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Voltage Regulation of Self-excited Induction Generator based on FC-TCR

Omar Saif, Fathy M M Bassiony, Adel El-Samahy and Maged A Abo-Adma

Electrical Machine and Power System Enginnering Depatement,
Faculty of Enginnering, Helwan university Cairo – Egypt
drfbass@hotmail.com, consultant_group@hotmail.com

ABSTRACT

This paper presents a simplified approach to regulate the terminal voltage of the self-excited induction generator under variable loading conditions. The approach is based on a fixed capacitor with thyristor controlled reactor (FCTCR) used to keep the terminal voltage at a certain regulated value with load variations. The main advantage of the proposed approach is its simple but accurate control technique with reduced circuit arrangements. The controller response and the voltage regulation obtained from the simulation results of the proposed system using Simulink are satisfactory.

Key words: Self-excited induction generator, Voltage regulation, Capacitance requirements, Thyristor controlled reactor

1. INTRODUCTION

The limited reserves of fossil fuels (coal, oil, and natural gas) remain the main source of electricity generation even today. The use of fossil fuels produces pollutant gases when they are burned in the process to generate electricity and has an adversarial effect on the environment. Due to the environmental concerns as well as the depletion of fossil energy lead the researchers to look for alternative sources of energy. However, renewable energy resources (wind, solar, hydro, ocean, biomass and geothermal) are recommended as a good alternative andmore attention is being given to it [1-3].
Induction generators are widely used for wind power electric generation, especially in remote and isolated areas, due to their major advantages such as:

- An induction generator requiresless maintenance.
- They could operate at different speeds which is compatible with wind speed variation.
- They are smaller in size and have high power to weight ratio.
- They need less auxiliary equipment.
- They don't need to synchronization process compared to synchronous generator.
- They have self-protection feature against short circuit as Their excitation fail under short circuit conditions

The self-excited induction generators suffer from bad voltage regulation under different loading conditions. The terminal voltage is sensitive to changes in the load impedance, load power factor, and generator speed. Therefore the value of the excitation capacitor needs to vary with load variations. Some researchers proposed a switched capacitor schemes to improve the voltage regulation of the self-excited induction generator [4-9], others proposed complicated schemes for static VAR control [10- 18]. In this paper a simple and accurate thyristor controlled reactor to improve the voltage regulation as well as its Simulink model is introduced.

2. CAPACITANCE REQUIREMENT FOR STANDALONE SELF-EXCITED INDUCTION GENERATOR (SEIG)

A squirrel cage induction can be used as a self-excited Induction Generator (SEIG) by connecting a suitable set of excitation capacitor across its terminals and driven at a suitable speed as shown in fig 1.
The main operational problem of the SEIG system is its poor voltage and frequency regulation under varying load conditions [19, 20, 21, 26].

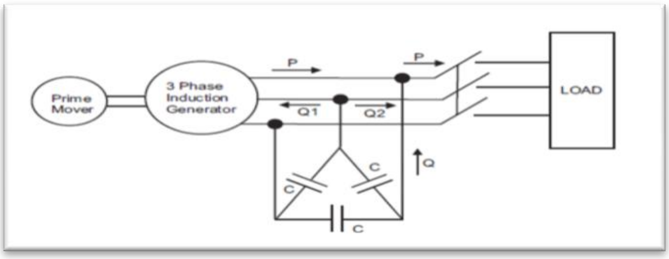

Fig. 1 Schematic diagram of a standalone self-excited induction generator

In this section, a simple method for predicting the steady state operation and determining the appropriate value of capacitance for either voltage build up process or maintaining constant voltage is presented. The proposed analysis is based on the nodal admittance approach applied to the equivalent circuit whenadopted for the self-excited induction generator which depicted in fig 2.

