoring the injection current [5], hence in this paper simple approach is introduced and applied through monitoring the phase current only, without the need of sub harmonic or 3rd harmonics injection.

2. The Proposed Technique

2.1 Wavelet transform WT

Wavelet transform is a signal processing tool used in the detection of abnormalities exist in non stationary signals, unlike Fourier transform, wavelet transform provides time-frequency localization of the signal by decomposing it into different ranges of frequencies, hence makes it a useful tool for identifying any abruption in electrical operating parameters such as voltages, currents, frequencies,...etc. There are two types of WT, continuous wavelet transform(CWT) and the digitized version which is discrete wavelet transform (DWT).

There are two types of (WT), continuous wavelet transform (CWT) and the digitized version which is discrete wavelet transform DWT.

The CWT is expressed as follows:

$$CWT(x, \Psi_{a,b}) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} x(t) \Psi^* \left[\frac{t-b}{a} \right] dt \quad (1)$$

where Ψ(t) is known as wavelet basis function or the mother wavelet, the asterisk denotes complex conjugate and a, b are the dilation and translation parameters respectively. Most of applications require discrete wavelet transform DWT, which can be achieved by discretizing the dilation (scaling) and translation parameters a, b, the most common method is the dyadic method as given in [6]:

$$\Psi^*(j,k) = \frac{1}{\sqrt{2^j}} \psi \left(\frac{t-2^j k}{2^j} \right) \quad (2)$$

where *a*, *b* in Eq. (1) are replaced by 2^j and $2^j k$ in (2) respectively and *j* is the scale parameter and *k* is the translation parameter.

The (DWT) is achieved by passing the sampled signal through low pass filter and high pass filter simultaneously then sub sampling by two. The output of the high pass filter is called the detailed coefficients (d) and the output of the low pass filter is called the approximation coefficients (a), they can be expressed as follows:

$$a_{j+1}[n] = \sum_k a_j[k]\, h[2n-k] \quad (3)$$

$$d_{j+1}[n] = \sum_k d_j[k]\, g[2n-k] \quad (4)$$

Hence DWT of the sampled signal X[n] is :

$$DWT\left[X[n], \Psi_{j,k}\right] = \sum X[n] \Psi_{j,k}[n] \quad (5)$$

X[n] can be written as:

$$X[n] = \sum_k a_{j,k} \emptyset_{j,k}[n] + \sum_{j=j_o}^{j-1} \sum_k d_{j,k} \Psi_{j,k}[n] \quad (6)$$

$$\phi_{j,k}[n] = \frac{1}{\sqrt{2^j}} \varphi[2^{-j}n - k] \quad (7)$$

$$\Psi_{j,k}[n] = \frac{1}{\sqrt{2^j}} \psi[2^{-j}n - k] \quad (8)$$

where $\varphi_{j,k}[n]$is the scale function, $\Psi_{j,k}[n]$ is the wavelet function and $a_{j,k}$ and $b_{j,k}$ are the approximation and detail coefficients, respectively. Also, the energy of the sampled signal is expressed according to Parseval's theorem to:

$$\sum_{n=1}^{N} |X[n]|^2 = \sum_{n=1}^{j} |a_j[n]|^2 + \sum_{n=1}^{m} \sum_{n=1}^{n} |d_j[n]|^2 \quad (9)$$

where $\sum_{n=1}^{N} |X[n]|^2$is the total wavelet energy of the signal. $\sum_{n=1}^{j} |a_j[n]|^2$is the total energy concentrated in the j^{th} level of the approximated wavelet version of the signal.$\sum_{n=1}^{m} \sum_{n=1}^{n} |d_j[n]|^2$is the total energy concentrated in the detailed version of the signal, *m* is the maximum level of wavelet decomposition.

