Fault detection of Self excited induction generator

Jyotirmayee Dalei
Department of Electrical Engineering
National Institute of Technology
Rourkela, India
Email-Jyoti_uce@yahoo.com

Kanungo Barada Mohanty
Department of Electrical Engineering
National Institute of Technology
Rourkela, India
Email-kbmohanty@nitrkl.ac.in

Abstract—In isolated and remote area researchers are motivated recently to generate power using wind. Self excited induction generator (SEIG) is selected as a good candidate to extract electric power from wind. In this paper transient performance of SEIG during short circuit fault has been studied. Though SEIG is capable to protect itself from faults, but it is also necessary convey the message to operator about the fault. For this fast detection scheme is essential, in this paper discrete wavelet transform (DWT) and second generation wavelet transform (SGWT) are used for fault detection. It is observed that processing time of SGWT is faster compared to DWT.

Keywords— ***Self-excited induction generator; Fault detection; Discrete Wavelet Transform; Second Generation Wavelet Transform.***

I. INTRODUCTION

Renewable energy sources are getting more attention due to increased pollutions and environmental impact of fossil fuels. Wind is used widely in isolated and remote generating areas because of low cost of generation, environment friendly and available with free of cost [1]. To generate electric power from wind in isolated and remote areas squirrel cage induction machine is referred. When a capacitor bank connected across induction machine driven externally by a prime mover is called self-excited induction generator (SEIG) [2]. SEIG has number of advantages such as low cost, simple construction, less maintenance and self-protection from faults. Though SEIG has fault tolerance capability but, detection of fault helps the operators to resume the operation and clear the faults. When short circuit fault occurs, voltage collapses instantly but due to inductive nature of SEIG it does not allow any sudden change in the current circuit but since voltage collapses SEIG takes 4 to 5 cycles to decay current completely. If the fault is clear before current decays completely to zero then SEIG starts to operate same manner as pre-fault condition. If not possible to clear the fault within this interval, SEIG has to re-excite as residual magnetism of the machine has lost. The SEIG takes more time to re-excite [3] compare to previous no-load excitation time of the SEIG. To clear fault within this interval fast fault detection schemes are required. To detect the fault, conventional over voltage sensors and over current sensors are not suitable because voltage and current collapses so quickly not able to detect by sensors. Using Fourier transform (FT), signal decomposition possible. But FT yields the information regarding spectral components of the signal only not able to provide the information regarding the instant of time where spectral components appear. However, fault is non-stationary in nature, so to detect fault FT is not suitable Wavelet Transform provides information regarding both time and frequency. In [7] multi resolution wavelet is used to detect fault for transmission lines. Discrete wavelet transform (DWT) scheme is used in [8] to detect SEIG short circuit fault. DWT is convolution based so time taken to detect fault is more, lifting based wavelet known as second generation wavelet transform (SGWT) is superior compared to DWT. Yilmaz *et:al* used SGWT in [9] SGWT to analyse power quality events and Song *et:al* used SGWT for extraction of partial discharge from electrical pulses in [10]. In this paper DWT and SGWT techniques are employed to detect SEIG fault and it is observed that processing time to detect fault using SGWT is less compared to DWT detect the fault, conventional over voltage sensors and over current sensors are not suitable because voltage and current collapses so quickly not able to detect by sensors. Using Fourier transform (FT) signal decomposition possible. But FT yields the information regarding spectral components of the signal only not able to provide the information regarding the instant of time where spectral components appear. However, fault is non-stationary in nature, so to detect fault FT is not suitable Wavelet Transform provides information regarding both time and frequency. In [7] multi resolution wavelet is used to detect fault for transmission lines. Discrete wavelet transform (DWT) scheme is used in [8] to detect SEIG short circuit fault. DWT is convolution based so time taken to detect fault is more, lifting based wavelet known as second generation wavelet transform (SGWT) is superior compared to DWT. Yilmaz et:al used SGWT in [9] SGWT to analyse power quality events and Song et:al used SGWT for extraction of partial discharge from electrical pulses in [10]. In this paper DWT and SGWT techniques are employed to detect SEIG fault and it is observed that processing time to detect fault using SGWT is less compared to DWT.