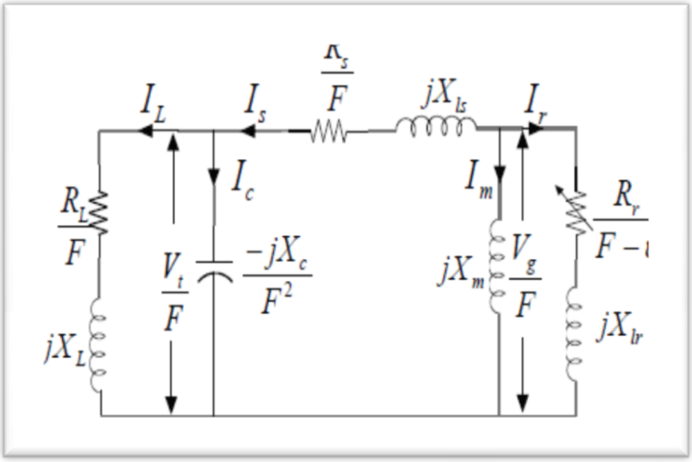

Fig. 2 Equivalent circuit of SEIG

$$Y_r = \frac{(F-v)(R_r - jX_{lr}(F-v)}{R_r^2 + X_{lr}^2(F-v)^2} \tag{1}$$

$$Y_m = \frac{-j}{X_m} \tag{2}$$

$$Z_1 = [(\frac{R_L}{F} + jX_L)//(\frac{-jX_c}{F^2})] + (\frac{R_s}{F} + jX_{ls}) \tag{3}$$

$$Y_1 = \frac{(N_1F^3 + N_2F^5 + X_cM_4F) + j(N_7F^2 + N_6F^4 - XM_2F^6)}{(M_1F - M_2F^3)^2 + (M_3F^2 - M_4)^2} \tag{4}$$

The M's coefficients are given in the appendix A.

When applying the nodal analysis to the above equivalent circuit the following formula is obtained

$$(\mathrm{Y_1} + \mathrm{Y_r} + \mathrm{Y_m})\frac{\mathrm{V_g}}{\mathrm{F}} = 0 \tag{5}$$

But for successful self-excitation process Vg≠0 so

$$(\mathrm{Y_1} + \mathrm{Y_r} + \mathrm{Y_m}) = 0 \tag{6}$$

by equating real part and imaginary part to zero, from the real part sixth order polynomial function of frequency is deduced

$$\alpha_6^6F^6 + \alpha_5^5F^5 + \alpha_4^4F^4 + \alpha_3^3F^3 + \alpha_2^2F^2 + \alpha_1F + \alpha_0 = 0$$

The coefficients of the polynomial are given in the appendix A

Solving the above polynomial for its roots, then the largest real root of frequency indicate the operation frequency corresponding to the self-excitation capacitance.

Again equating the imaginary part of equation (6) to zero and after some arrangements the value of saturated magnetizing reactance is given as

$$X_m = \frac{1}{\frac{N_7F^2 + N_6F^4 - XM_2F^6}{(M_1F - M_2F^3)^2 + (M_3F^2 - M_4)^2} - \frac{X_r(F-v)^2}{R_r^2 + X_r^2(F-v)^2}} \tag{7}$$

Solving the above polynomial gives the self-excitation frequency which will be supplied to equation 7 to find the equivalent value of the saturated magnetizing capacitor X_m. Once the value of X_m is known the value of the airgap voltageV_g is obtained from the machine's magnetization curve and the corresponding value of the terminal voltage is calculated as following.

$$V_t = \frac{V_g}{\left|(\frac{R_s}{F} + jX_s)(\frac{1}{\frac{R}{F} + jX} + \frac{1}{\frac{R_s}{F} + jX_s} + \frac{jF^2}{X_c})\right|}$$

If the value of terminal voltage is known then all performance parameters could be easily obtained by soling the equivalent circuit as following:

Stator current $I_s = \frac{V_t F}{|-jX_c|}$

Load current $I_l = \frac{V_t/F}{\left|\frac{R}{F}+jX\right|}$

Apparent load power $S = 3\frac{V_t}{F} I_l$

Apparent machine extracted power $S = 3\frac{V_t}{F} I_s$

The flow chart shown belowintroduces an approach to calculate the capacitance required to maintain the terminal voltage at constant prescribed value under different loadand speed conditions; it's also used to evaluate the performance parameters under steady state operation.

