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Wavelet spectrum energy feature extraction based fault detection scheme for synchronous generators

Nagireddy Ravi* and Narri Yadaiah**

This paper presents a wavelet transform based fault detection scheme for synchronous generators of power system equipment. The proposed method analyzes characterization of faults using a multi resolution analysis and defines a novel feature extraction, which is called wavelet spectrum energy. The multi-resolution signal analysis based on wavelet transform is utilized to decompose a given signal into approximate and detail signals of original signal. The detail signal coefficients are utilized for calculating wavelet spectrum energy. The fault detection technique utilizes the wavelet spectrum energy as feature extraction to extract information of fault signals for transient analysis. The simulation results show accurate discrimination of faults and also in characterization of internal and external faults.

Keywords: *Synchronous generator, multi resolution analysis, wavelet spectrum energy, fault detection, internal fault, external fault.*

1.0 INTRODUCTION

Synchronous generator is most expensive equipment in the power system network and it is designed to run at high load factor. Its reliable operation and proper functioning is important factor of the electric utilities in order to give continuous supply to the customers. Generally the faults in generator are electrical and mechanical faults. The electrical faults are normally initiated by thermal damage to the insulating material and anti-corona paint on a stator coil. The most common faults in the synchronous generators are in stator winding which are due to short circuit between the winding in the slots and the stator core. These faults are most dangerous and are likely to cause considerable damage to the expensive machinery. Hence, requires a lot of time and high cost of maintenance. Hence it is necessary to safeguard the equipment and prevent from the faults by incorporating the reliable and fast fault detection system [1].

The synchronous generator is subjected to a wide variety of abnormal electrical conditions and faults. Abnormal electrical conditions can arise as a result of failure within the generating plant itself. It may be subjected to faults in stator and rotor. The most serious faults on synchronous generator which require immediate attention are the stator winding faults. Hence it is necessary to develop a fault detection scheme which detect the faults very fast and prevent the equipment and reduce the damage [2].

At present, the electric utilities are using electromagnetic relays, solid state relays, and numerical relays for the protection of synchronous generators. The most recent relay technology is directed towards digital relay development. The performance of protective schemes of digital relays has been enhanced but shortcomings of the detection rules have not been eliminated.

*Pulichintala HES, Telangana State Power Generation Corporation Limited, India. E-mail: nagireddyravi@rediffmail.com
**Department. of EEE, JNTUH College of Engineering, Hyderabad – 500 085, India. E-mail: svpnarri@yahoo.com

In the past decade many techniques have been developed for the fault detection of synchronous generators. A novel protection scheme for detecting faults in synchronous generator is proposed utilizing fault transients [3]. In [4] a fault detection scheme is proposed which was based on measuring third harmonic voltages are at the generator terminals and generator neutral. In the paper [5] and [6] artificial neural network (ANN) algorithm is applied to detect the faults in generator stator windings protection. ANN is also used for classification of internal and external faults.

In past three decades several algorithms have been implemented for fault detection in power system equipment using wavelet transforms (WT) and the wavelet transform technique is very useful and efficient in fault detection of power system components [7]. The WT technique has been reported for fault detection in transformers [8] - [10]. Wavelet transform has been chosen as an effective signal processing tool for the fault detection in transmission lines [11]-[14]. In [15] a High Impedance Fault Detection in distribution systems was implemented using wavelet transforms.

The multi-resolution analysis a signal processing technique based on the wavelet transforms are utilized for calculating wavelet spectrum energy (WSE) [16]. The WSE have been used for interpreting the different fault signals. This technique has the capability to extract features of faults signals. The proposed fault detection scheme identifies the internal faults which are close to neutral and external faults on the terminals of synchronous generator.

