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Application of Second Generation Wavelet Transform for SEIG Load Transient Detection

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***Abstract*—Self-excited induction generator (SEIG) is preferred in isolated and remote power generating systems. But the major problem associated with SEIG is change in voltage and frequency during loading condition. For the development of simple voltage and frequency controller it is essential to detect the load transient in less time using less hardware. In this paper Second Generation Wavelet Transform (SGWT) and Discrete Wavelet Transform (DWT) are used for SEIG to detect load transient. It is observed that SGWT is more powerful and capable than DWT. Its computation time to detect load transient is less and also requires less hardware in real time.**

***Index Terms*—Self-excited induction generator; Transient detection; Discrete Wavelet Transform; Second Generation Wavelet Transform.**

NOMENCLATURE

d Direct axis.
q Quadrature axis.
s Stator variables.
r Rotor variables.
l Leakage component.
v Instantaneous voltage.
i Instantaneous current.
i_m Magnetizing current.
L_m Magnetizing inductance.
r Resistance.
L Inductance.
ω_r Electrical rotor speed of SEIG.
T_{drive} Mechanical input torque of the SEIG.
T_e electromagnetic torque of the SEIG.
J Moment of inertia
P number of poles of SEIG.
i_{ed} Current through the excitation capacitor in d axis
i_{eq} Current through the excitation capacitor in q axis
C_{ed} Excitation capacitor values in d axis.
C_{eq} Excitation capacitor values in q axis.

I. INTRODUCTION

Due to increased pollutions and environmental impact of fossil fuels, non-conventional energy sources such as, wind, PV, bio-mass gas etc. are getting increased attention. Generation of electricity from wind is widely in use because low cost generation and abundance of availability. Squirrel cage induction machine is most suitable as compared with synchronous machine to extract electric power from wind especially in isolated and remote areas [1] because of its precise advantages such as low cost, simple brushless construction, requirement of less maintenance, ability to produce power from variable speed and self-protection from short circuits faults and over-load. A capacitor bank when connected with an externally driven squirrel cage induction machine is known as self-excited induction generator (SEIG). Though SEIG has advantages, the major drawback is voltage and frequency variation [2] during loading condition. To control voltage of SEIG, use of static var compensator (SVC) consisting of a fixed capacitor and and thyristor controlled inductor is reported in [3] and [4]. But the problems with SVC are injection of harmonic caused by switching of line currents and large size of passive elements. Development of fast acting self-commutating switches such as insulated gate bipolar transistor (IGBT) and metal oxide semi conductor field effect transistor (MOSFET), made possible to control voltage and frequency of SEIG with pulse width modulated (PWM) voltage source inverter (VSI) [5] - [7]. This type of reactive power compensator is basically known as static reactive power compensators (STATCOM). But this type of scheme involves complex electronic circuit and requires stator and load current sensors and PI controllers. In [8], technique having discrete wavelet transform (DWT) to detect load transients and particle swarm optimization (PSO) method to estimate capacitance value to maintain rated voltage are reported sensing stator current. Second generation wavelet transform (SGWT) is used in [9] for detecting power quality events and in [10] to extract Partial discharge pulse from electrical noise. In this paper DWT and SGWT, are used to detect load transients.

II. SYSTEM DESCRIPTION

Fig. 1 shows the schematic diagram of wavelet based module integration to the SEIG. The system consists of an induction machine with capacitor bank used as a self-excited induction generator (SEIG) driven by renewable energy based prime-mover, detection unit, VAR estimation unit, STATCOM and load. When load connects with SEIG voltage and frequency vary, so SEIG needs voltage and frequency controller for maintaining voltage and frequency of SEIG.