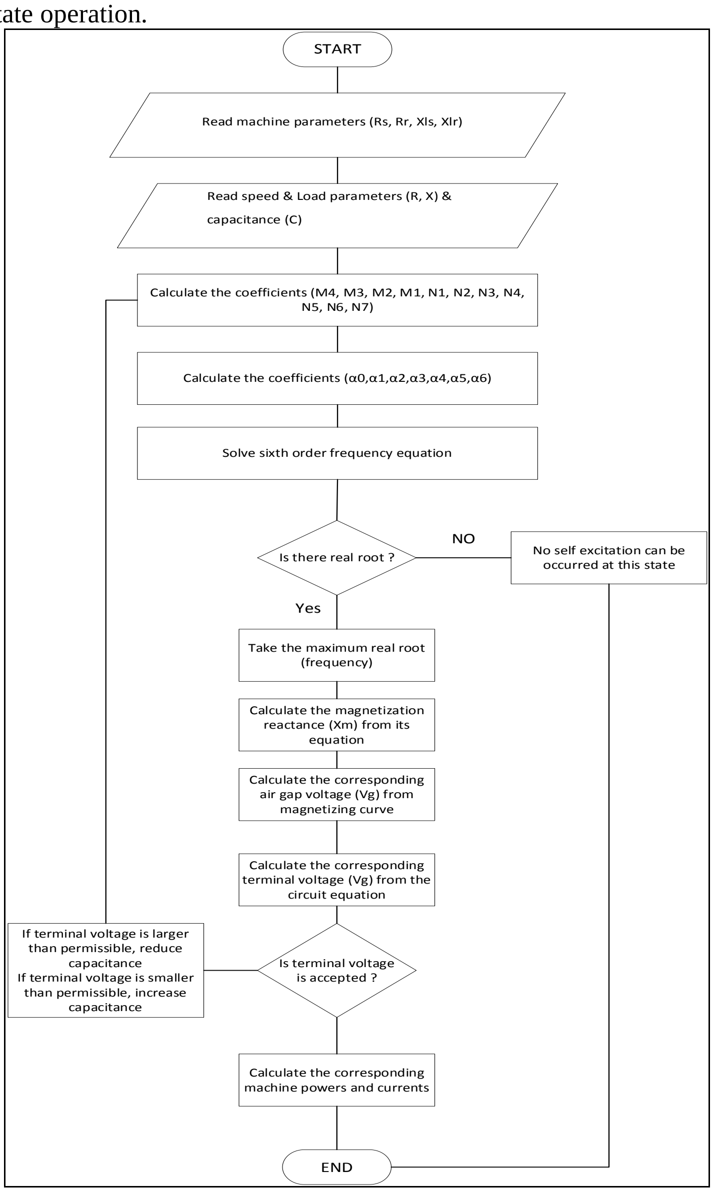

Fig. 3 Flow chart to evaluate capacitance for maintaining constant terminal voltage

From the previous discussion, we noted that with varying either load (amount or type) or speed, an additional capacitance is required to maintain constant terminal voltage. The additional value of capacitance could be added in steps or using a fixed capacitor and smoothly varying its value using thyristor controlled reactor (FC-TCR). The first choice is not recommended due to the large switching current associated with it.

3. FIXED CAPACITOR – THYRISTOR CONTROLLED REACTOR (FC-TCR) AS VOLTAGE REGULATOR OF SEIG

To solve the problem of voltage fluctuation of SEIG, asuitable amount of reactive power is needed to maintain constant terminal voltage. Fixed Capacitor-Thyristor Controlled Reactor (FC-TCR) will be used to regulate the terminal voltage of the stand-alone induction generator under variable loading conditions. The FC-TCR consists of a fixed capacitor connected in parallel with a combination of two antiparallel thyristors connected in series with a reactor as shown in fig 4. The feedback control system is used to control the firing angles of antiparallel thyristor which are indirectly control the reactive power injected into the system by controlling current through the reactor. The use of FC-TCR has the following impacts:

- Improvement of both dynamic and transient stability.
- Improvements of both voltage stability and security.
- Less active and reactive Power loss
- Improves voltage and power profile
- Power Quality Managements [22].