2.0 PROBLEM FORMULATION

In this paper, the problem for identification of internal faults and external faults of synchronous generator are considered. The differential protection scheme is used to detect the faults in synchronous generator. The single line to ground fault is dangerous and very much difficult to identify. The detection of single line to ground fault is depend on the grounding type of synchronous generator. There are two different types of grounding the synchronous generator which are i) low impedance and ii) high impedance grounding. The common practice is to ground the generator neutral through a resistor and tuned reactors. The differential relay can provide the protection for 95% of the windings. In order to provide protection for 100% of the windings against ground fault a third harmonic voltage method is now in use as generators which produce about 1 % or more third harmonic voltage under all service conditions. Lot of attention has been focused on fault detection, which is identification of generator's single phase to ground fault and stator winding faults (internal faults) of Synchronous Generator.

The power system consisting of synchronous generator which is fed to the load through a step down transformer and a transmission line is shown in Figure 1. The internal faults and external faults are created at position A and position B respectively.

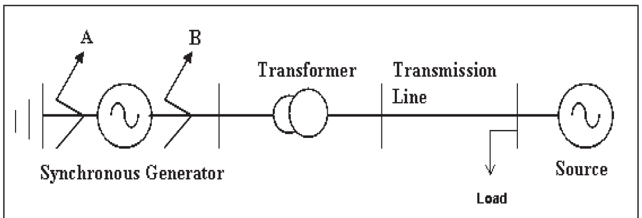


FIG. 1 SINGLE LINE DIAGRAM OF POWER SYSTEM NETWORK

In order to simulate stator internal faults near the generator neutral an equivalent circuit described in [17], a model shown in the Figure 2 is considered. In this approach the generator internal fault is simulated by the addition of two series voltage sources of reverse polarities to each other, in series with each of the faulty phases at the external terminals. Each of these voltage sources is equal to the EMF of the sound portion of the windings. The generator sub transient, transient and synchronous is reduced by a value of x which is equal to the sub transient reactance of the sound portion of the windings.

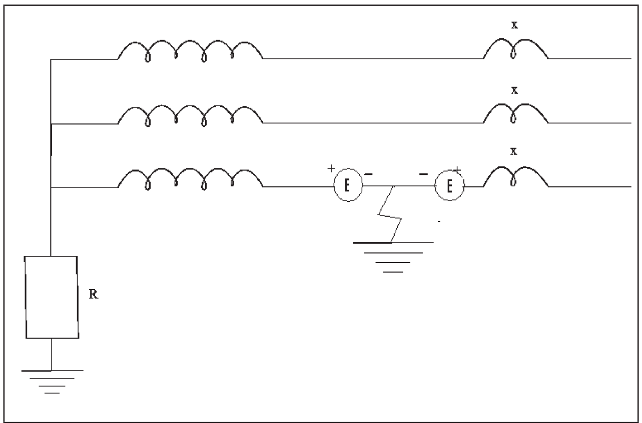


FIG. 2 INTERNAL EQUIVALENT CIRCUIT

3.0 THEORY OF WAVELET TRANSFORMS

The wavelet transform technique is a great tool of signal processing. This technique is utilized for many applications related to Engineering, Applied Mathematics, Physics and other Sciences. Recently it is also used for fault detection in power system components for transient analysis because of its ability to extract information of a transient signal in time – scale region. A wavelet is a waveform of effectively limited duration that has an average value of zero and its relation is given in Eq. 1.

$$\int_{-\infty}^{\infty} \psi(t) dt = 0 \qquad ....(1)$$

3.1 Continuous Wavelet Transform

The Continuous wavelet transform (CWT) of for a given signal x(t) with respect to a mother wavelet ψ (t) is defined in Eq. 2.

$$CWT(x,a,b) = \frac{1}{\sqrt{|a|}} \int_{-\infty}^{\infty} x(t)\, \overline{\psi} \left(\frac{t-a}{b} \right) dt \qquad ....(2)$$

where 'a' and 'b' represent the scaling (dilation) and translation (time shift) constants respectively and ψ(t) is a complex conjugation. The x(t) and ψ(t) belong to Hilbert Space $L^2(R)$, the set of integral functions [18].