II. SYSTEM DESCRIPTION

Schematic diagram of the SEIG to detect fault is shown in Fig. 1 and consists of an induction machine with capacitor bank used as a self-excited induction generator (SEIG) driven by prime-mover, fault detection unit and load.

A. Modeling of SEIG

Modeling of SEIG is developed, for the simulation in MATLAB/Simulink using *d-q* axes stationary reference frame. The *d-q* axes stator and rotor current equations of the SEIG represented through fourth-order state-space model and expressed by:

$$\dot{i}_{sd} = \frac{1}{K}\left[\omega_r L_m^2 i_{sq} - L_r R_s i_{sd} + \omega_r L_m L_r i_{rq} + L_m R_r i_{rd} + L_r v_{sd}\right] \quad (1)$$

$$\dot{i}_{sq} = \frac{1}{K}\left[-L_s R_s i_{sq} - \omega_r L_m^2 i_{sd} + L_m R_r i_{rq} - \omega_r L_m L_r i_{rd} + L_r v_{sq}\right] \quad (2)$$

$$\dot{i}_{rd} = \frac{1}{K}\left[-\omega_r L_m L_s i_{sq} + L_m R_s i_{sd} - \omega_r L_s L_r i_{rq} - L_s R_r i_{rd} - L_m v_{sd}\right] \quad (3)$$

$$\dot{i}_{rq} = \frac{1}{K}\left[L_m R_s i_{sq} + \omega_r L_m L_s i_{sd} - L_s R_r i_{rq} + \omega_r L_s L_r i_{rd} - L_m v_{sq}\right] \quad (4)$$

Where $L_s = L_{ls} + L_m$, $L_r = L_{lr} + L_m$ and $K = \left(L_s L_r - L_m^2\right)$.

Here the subscripts *q* and *d* are for quadrature and direct axes, subscripts *s* and *r* are for stator and rotor variables, *l* for leakage component *v* and *i* instantaneous voltage and current respectively. λ = flux linkage, i_m = magnetizing current, L_m = magnetizing inductance, *r* = resistance, *L* = inductance and ω_r = electrical rotor speed.

Magnetizing current i_m is determined from i_{sd}, i_{sq}, i_{rd} *and* i_{rq} using expression

$$i_m = \sqrt{\left(i_{sd} + i_{rd}\right)^2 + \left(i_{sq} + i_{rq}\right)^2} \quad (5)$$

The magnetization characteristic of the SEIG has a great role for achieving steady state voltage. Relation between magnetizing inductance L_m and magnetizing current i_m are obtained from synchronous speed test. Fifth-degree polynomial is used in [11], and same polynomial is taken in this paper and given as:

$$L_m = a_5 i_m^5 + a_4 i_m^4 + a_3 i_m^3 + a_2 i_m^2 + a_1 i_m + a_0 \quad (6)$$

where $a_5, a_4, .., a_0$ are constants obtained through curve fitting of experimentally obtained characteristics given in Figure 2. The value of these constants is given in appendix. The electromagnetic torque T_e of SEIG is

$$T_e = \left(\frac{3}{2}\right)\left(\frac{P}{2}\right) L_m \left[i_{sq} i_{rd} - i_{sd} i_{rq}\right] \quad (7)$$

Torque balance equation of SEIG is

$$T_{drive} = T_e + J\left(\frac{2}{P}\right)\frac{d\omega_r}{dt} \quad (8)$$

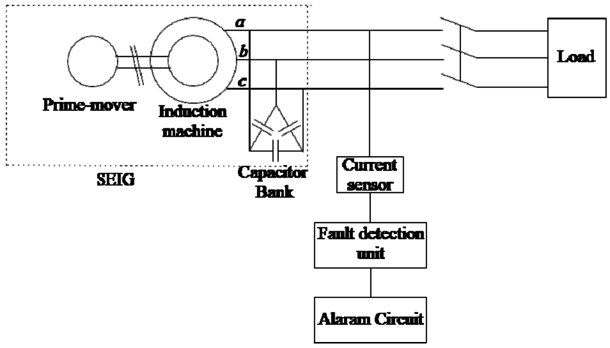

Fig. 1: Schematic diagram of fault detection of SEIG system.