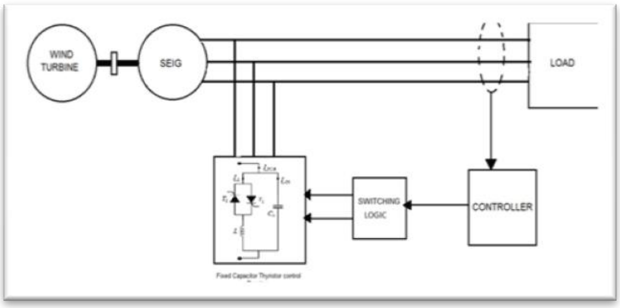

Fig. 4 Schematic of SEIG with FC-TCR regulator

The principle of operation of the static varcompensator, SVC is to adjust the susceptance in each phase by controlling the conducting angles of thyristor controlled reactor [23-24], SVC is commonly used and studied under sinusoidal voltage conditions, waveforms of controlled current present high harmonic content [25].

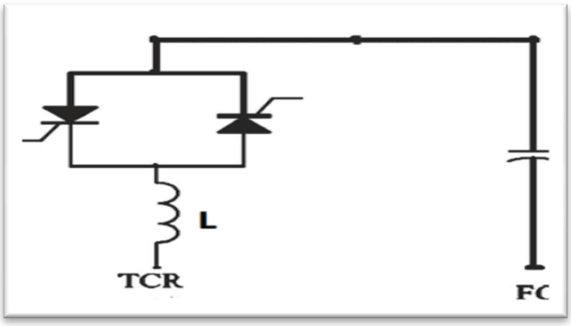

Fig. 5 Schematic of FC-TCR

Fig. 5 shows an elementary single phase thyristor controlled reactor (TCR) with FC. It consists of a fixed (usually air core) reactor of inductance L in series with two anti-parallel SCRs and the combination is parallel with fixed capacitor (FC). The reactor is brought into conduction by successive application of gate pulses to the forward biased SCR in each half-cycle. In addition, it will automatically block immediately after the ac current crosses zero, unless the gate signal is reapplied. The current in the reactor can be controlled from maximum (SCR closed) to zero (SCR open) by the method of firing angle control. That is, the SCR conduction is delayed with respect to the peak of the applied voltage in each half-cycle, and thus the duration of the current conduction interval is controlled.

4. CONTROL TECHNIQUE FC-TCR TO REGULATE VOLTAGE

To use FC-TCR in voltage regulation, control technique as shown in fig 6, is based on measuring the actual voltage and comparing it with the required reference voltage then the error signal is handled via a proportional-integral (PI) controller. The output of the controller is the required FC-TCR suscepatance (B_{SVS}). The maximum value of susceptance occurswhen $\alpha = 180$ while its minimum limit at α =90, this value of susceptance (B_{SVS}) can be transferred to thyristor controlled reactor suscepatance (B_{TCR}) from the relation $B_{TCR} = B_{svs} - B_c$ based on constant values of capacitance (C) and inductance (L). Then the value of (B_{TCR}) is then used to determine the corresponding firing angle (α)based on a look-up table using the following relation

$$B_{TCR}(\alpha) = \frac{2\pi - 2\alpha + \sin(2\alpha)}{\pi\omega L_1}$$

This value of firing angle (α)is then used to control the thyristorsconduction and consequently control the reactor current.

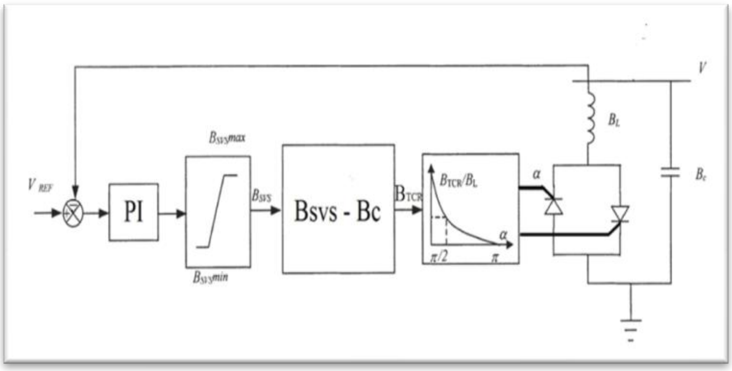

Fig. 6 The control technique of FC-TCR

5. IMPLEMENTATION OF FC-TCR FOR VOLTAGE REGULATION OF SEIG

Thyristor controlled reactors are also called shunt compensators that are used for voltage regulation of SEIG as shown in fig 7.