3.2 Discrete Wavelet Transform

In CWT, the signals are analyzed using a mother wavelet or basis function which relate to each other by simple scaling and translation. In CWT, the information relates to close scales or times is redundant and high computational cost. To avoid these disadvantages, a discrete wavelet transform (DWT) can be used and is defined in Eq. 3.

$$DWT(x,m,n) = \frac{1}{\sqrt{a_0^m}} \sum_{t=-\infty}^{\infty} x(t)\overline{\psi}[(t - n a_0^m b_0)/a_0^m] \qquad ....(3)$$

The parameters 'a' and 'b' used in CWT are replaced by their equivalent as $a=a_0^m$ and $b=nb_0 a_0^m$, where a_0 and b_0 are fixed constants with $a_0>1$ and $b_0>1$ and m, n are positive integer variables. The choice a_0 and b_0 must be so that mother wavelets form an orthonormal basis. The othonormal basis satisfies if $a_0 = 2$ and $b_0 = 1$. This leads to Multi-resolution analysis.

3.3 Multi-resolution analysis

MRA is one of the tools of discrete wavelet transform which decomposes the original signal into two other signals which represents a smooth and detailed version of the original signal. This algorithm is developed by Mallet [19-20]. MRA is effective for analyzing the information of the signals. The DWT is computed by analyzing the signal at different frequency band with different resolutions by decomposing the signal into coarse approximation and detail information.

Let x[n] be a discrete time signal, where n is an integer and this signal will be passed through low and high pass filters to find the coarse and detail approximations respectively. If the low pass filter is denoted by its weighted sequence g[n], the output signal of low pass filter is then down sampled by 2 to produce the coarse approximation signal a[n] for the original signal x[n] and is shown in Eq. 4.

$$a[n] = \sum_{n} x[n].g[2k-n] \qquad ....(4)$$

The high pass filter is denoted by its weighted sequence h[n], the output signal of high pass filter is then down sampled by 2 to produce the detail signal d[n] for the original signal x[n] and is shown in Eq. 5.

$$d[n] = \sum_{n} x[n].h[2k - n] \qquad ....(5)$$

The decomposition process can be done with successive approximations so that the original signal is broken down into many lower resolution components. Figure 3. illustrates the procedure of wavelet decomposition for two levels with the bandwidth of the signal at each level. Let x[n] be a discrete time signal with sample rate of f Hz, where n is an integer and this signal will be passed through low and high pass filters to find the coarse and detail approximations respectively. The highest frequency component detail signal (d1) will be f/2 Hz. The band of frequencies represents the d1 signal will be f/2 Hz to f Hz. Similarly the band of frequencies in detail signal (d2) will be f/4 to f/2 Hz. The band frequency of low pass filter output, approximate signal (a1) will be in the range of 0 to f/2 Hz. Similarly, the band of frequencies of an approximate signal (a2) will be 0 to f/4 Hz.

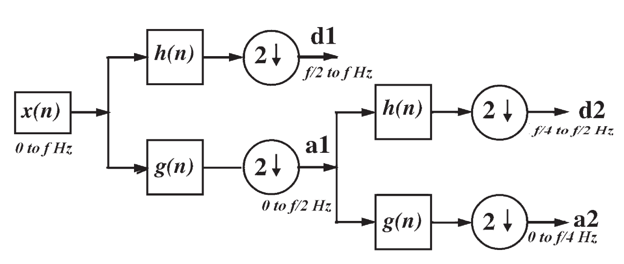


FIG. 3 WAVELET DECOMPOSITION TREE

4.0 PROPOSED FAULT DETECTION SCHEME

The structure of the proposed fault detection scheme of synchronous generator is shown in Figure 4. In this scheme the current signal is acquired from the output of current transformer at terminals of synchronous generator. The Daubechies Db - 5 type wavelet was used as mother wavelet for obtaining MRA. The Daubechies Db - 5 wavelet function is widely used for identification of faults [21]. The detail signal scale 3 is selected as it is superior to the other details signals.