A. Modeling of SEIG

Stator and rotor equations of SEIG in stationary frame $d-q$ axis are derived as [11]

$$\dot{i_{sd}} = \frac{1}{K}[\omega_r L_m^2 i_{sq} - L_r r_s i_{sd} + \omega_r L_m L_r i_{rq} + L_m r_r i_{rd} + L_r v_{sd}] \quad (1)$$

$$\dot{i_{sq}} = \frac{1}{K}[-L_s r_s i_{sq} - \omega_r L_m^2 i_{sd} + L_m r_r i_{rq} - \omega_r L_m L_r i_{rd} + L_r v_{sq}] \quad (2)$$

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$$\dot{i_{rd}} = \frac{1}{K}[\omega_r L_m L_s i_{sq} + r_s L_m i_{sd} - \omega_r L_s L_r i_{rq} - r_r L_s i_{rd} + L_m v_{sd}] \quad (3)$$

$$\dot{i_{rq}} = \frac{1}{K}[r_s L_m i_{sq} + \omega_r L_m L_s i_{sd} - L_s r_r i_{rq} + \omega_r L_s L_r i_{rd} - L_m v_{sq}] \quad (4)$$

where $L_s = L_{ls} + L_m$ and $L_r = L_{lr} + L_m$ and $K = (L_s L_r - L_m^2)$. Magnetizing current i_m is determined from i_{sd}, i_{sq}, i_{rd} and i_{rq} using expression

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

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

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

The torque balance equation of the SEIG is

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

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

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

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

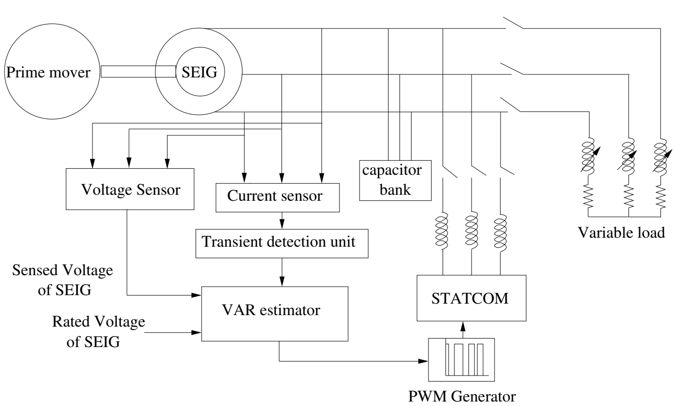


Fig. 1: Schematic diagram of standalone SEIG system.

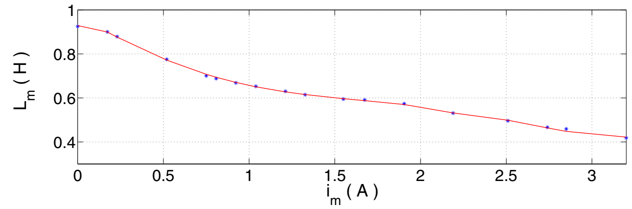


Fig. 2: Graph of the measured (blue) and approximated (red) magnetizing inductances vrs magnetising current

C. Modeling of static load

The d and q axes current equations for the balanced resistive load can be derived as

$$i_{ld} = \frac{v_{sd}}{R_L} \quad (11)$$

$$i_{lq} = \frac{v_{sq}}{R_L} \quad (12)$$

The d and q axes current equations for the balanced RL load are given as

$$\frac{di_{ld}}{dt} = \frac{v_{sd} - R_L i_{ld}}{L_L} \quad (13)$$

$$\frac{di_{lq}}{dt} = \frac{v_{sq} - R_L i_{ld}}{L_L} \quad (14)$$

D. Wavelet based transient detection unit

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

1) DWT: DWT convert data from the time domain (the original signal) to the wavelet domain. It decomposes the original signal $S[k]$ into approximation coefficients $A_1[k]$ and detail coefficient $D_1[k]$ at different frequency bands through low pass and high pass filters respectively using down sampling algorithm (by a factor of 2) [12], 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. Continuous Wavelet transform can be implemented both in continuous and discrete domain. Continuous wavelet can be defined as:

$$CWT = \frac{1}{\sqrt{i}} \int_{-\infty}^{\infty} S(t)\phi\left(\frac{t-j}{i}\right) dt \quad (15)$$