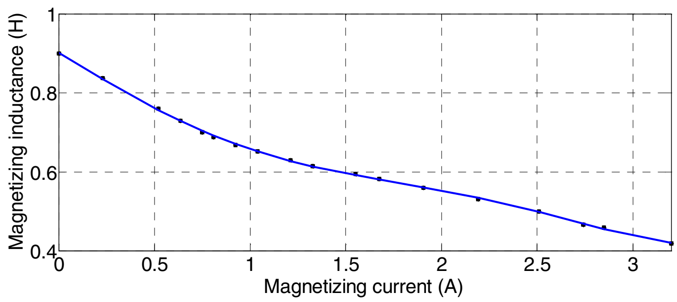

Fig. 2: Graph of the identified (black) and approximated (blue) magnetizing inductances vrs magnetizing current.

B. Excitation modeling

The excitation system dynamics are introduced using d-q components of stator voltage (v_{sd} and v_{sq}) as state variables, given as

$$\frac{dv_{sd}}{dt} = \frac{i_{eq}}{C_{ed}} \quad (9)$$

$$\frac{dv_{sq}}{dt} = \frac{i_{eq}}{C_{eq}} \quad (10)$$

SEIG has fault tolerant capability means de-excitation occurs in the stator winding and voltage collapse occurs, but in order to prevent the operation of SEIG fast fault detecting schemes are essential and discussed in next subsection.

C. Fault detection unit

Stator current signals are captured and send to the wavelet based fault detection unit. Two techniques i) discrete wavelet Transform (DWT) and ii) second generation wavelet transform (SGWT) are used in this paper for detection of fault.

1) DWT: The wavelet transform (WT) is a a mathematical tool used to decompose a signal into different scales; each cale is assigned with a frequency. The WT of a continuous signal (t) is expressed as

$$CWT(m,n) = \frac{1}{\sqrt{m}} \int_{-\infty}^{\infty} S(t)\phi\left(\frac{t-n}{m}\right)dt \quad (11)$$

where m and n are the scale or, dilation factor and shift or, translation factor respectively and □ ( ) is the mother wavelet. m,n € R, $m \neq 0$. The mother wavelet can be discretized, by selecting $m = m_0^j$ and $n = kn_0m_0^j$, where m_0 and n_0 are fixed constants with m_0 □ 1, n_0 □ 1, j,k € Z and Z is the set of positive numbers. Discretized mother waveley is expressed as

$$\phi_{j,k}(t) = m_0^{(-\frac{j}{2})} \phi\left(\frac{t - kn_0 m_0^j}{m_0^j}\right) \quad (12)$$

The simplest choice [12] of m_0, n_0 are 2 and 1 respectively. The DWT is expressed as

$$DWT(j,k) = \frac{1}{\sqrt{2^j}} \int_{-\infty}^{\infty} S(t)\phi\left(\frac{t-k2^j}{2^j}\right) \quad (13)$$

In DWT the original discrete-time signal $S[k]$ passes through a series of low-pass (LP) and high pass (HP) filters and decomposes thje signal into approximation coefficients $A_1[k]$ and detail coefficient $D_1[k]$ at different frequency bands, using down sampling algorithm (by a factor of 2) [13], this process is known as first level decomposition. In second level decomposition $A_1[k]$ is further fed to low pass and high pass filters and obtain approximation coefficient $A_2[k]$ and detail $D_2[k]$, this process continues up to n levels. Fig. 3 shows the DWT decomposition of the original signal for two levels.