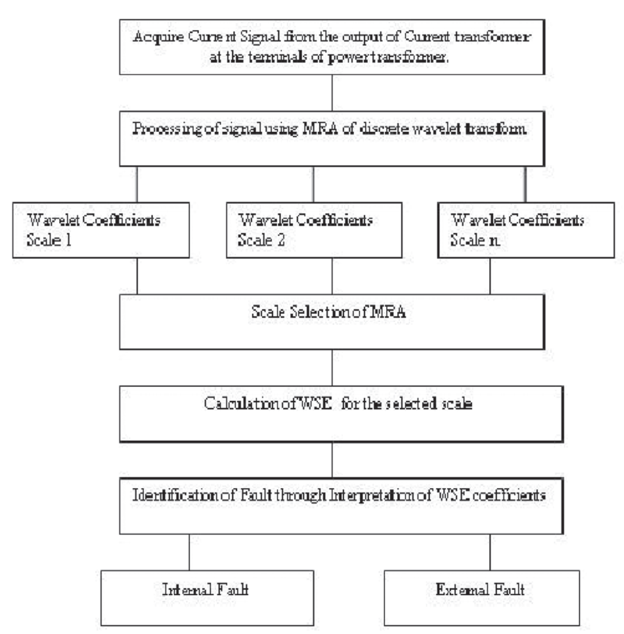


FIG. 4 STRUCTURE OF FAULT DETECTION SCHEME

To improve the fault detection scheme, the fault features are extracted from MRA of detail signal scale 3 using WSE. WSE is calculated by squared wavelet coefficients of the detail signal scale 3 of MRA. The coefficients of WSE are utilized for identification of and external faults.

4.1 Feature Extraction Using WSE

The importance of feature extraction is to obtain a unique feature with a good accuracy. The feature extraction involves processing of the original raw signals obtained to extract suitable information. It gives unique feature of each fault transient and able to distinguish internal and external faults accurately.

To improve the performance of detection technique for distinguishing the internal and external faults, a feature extraction technique is utilized wavelet spectrum energy to retain relevant information. WSE is calculated by squared detail wavelet coefficients of the selected scale. The obtained detailed coefficients of current signal are multiplied at a time using the Eq. 6.

$$WSE = \sum_{n=1}^{N} d_j^2(n) \quad ....(6)$$

Where N is the length of the discrete vector, d is the detail coefficient signal of MRA at scale j.

4.2 Algorithm for Fault Detection in Synchronous Generators

The algorithm to identify the faults is given below [22].

Step 1: Acquire the current signals for each phase IR, IY, IB, from the terminals of synchronous generator.

Step 2: The obtained current signals are analyzed using MRA of discrete wavelet transform to get the wavelet coefficients.

Step 3: The appropriate scale will be selected which will give precise information on the local regularity.

Step 4: Calculate the WSE for each phase currents for the detailed coefficients of the appropriate scale obtained in 3.

Step 5: Identify the fault through interpretation of WSE.

Step 6: Distinguish an internal fault current and external fault currents, for tripping the relay for internal faults and restraining the relay for external faults.

5.0 RESULTS AND DISCUSSIONS

The power system network with synchronous generator, three phase step up transformer connected to load and source through transmission line shown in the Figure 1. is considered for simulation. This power system network is developed in MATLAB7® using SIMULINK software [23]. The ratings of a typical synchronous generator are given in Table 1. The simulations are carried out to investigate the internal and external faults using multi-resolution analysis of wavelet transform technique. The internal faults and external faults of synchronous generators are simulated for single line to ground fault (L-G), line to line fault (L-L) and three phase faults (L-L-L).