where i is the scaling(dilation) factor and j is the translation (time shift) factor and ϕ is the mother wavelet. Sampled waveform implemented by DWT and expressed as

$$DWT = \frac{1}{\sqrt{2^m}} \sum_k S[k]\phi\left(\frac{k - k.2^m}{2^m}\right) \quad (16)$$

where k and m are integers and the parameters i and j are replaced by 2^m and $k2^m$. Fig. 3 (a) shows block diagram of DWT decomposition. DWT is convolution based hence computation time to detect transient and hardware requirements to implement in real time is more. These problems can be sort out through SGWT.

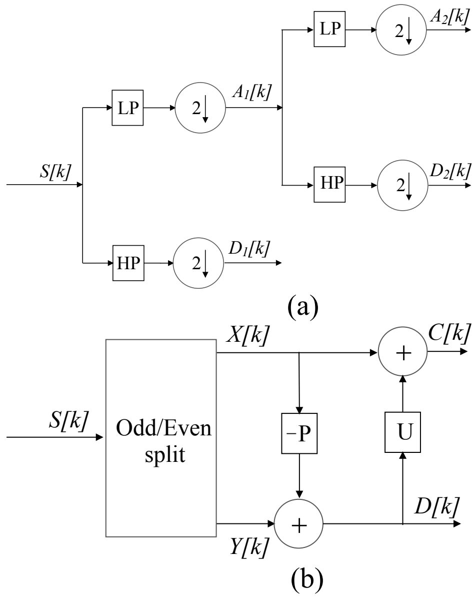


Fig. 3: Block diagram. (a) Discrete Wavelet Transform decomposition tree up to second level. (b) Second Generation Wavelet Transform decomposition.

2) SGWT: In SGWT, biorthogonal wavelets are constructed, [9] using lifting scheme (LS) and applied to detect power quality events. For constructing wavelets in SGWT, translation and dilation are not required as required in case of DWT. Convolution is not required in case of SGWT. SGWT is fully spatial domain interpretation transform [10], consists of three steps split, predict and update.

Split: In this step the original signal $S[k]$, divides into two disjoint subsets $i.e.$ $X[k] = S[k]_{even}$ and $Y[k] = S[k]_{odd}$, where $X[k]$ and $Y[k]$ are the even and odd index points of $S[k]$ respectively and both are correlated.

Predict: Detail coefficients, $D[k]$ are determined using expression is given as:

$$D[k] = Y[k] - P(X[k]) \tag{17}$$

where $P(X[k])$ is the prediction of $Y[k]$ based on $X[k]$ and P is the prediction operator. Linear combination of $Y[k]$ is $P(X[k]$.

Update: Approximation coefficients, $C[k]$ are determined using the expression is given as:

$$C[k] = X[k] + U(D[k]) \tag{18}$$

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. 3 (b) shows the Block diagram of SGWT decomposition tree for first level only.

E. VAR estimator unit

When load connects with SEIG, transient detection unit sends signal to VAR estimator unit. VAR estimator unit activates and calculates exact amount of extra VAR needs using any optimization technique such as genetic algorithm or, particle swarm optimization technique, to meet the VAR demands by load connect to SEIG. However, it estimates the capacitance value requires providing VAR demands by load and compensation current [8] is computed as:

$$I_{Compensation} = \frac{V_{terminal}}{X_{estimate} - X_{noload}} \tag{19}$$

Where $V_{terminal}$ is the terminal phase voltage of SEIG, X_{noload} is the capacitive reactance value per phase connect with SEIG and $X_{estimate}$ is the estimated capacitive reactance value per phase required to meet the VAR demands required by load.