2.2 Adaptive neuro fuzzy inference system ANFIS

ANFIS is an artificial intelligent tool that is used to transform a given input into a target output by optimizes fuzzy system parameters of first order Sugeno system [7]. It consists of five main processing layers which are the (1) input fuzzification, (2) application of fuzzy operators,(3) application method,(4) output aggregation and (5) difuzzification. Figure 1 is the description of two inputs first order Sugeno system:

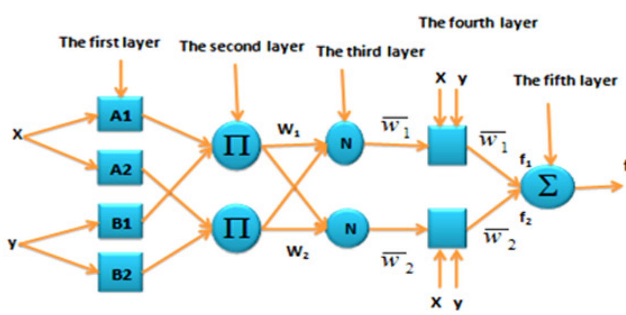


Fig. 1. ANFIS architecture

The first layer or stage is the fuzzification of the two inputs, generates the membership grades as given[8]:

$$O_{i,1} = \mu A_i(x), \quad i = 1, 2 \quad (10)$$

$$O_{i,1} = \mu B_{i-2}(y), \quad i = 3, 4 \quad (11)$$

where µ is the membership function (MF), x,yare the input node, Aand Bare the linguistic variables associated with the node. The second layer is the firing strength layer, it consists of fixed nodes which are an AND gate function or product function, the output of these nodes is the product of the remaining signals:

$$O_{2,i} = \omega_i = \mu A_i(x).\mu B_i(y) \tag{12}$$

The third layer is the normalizing layer it performs the calculation of the ratio of the ith rule firing strength to the sum of all firing strengths

$$O_{3,i} = \overline{\omega_i} = \frac{\omega_i}{\omega_1+\omega_2}, \quad i = 1,2 \tag{13}$$

In the fourth layer each node is adaptive with the function of:

$$O_{4,i} = \overline{\omega_i} f_i = \overline{\omega_i}(p_i x + q_i y + r_i) \tag{14}$$

where $\overline{\omega_i}$ is the normalized firing strength from previous layer, p_i, q_i and r_i are the parameters set of this node. The fifth layer is the output layer which compute (summation) of the incoming signals described by:

$$O_T = O_{5,i} = \sum_i \overline{\omega_i} f_i = \frac{\sum \omega_i f_i}{\sum \omega_i} \tag{15}$$

Based on the equations from (1) to (15) simulation analysis of the proposed technique will be illustrated in the following section.

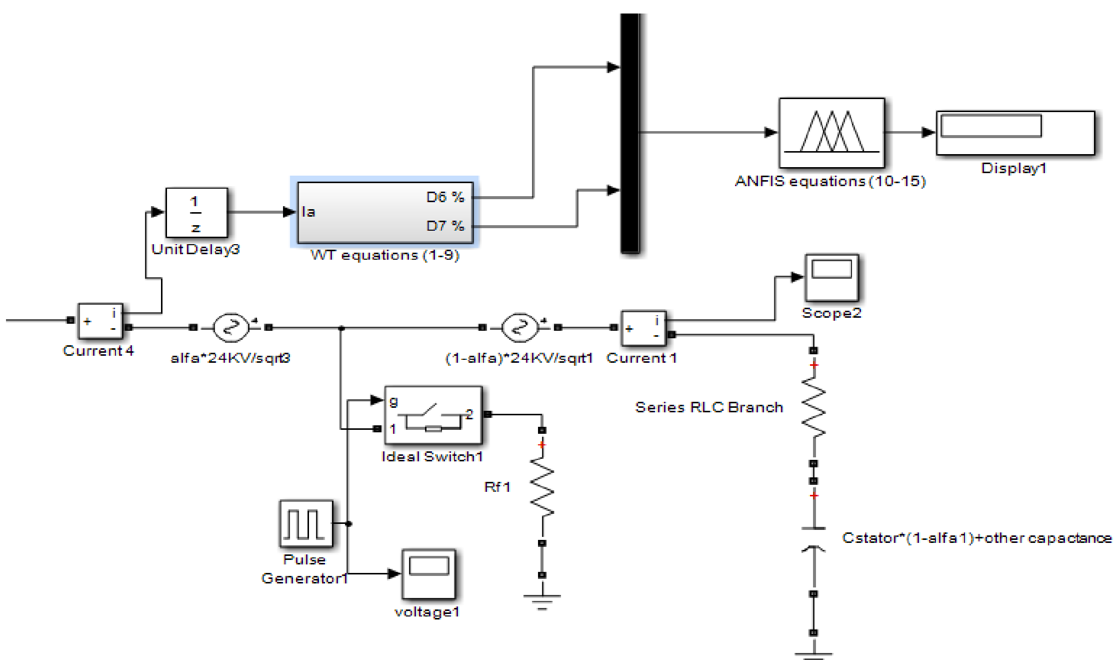
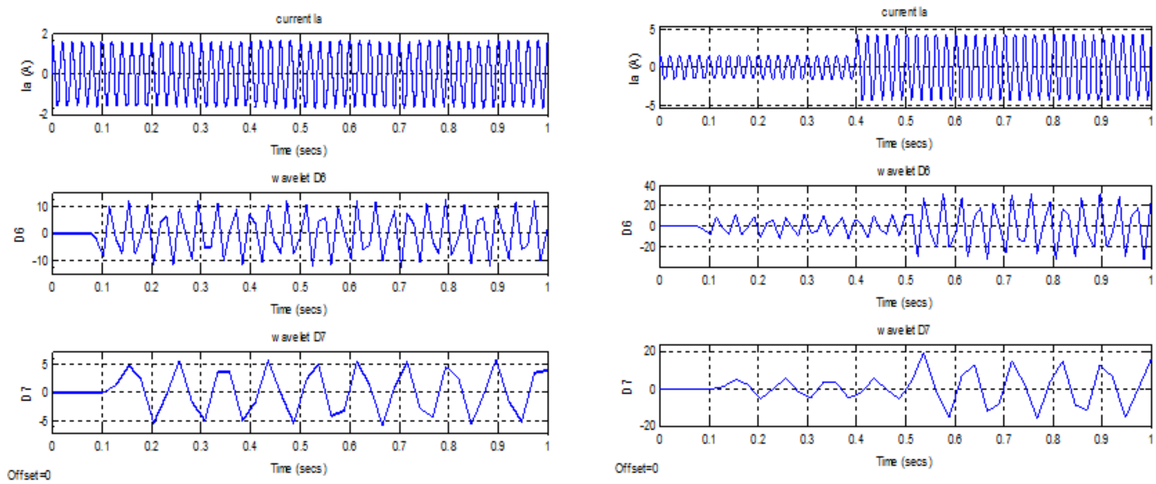