TABLE 1

SYNCHRONOUS GENERATOR DATA

Parameter	Rated Value
Rated Power (P)	200 MVA
Rated Voltage (V)	13.8 kV
Rated Frequency (f)	50 Hz
Stator Resistance	0.0028544 pu
d- axis synchronous reactance (Xd)	1.305 pu
q- axis synchronous reactance (Xq)	0.474 pu
d- axis sub transient reactance (Xd'')	0.252 pu
q- axis sub transient reactance (Xq'')	0.243 pu

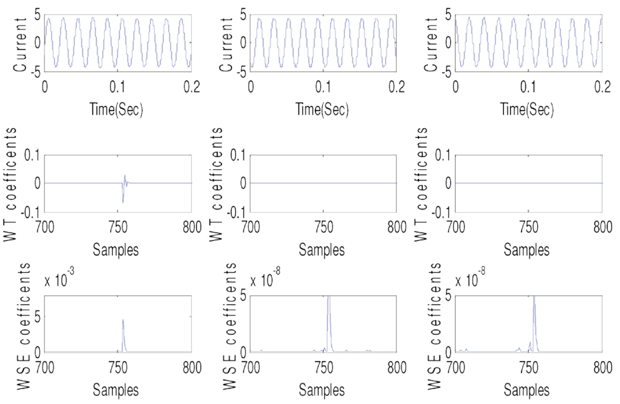
The current signals of three phases for synchronous generator are acquired from the output terminals of current transformer (CT) of ratio 10000/5 for fault analysis. These signals are passed through a high pass and a low pass filters to obtain approximate coefficients and detail coefficients. The MRA of fault current signal indicates the instances of transients at detail signal scale 3 of db5. Hence to get the sharpness and localization the detail signal scale 3 is chosen for calculating the WSE coefficients. The WSE will aid to retain information for identification of faults.

5.1 Internal faults in synchronous generator

Internal faults are faults that occur in synchronous generator protection zone. Internal faults are subjected to faults in stator core, stator winding and rotor. These faults in stator are due to short circuits between turn to earth or turn to turn in the winding. The most dangerous fault to identify is low level earth fault in the stator which occurs near the generator neutral. In order to simulate, the internal faults such as L-G, L-L and L-L-L of synchronous generator were considered. The current signals are measured at output of CT terminals of synchronous generators and these signals are used for the MRA and the detection is carried out using WSE of phase currents.

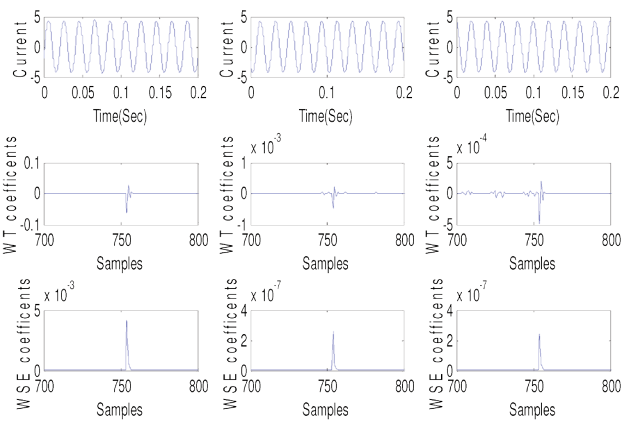
5.1.1 Single Line to Ground Fault.

The single line to ground fault is simulated for 1%, 2%, 3%, 4% and 5 % of stator phase R of the winding from generator neutral as the faults near the generator neutral are very difficult to detect. The total simulation time is 0.2 Sec. The faults are set to occur between R Phase to ground at instant of 0.06 sec and cleared at 0.08 sec. The WSE is applied to detail signal 3 of MRA and the fault is clearly observed at the time of fault. The measured current signal, MRA coefficients of detail signal scale 3 and its WSE coefficients of the internal single line to ground fault for 1%, 2%, 3%, 4% and 5 % of the windings from generator neutral are shown in Figures 5, 6, 7, 8 and 9 respectively.