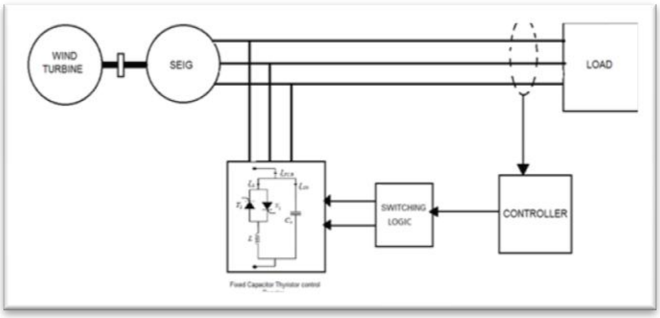

Fig. 7 Schematic of SEIG with FC-TCR regulator.

The operating principle of TCR is characterized by its operational simplicity, and less harmonics generation. In FC-TCR, fixed capacitor injects reactive power into the system whereas thyristor controlled reactor absorbs the reactive power from the system.By adjusting the reactive power absorbed by the reactor, the reactive power requirements to continuously regulate the system voltage due to the load current variation is adjusted.

Therefore, the value of capacitor is fixed so that the reactive power injection into the system is constant whereas the effect of the reactor can be controlled by controlling thyristor firing angle and hence the reactive power absorption can be controlled.

A control circuit based on switching logic computations is carefully designed to control the conduction instant as well as the conduction period of the Thyristor. Therefore, the value of the absorbed reactive power is a function of the conduction period. This means that, as the conduction period of the thyristor increases the reactive power absorbed by the reactor increases and vice versa. In other words the reactive power absorbed by the reactor is maximum when the firing angle is minimum and vice versa.

6. MATLAB/SIMULINK OF SEIG REGULATOR WITH FC-TCR

The Simulink model of SEIG regulator with FC-TCR as is shown in fig 8. The model consists of SEIG with a fixed capacitor shunted with a series combination of a reactor and antiparallel thyristors in addition to the control system necessary to generate the firing signal.

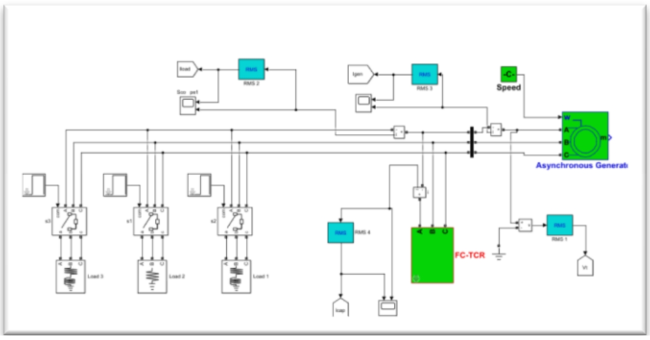

Fig. 8 Schematic of TCR

The complete voltage regulator FC-TCR is shown in fig 9, capacitor value should be suitable to give rated voltage at rated load, and the value of inductor inductance is continuously adjusted to maintain the terminal voltage at the machine rated value under load variations. This means that the value of inductance must be suitable for absorbing the difference in reactive power between no load and full load operation. Therefore, this value of inductance can be evaluated as follow:

$$L = \frac{1}{\omega^2 (C_{max} - C_{min})} \quad (10)$$

Where: C_{max} : Capacitance value at full load operation
C_{min} : Capacitance value at no load operation

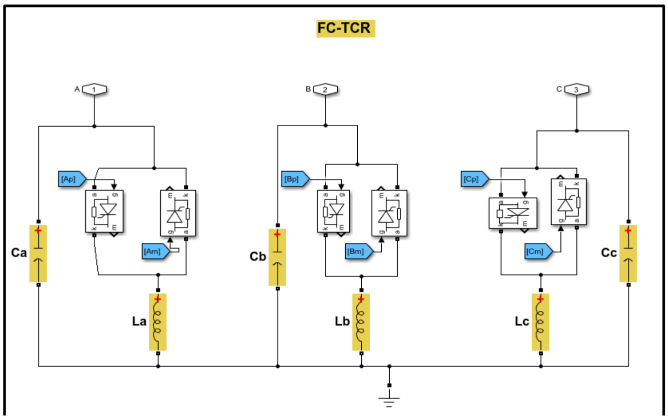

Fig. 9 Schematic of TCR

The control system ~~as~~ shown in fig 6 consists of:

1. Voltage regulator as shown in fig 10 to compute the difference between the actual terminal voltage and reference voltage, proceeding error through PI controller which optimized by particle swarm technique and then deduces the requiredsuscepatance from FC-TCR (Bsvc).