Fig. 2. Analysis of generator phase (A) current using Simulink model

3. Simulation Analysis

Simplified model of synchronous generator used in [5] has been utilized in the simulation using Simulink/Matlab software as shown in Figure 2. The signal phase current were decomposed to eight levels by wavelet transform using Daubechies 4 wavelet (db4)as in [9] and [10], the feature extracted was the energies of the highest levels of decomposed details, then energies were utilized to train the ANFIS to locate the fault.

The analysis is done for the current of phase A at fault resistance R_f about 0.001Ω and fault is applied after 0.4 sec from the starting of the simulation. Figure 3 represents the main current signal with the wavelet detail levels D6 and D7 (the highest energy levels) respectively with fault applied at 0.4 sec at different fault locations (1%, 50%, 100% of the winding length). Table 1 summarizes the output of the trained ANFIS and the measured energies corresponds to three different fault locations (1%, 50%, 100%) on the winding of phase A and the percentage error for each measurement.



(a) (b)

Fig. 3. Main current signal and corresponding wavelet detail D6 and D7 at different fault locations (a) at 1% of the winding length and (b) at 50% of the winding length.

Table 1
Trained ANFIS and the measured energies corresponds to three fault locations

Applied fault location%	D6 energy %	D7 energy %	ANFIS output of fault location%	Error %
1	78.72	17.93	1.12	12
50	77.84	18.36	49.72	0.56
100	77.52	18.46	98.74	1.26

From the previous table it has been noticed that highest percentage energies of D6 and D7 are varying according to the location of the fault which make them useful features to be utilized in training the ANFIS. Percentage error is calculated according to the formula

$$\frac{|\text{measured value} - \text{applied value}|}{|\text{applied value}|} \text{x}100 \tag{16}$$

4. Conclusion

The proposed approach based on wavelet transform and ANFIS has been introduced and utilized for locating short circuit between phase and ground through very small resistance for validation. Based on different operating and testing simulated conditions, the proposed system has been noticed to be effective in detecting and locating the fault starting from more than 0% of the per unit length of the winding to 100% of its length. The simulation has been done on a simplified generator model for prove of concept, however applying the system on dynamic generator model to include all operational parameters together with practical validity of the proposed technique is the main future prospective of such work.

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