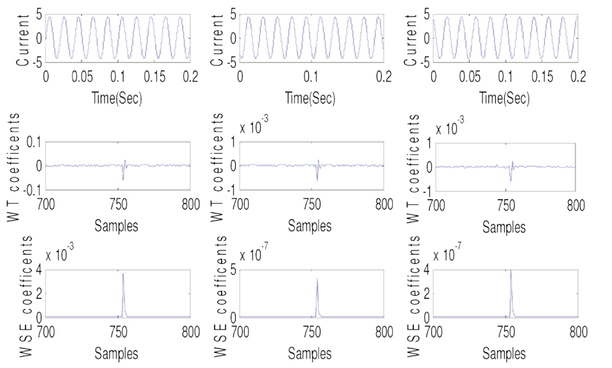
A) R PHASE B) Y PHASE C) B PHASE

FIG. 5 MRA OF DETAIL SIGNAL 3 AND WSE FOR INTERNAL L-G FAULT AT 1 % FAULT LOCATION FROM GENERATOR NEUTRAL.



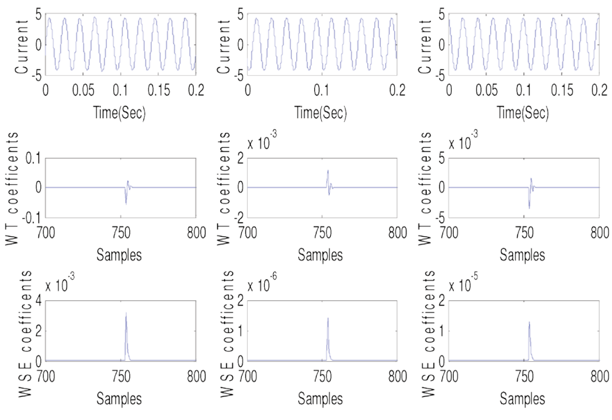
A) R PHASE B) Y PHASE C) B PHASE

FIG. 6 MRA OF DETAIL SIGNAL 3 AND WSE FOR INTERNAL L-G FAULT AT 2 % FAULT LOCATION FROM GENERATOR NEUTRAL.



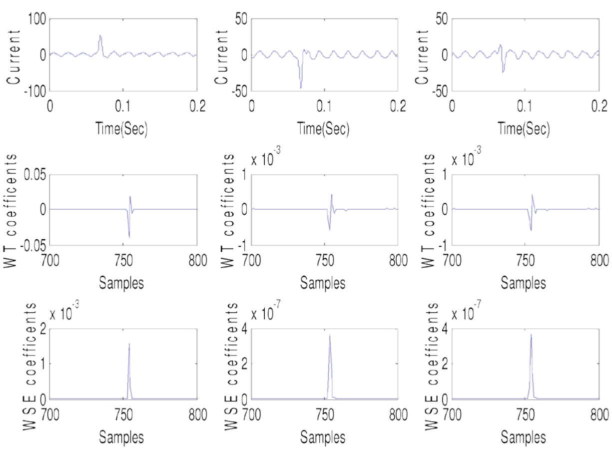
A) R PHASE B) Y PHASE C) B PHASE

FIG. 7 MRA OF DETAIL SIGNAL 3 AND WSE FOR INTERNAL L-G FAULT AT 3 % FAULT LOCATION FROM GENERATOR NEUTRAL.



A) R PHASE B) Y PHASE C) B PHASE

FIG. 8 MRA OF DETAIL SIGNAL 3 AND WSE FOR INTERNAL L-G FAULT AT 4 % FAULT LOCATION FROM GENERATOR NEUTRAL.

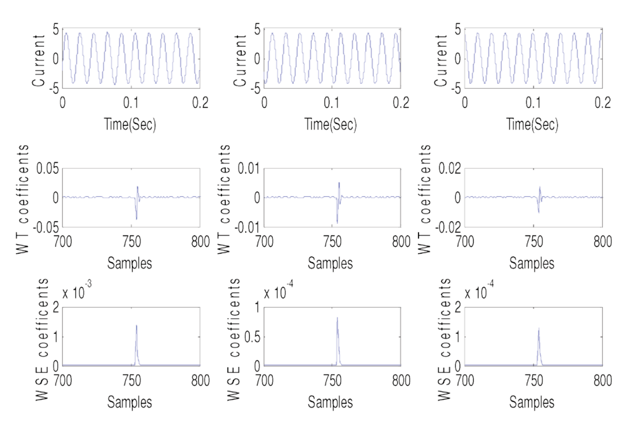


A) R PHASE B) Y PHASE C) B PHASE

FIG. 9 MRA OF DETAIL SIGNAL 3 AND WSE FOR INTERNAL L-G FAULT AT 5 % FAULT LOCATION FROM GENERATOR NEUTRAL.