2) SGWT: In [9] SGWT is applied to detect power quality events with the help of lifting scheme (LS). For constructing wavelets translation and dilation are not required in SGWT, as required in case of DWT. Convolution is also not required in case of SGWT. In SGWT there are three steps [10] , split, predict and update.
Split: In the first step the original discrete signal $S[K]$, splits into two disjoint subsets *i.e.* $X[k]=S[k]_{\text{even}}$ and $Y[k]=S[k]_{\text{odd}}$, where $X[k]$ and $Y[k]$ are the even and odd index points *of* $S[k]$ respectively and both are correlated.
Predict: In this step, detail coefficients, $D[k]$ are computed using the expression is given as:

$$D[k] = Y[k] - P(X[k]) \quad [14]$$

where $P(X[k])$ is the prediction of $Y[k]$ based on $X[k]$ and P is the prediction operator.
Update: Approximation coefficients, $A[k]$ are determined using $D[k]$, and the expression is given as:

$$A[k] = X[k] + U(D[k]) \quad [15]$$

where U is the update operator applied to details. The approximation further is fed through filter again and decomposed at a higher level as in the case of DWT. Fig. 4 shows the block diagram of first level SGWT decomposition.

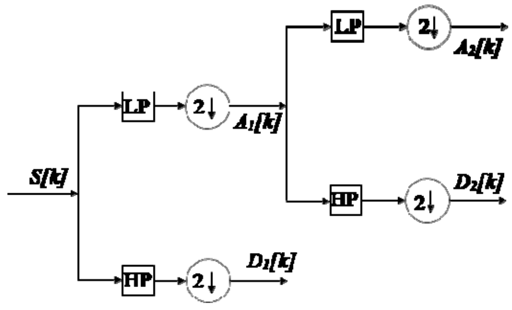

Fig. 3: Block diagram of DWT decomposition.

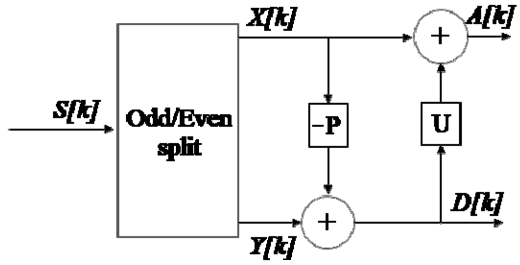

Fig. 4: Block diagram of SGWT decomposition.

III. Results and Discussion

In order to validate the developed conventional two-axis model of SEIG, a 3.7-kW, 415-V, 50-Hz, 4 pole delta connected induction machine has been taken for both simulation and experiment. Parameters of the induction machine are determined from the standard dc resistance test, no-load test and blocked rotor tests are given in Appendix. Capacitor bank is connected with induction machine to operate as self-excited induction generator. Capacitor taken both for simulation and experiment is 21 μF per phase at no load, which is more than is more than the minimum excitation capacitor required to develop rated SEIG voltage of 415 V (r. m. s.).

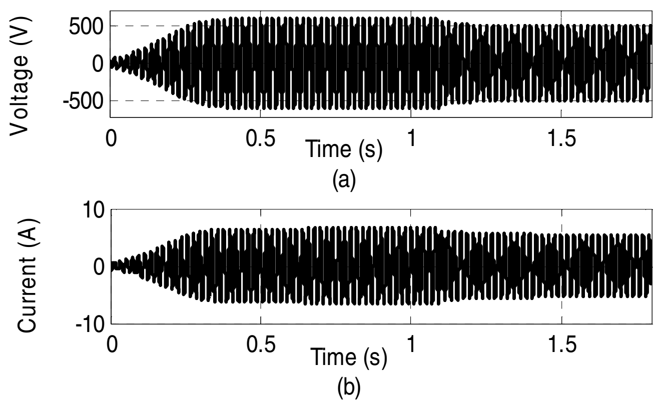

Fig. 5: Stator terminal voltage and current of SEIG during loading (a) Voltage. (b) Current.

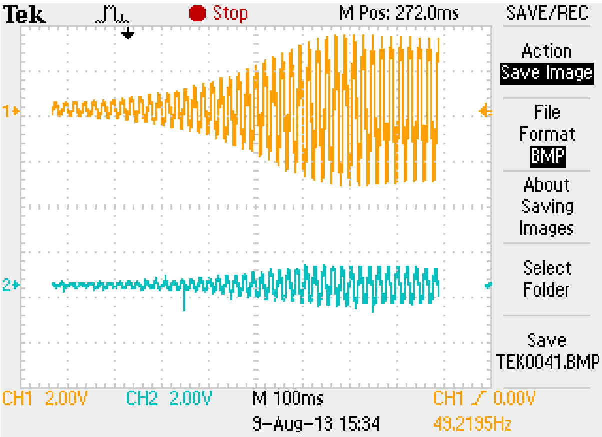

Fig. 6: Experimental results of stator voltage build up of SEIG at no-load (top) and stator line current (bottom).