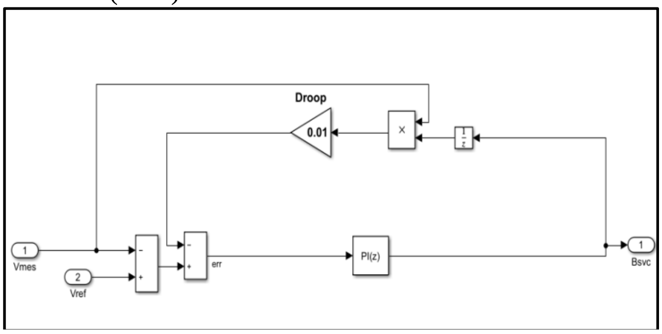

Fig. 10 Schematic of voltage regulator

2. Distribution unit: as shown in fig11, transform the suscepatance detected by the voltage regulator to the required firing angle (α) based on the modeling of FC-TCR and the values of capacitor and reactor.

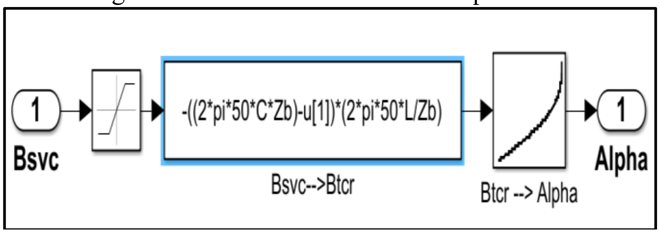

Fig. 11 Schematic of Distribution unit

3. Firing unit as shown in fig 12 to converts the value of firing angle (α) into ~~6~~six pulses by considering zero crossing voltage detectors.

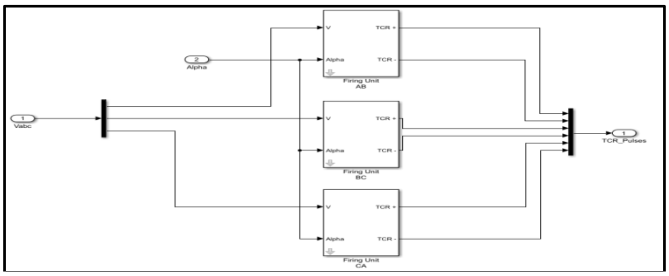

Fig. 12 Schematic of firing unit

7. SIMULATION AND RESULTS

The machine used in the following simulations has the following parameters, 4 KW, 220/380 V (delta/Y), 16/9.3 A (delta/Y), 1415 rpm.The overall Simulink model is depicted in fig 13.

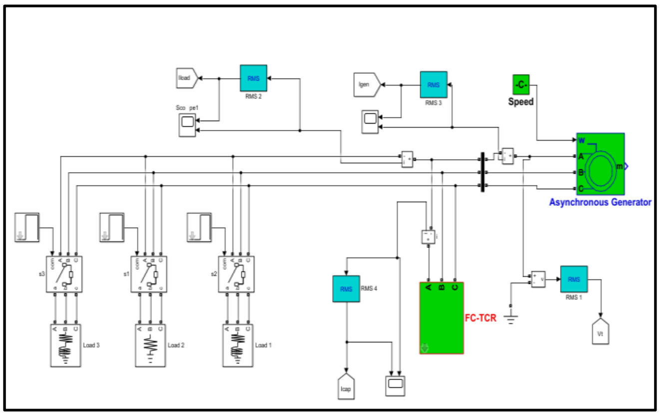

Fig. 13 Schematic of TCR

Since the main objective is to keep the terminal voltage at its rated value during the load variations from no-load to full-load, therefore the value of capacitor is selected on the basis of the rated power and speed operation. Based on the capacitance requirement model of the used machine, the value of capacitor is calculated to be 224 μF. The required value of the inductor's inductance to absorb the extra reactive power at loading conditions less than the rated load is also determined to be 28 mH.