III. RESULTS AND DISCUSSION

A 3.7-kW, 415-V, 50-Hz, 4 pole delta connected induction machine has been taken for simulation and experiment. Parameters of the induction machine are determined from the standard dc resistance test, no-load test and blocked rotor tests and measured values are given in Appendix. Capacitor bank is connected with induction machine to operate as self excited induction generator. Fig. 4(a) and (b) shows the voltage and current build process of SEIG during loading condition. Steady state rated voltage of 586.81 V (415 r. m. s.) is obtained for rated speed of 1500 r. p. m with 21 μF capacitor connected across stator of SEIG. At t=1.1 s load is connected to SEIG and SEIG voltage and current starts to fall observed from the figure. When load is connected to SEIG, a transient case occurs. To detect this load switching DWT and SGWT are used.

Fig. 5 (a) is the captured SEIG current signal for a resistive load and Fig. 5(b) and (c) shows the obtained high frequency detail coefficients using DWT and SGWT. It is observed from the figure that load is connected to SEIG at t=1.1 s and computation time taken using DWT is 0.0925 s and SGWT is 0.0855 s. Fig. 6 (a) is the captured stator current signal for a RL load and Fig. 6 (b) and (c) shows the obtained high frequency detail coefficients using DWT and SGWT. It is observed from the figure that load is connected to SEIG at t=1.3 s. and computation time taken using DWT is 0.0937 s and SGWT is 0.0864 s.

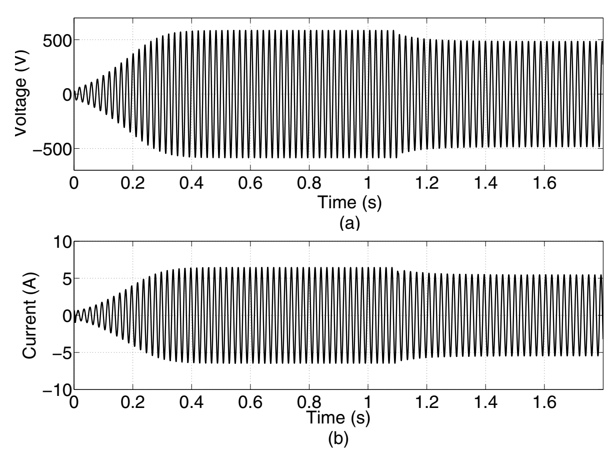


Fig. 4: Stator terminal voltage and current of SEIG during loading (a) Voltage. (b) Current.

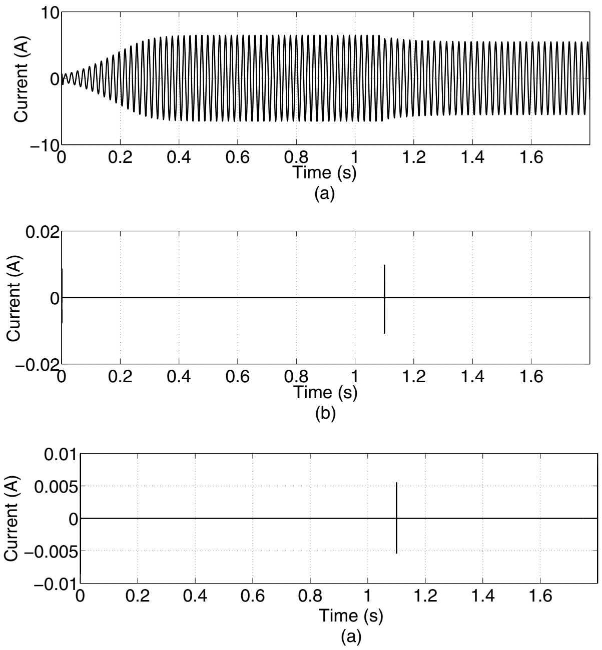


Fig. 5: Stator current decomposition of SEIG for resistive load. (a) Captured current signal. (b) Using DWT. (c) Using SGWT.