Fig. 5 (a) and (b) shows the simulation results of voltage and current build process of SEIG during loading condition. Experimental results of voltage and current build process of SEIG during loading condition is shown in Fig. 6. At t=1.6 s, short circuit fault is initiated and it is observed that voltage collapses immediately but due to inductive nature of SEIG the stator current opposes the sudden change in the circuit. Due to voltage collapse instantly, stator current starts to decay and becomes zero after 4 to 5 cycles as shown in Fig. 7. If the fault is cleared within this interval (0.1 s) after the fault initiation, the SEIG regains to normal operating condition. So to detect fault with the help of DWT processing time taken is .078 s. The processing time to detect the same fault using SGWT is .065 s. High-frequency detail coefficients of the stator fault current signal using DWT and SGWT are shown in Fig. 8 and Fig. 9 respectively. Sometimes the original data has undesirable transients because of noise, so a threshold value is set and after that high-frequency detail coefficients are compared with a threshold value to identify the faulty zone and if the detail coefficients are above the threshold value then alarm signal will activate. Getting alarm fault can be mitigated and load will be disconnected.

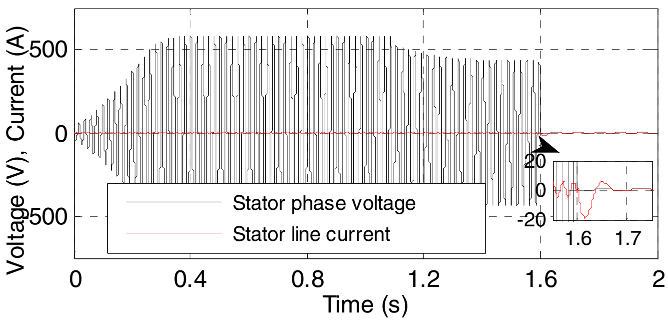

Fig. 7: SEIG stator voltage and current during short circuit fault condition.

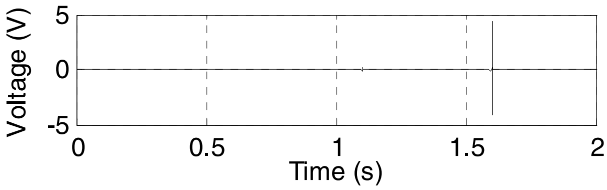

Fig. 8: DWT decomposition of SEIG stator current.

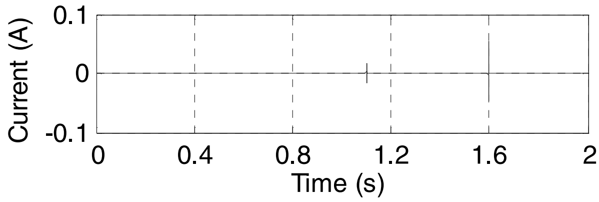

Fig. 9: SGW decomposition of SEIG stator current.

IV. CONCLUSIONS

Self excited induction generator is suitable in isolated and remote areas to produce electric power using renewable energy. Using DWT and SGWT short circuit fault of SEIG is detected. It is observed that processing time taken using SGWT is less compared to DWT.

APPENDIX

Parameters of SEIG: 3.7kW, 415 V, 7.5A (line), P=4 pole, R_s= 7.34 Ω, R_r= 5.64 Ω, Xl_s= 6.7 Ω, X_{lr}= 6.7 Ω,and J= 0.16 kg/m^2. The constants of the magnetization characteristics of SEIG are given as, a_5= -0.0038, a_4= 0.0576, a_3= -0.304, a_2= 0.713, a_1= -0.853 and a_0= 1.043.

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