The load variations considered in the following simulation is depicted in fig. 15 and has the following describtion.

- At the beginning, the machine is driven at no load
- At 7seconda load of 1 kW is applied at the machine terminals.
- At 8 second the load is stepped to (3 kW and 1.5 kVAR)
- At 10 secondtheload is stepped to (3.5kW, 1.7kVAR).
- At 15 second the load is stepped to (1.5kW, 0.2kVAR).
- At 20 second the load is stepped to (0.5 kW, 0.2 kVAR).
- At 25 second the load is then reduced to zero.

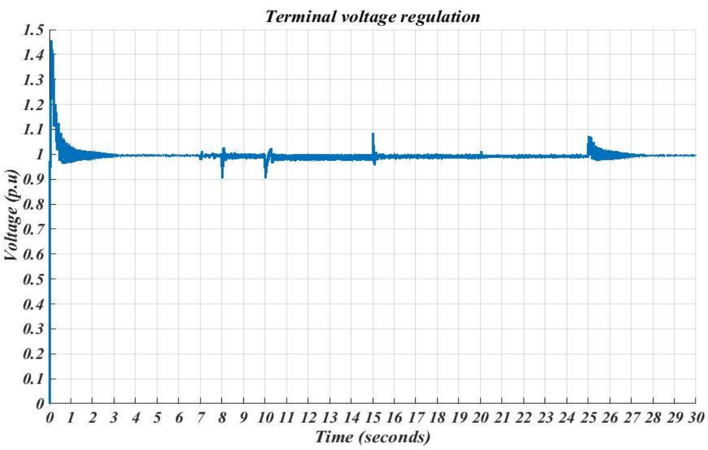

Fig. 14 Terminal voltage of SEIG

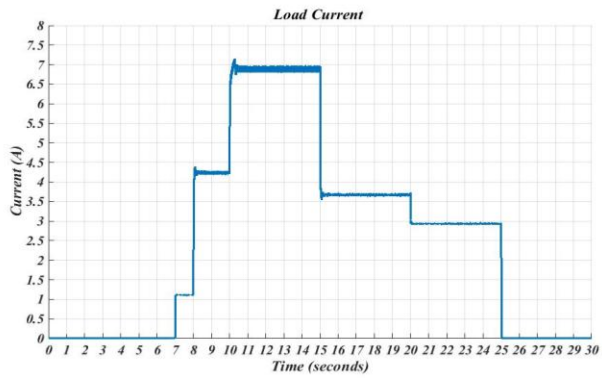

Fig. 15 Load current

The simulation results for the terminal voltage corresponding to the load variations depicted in fig. 15 is shown in fig. 14 and is described as following:

- From 0 to 7 sec. the machine working at no load and while terminal voltage is maintained at its rated
- From 7 to 8 sec. the machine is loaded by (1kW) at a load current of 1.2 A, and the terminal voltage is maintained at its rated value.
- From 8 to 10 sec. the load was increased to (3 kW, 1.5kVAR) at a load current of 4.25 A
- From 10 to 15 sec. the load is stepped to (3.5 kW, 1.7kVAR) at a load current of 7 A.
- From 15 to 20 sec. the machine is loaded by (1.5 kW, 0.2kVAR) at a load current of 3.6 A.
- From 20 to 25 sec. the machine is loaded by (0.5 kW, 0.2 kVAR) at a load current of 3.6 A.
- From 25 to 30 sec. the generator is running under no load conditions.

In all of the previous loading conditions the terminal voltage is maintained at its rated value as could be seen from the results of fig. 14.

Fig. 16 shows the necessary adjustment of the thyristors firing angles during the load variations depicted in fig. 15. The corresponding variation in the reactive power supplied to the generator is shown in fig. 17.