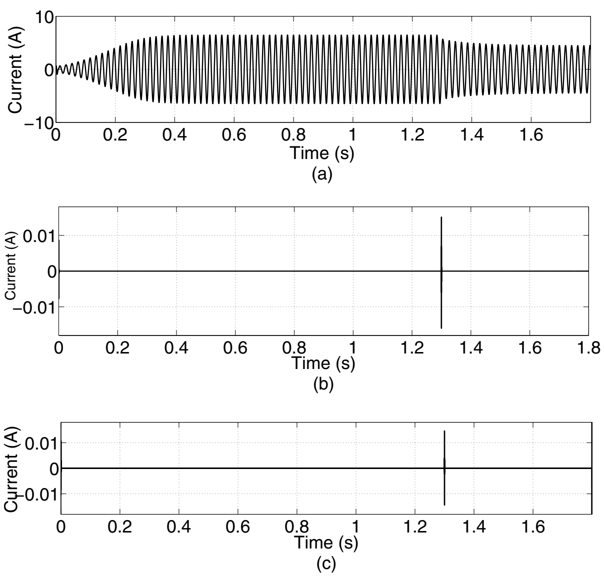


Fig. 6: Stator current decomposition of SEIG for RL load. (a) Captured current signal. (b) Using DWT. (c) Using SGWT.

Table- I shows the computation time to detect load switching for four different cases using both DWT and SGWT. Fig. 7 shows the experimental setup of SEIG. Experimental results of voltage build-up of stator terminal voltage and stator current are shown in Fig. 8(a) at no load condition and Fig. 8(b) shows the SEIG stator voltage and load current during loading condition.

TABLE I: Computation time to detect Load switching using DWT and SGWT.

CASE	DWT	SGWT
I	0.0925 s	0.0855 s
II	0.0937 s	0.0864 s
III	0.113 s	0.091 s
IV	0.114 s	0.095 s

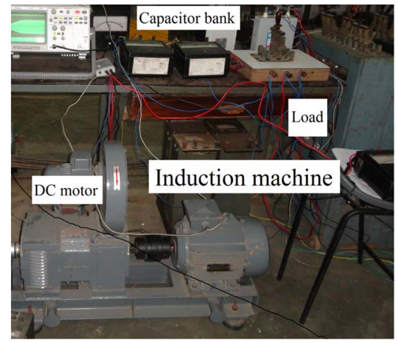
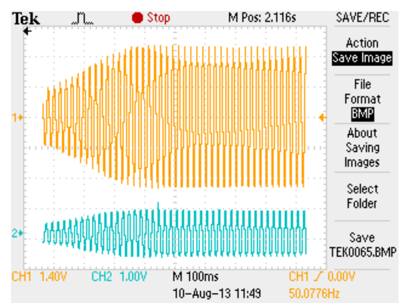
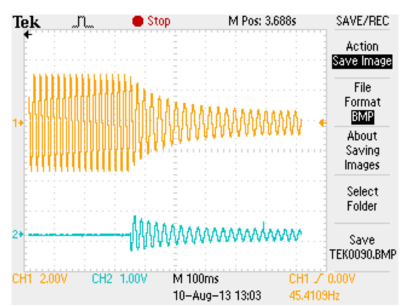


Fig. 7: Experimental setup of the dc motor coupled with induction machine used in the investigations.



(a)



(b)

Fig. 8: Experimental results. (a) SEIG stator voltage at no-load (top) and stator line current (bottom). (b) Stator terminal voltage of SEIG during loading condition (top) and load current (bottom).

IV. Conclusions

Self-excited induction generator is suitable in isolated and remote areas to produce electric power using renewable energy. But the problem is voltage and frequency of SEIG, vary when loads are switched to SEIG. For the development of simple voltage and frequency controller load transient detection is essential. In this paper two techniques, DWT and SGWT are employed to detect load transients. It is observed that computation time taken using SGWT is less compared to DWT.

Appendix

Parameters of SEIG: 3.7 kW, 415 V, 7.5 A (line), 50 Hz, 1500 r/min, four poles, delta connected, $R_s = 7.34\ \Omega$, $R_r = 5.64\ \Omega$, $X_{ls} = 6.7\ \Omega$, $X_{lr} = 6.7\ \Omega$ 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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