5.1.2 Line to Line Fault

The internal fault L-L is created between stator phase R and Y at the 1% of stator winding. The WSE results clearly show the higher energy content than L- G and the magnitude of peak value locate actual fault at which it takes place. The measured current signal, MRA coefficients of detail signal scale 3 and its WSE coefficients for internal fault L-L created between R phase and Y phase at 1% of the winding from generator neutral are shown in Figure 10.

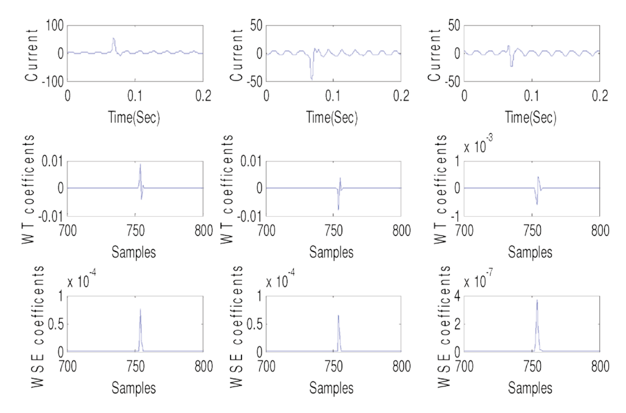


A) R PHASE B) Y PHASE C) B PHASE

FIG. 10 MRA OF DETAIL SIGNAL 3 AND WSE FOR INTERNAL L-L FAULT AT 1 % FAULT LOCATION FROM GENERATOR NEUTRAL.

5.1.3 Line to Line to Line Fault

The internal fault L-L-L is created between stator R phase, Y phase and B phase at the 1% of stator winding. The WSE results clearly show the magnitude of the peak value has higher than the internal fault L- G and internal fault L-L. The magnitude of the peak shows the exact location of the fault at which actual fault takes place. The measured current signal, MRA coefficients of detail signal scale 3 and its WSE coefficients for three phase internal fault at 1% of stator winding is shown Figure 11.

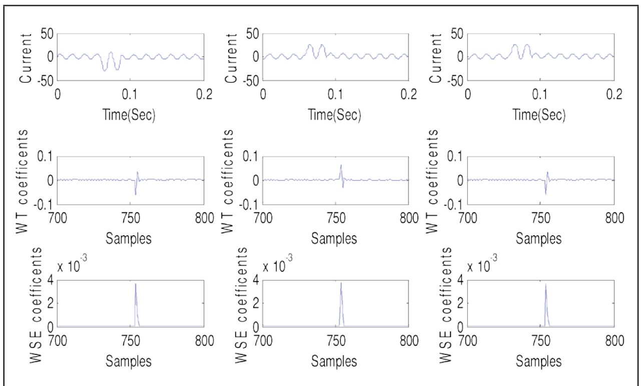


A) R PHASE B) Y PHASE C) B PHASE

FIG. 11 MRA OF DETAIL SIGNAL 3 AND WSE FOR INTERNAL L-L-L FAULT AT 1 % FAULT LOCATION FROM GENERATOR NEUTRAL.