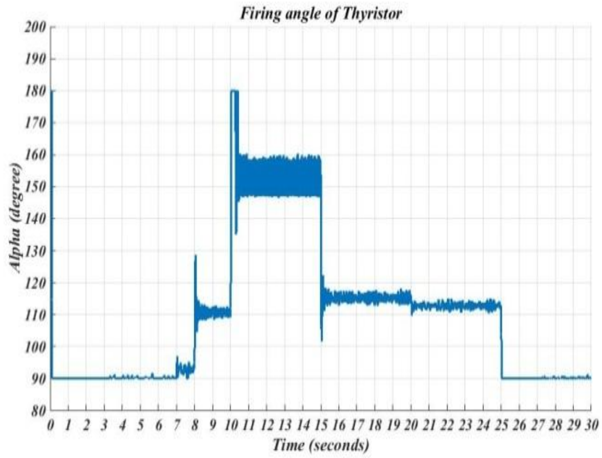

Fig. 16 Angle of alpha

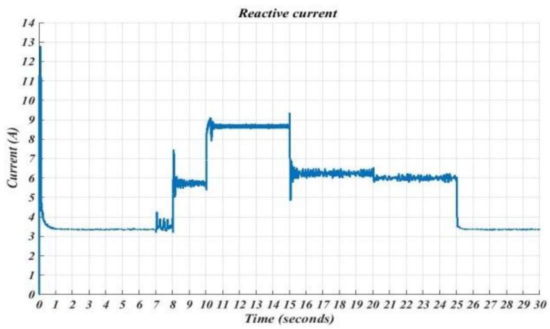

Fig. 17 Reactive current injected to the system

As expected the machine needs less reactive power under no-load conditions and therefore the firing angle is 90^o, this is corresponding to a minimum reactive power to the generator while that absorbed by the reactor is maximum.

At any load condition, alpha is adjusted to accomplish the balance between reactive current required to maintain constant terminal voltage and the extra reactive power absorbed by the inductor. The variations in the generator current during load variations are depicted in fig.18.

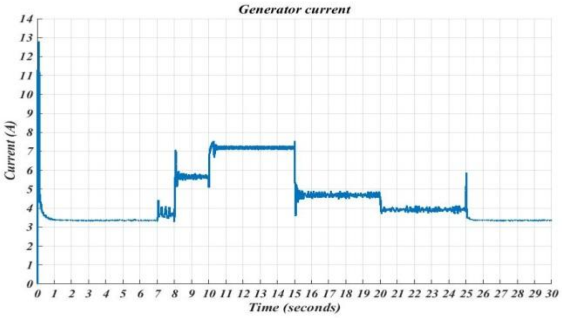

Fig. 18 Generator current during load variation

8. CONCLUSION

A simplified approach to regulate the terminal voltage of the self-excited induction generator under variable loading conditions has been proposed in this paper. The approach is based on a fixed capacitor with thyristor controlled reactor (FC-TCR). A Simulink model for the FC-TCR and its necessary control scheme is built and tested. The simulation results proved that, the FC-TCR voltage regulator is an effective technique to regulate the terminal voltage of SEIG. The main advantage of the proposed approach is that, it’s simple but accurate control technique with reduced circuit arrangements. The controller response and the voltage regulation obtained from the simulation results of the proposed system using Simulink showed satisfactory operation of the SEIG.

Appendices

Appendix A

$M_1 = XX_c + RR_s + X_sX_c$, $M_2 = XX_s$, $M_3 = XR_s + RX_s$,
$M_4 = X_cR_s + RX_c$, $N_1 = RM_1 - XM_4 - X_cM_3$,
$N_2 = XM_3 - RM_2$, $N_3 = M_4X_c$, $N_4 = M_3^2 - 2M_1M_2$,
$N_5 = M_1^2 - 2M_3M_4$, $N_6 = -RM_3 + XM_1 + X_cM_2$,
$N_7 = -X_cM_1 + RM_4$
$\alpha_6 = M_2R_r + N_2X_r^2$, $\alpha_5 = M_2^2R_r v - 2N_2vX_r$,
$\alpha_4 = N_4R_r + N_2R_r^2 + X_r^2N_1 + X_r^2v^2N_2$, $\alpha_3 = -N_4R_rv - 2N_1vX_r$, $\alpha_2 = N_5R_r + N_3X_r^2 + X_r^2v^2N_1$, $\alpha_1 = -N_5R_rv + N_1R_r^2 - 2N_3X_rv$, $\alpha_0 = N_3R_r^2 + X_r^2v^2N_3$

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