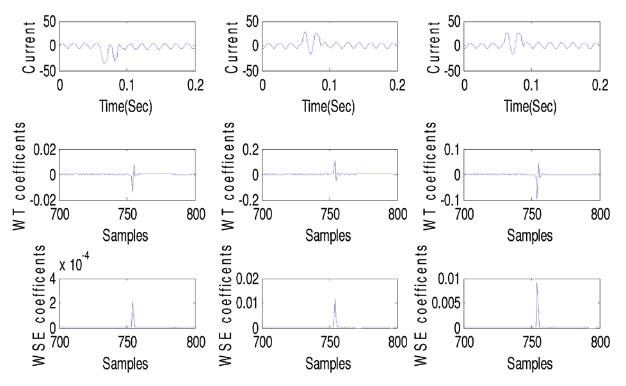
5.2 External Faults

The simulation is also carried out for external faults of L-G, L-L and L-L-L at the external terminals of the synchronous generators and the current signal is obtained at the output of CT terminals of synchronous generator for fault analysis. The total simulation time for external fault is 0.2 sec. The fault is created at 0.06 sec and cleared at 0.08 sec. In the WSE analysis the energy content for external faults has the highest compared to internal faults. The measured current signal, MRA coefficients of detail signal scale 3 and its WSE coefficients for external L-G, L-L and L-L-L at the terminals of synchronous generator are shown in Figures 12, 13 and 14 respectively.



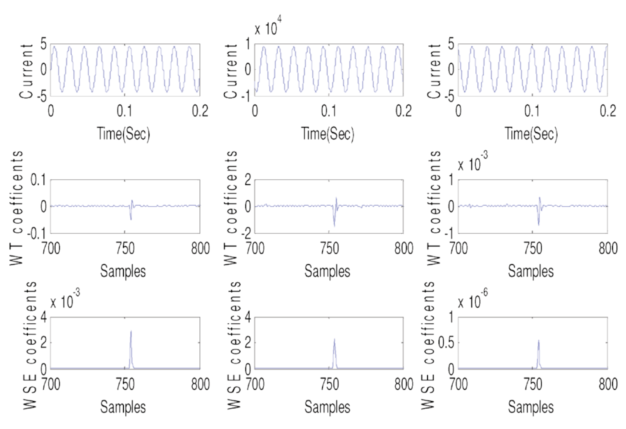
A) R PHASE B) Y PHASE C) B PHASE

FIG. 12 MRA OF DETAIL SIGNAL 3 AND WSE FOR EXTERNAL L-G FAULT.



A) R PHASE B) Y PHASE C) B PHASE

FIG. 13 MRA OF DETAIL SIGNAL 3 AND WSE FOR EXTERNAL L-L FAULT.



A) R PHASE B) Y PHASE C) B PHASE

FIG. 14 MRA OF DETAIL SIGNAL 3 AND WSE FOR EXTERNAL L-L-L FAULT.

The proposed method for detection of internal faults in synchronous generator is evaluated up to 1 % of stator winding from the generator neutral and found to be effective in detecting the internal faults, which is difficult in some of the conventional methods as there is not enough voltage to drive current for operation of relay. The most important limitation of the conventional schemes is the ground faults which are close to neutral would not be detected.

The simulations results depict the capability of wavelet transforms to detect locate and identify fault. The WSE of wavelet transform is found to be good tool in feature extraction of fault signals. The energy content of WSE is very effective in distinguishing of internal and external faults. The WSE is applied to detail signal 3 of MRA and the fault is clearly observed at the time of fault. The WSE clearly indicates the overshoot comes across the sample 752^{nd} which is the fault instant at 0.06 sec. On the contrary, the fault transient phenomenon is not clear in time response signal analysis. The characterization of fault transients will aid in the development of an automatic protection method for synchronous generators.

6.0 CONCLUSIONS

A method for fault detection in synchronous generators is presented. The fault detection is carried out using db5 mother wavelet and found to be good for the analysis of different transient events. The approach is based on wavelet spectrum energy which is applied to the current signals of various faults. This technique is capable for the fault detection and distinguishing of internal, external and normal conditions. The results have shown that the ground faults which are very close to the neutral point can be detected using WSE. The technique gives 100% sensitivity for faults in stator windings.

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