JPE 5-2-4

A Solid State Controller for Self-Excited Induction Generator for Voltage Regulation, Harmonic Compensation and Load Balancing

Bhim Singh†, S. S. Murthy* and Sushma Gupta**

†**Department of Electrical Engineering, Indian Institute of Technology Delhi, New Delhi, India
*N.I.T., Karnataka Surathkal-575025, Dakshin Karnataka, India

ABSTRACT

This paper deals with the performance analysis of static compensator (STATCOM) based voltage regulator for self-excited induction generators (SEIGs) supplying balanced/unbalanced and linear/ non-linear loads. In practice, most of the loads are linear. But the presence of non-linear loads in some applications injects harmonics into the generating system. Because an SEIG is a weak isolated system, these harmonics have a great effect on its performance. Additionally, SEIG's offer poor voltage regulation and require an adjustable reactive power source to maintain a constant terminal voltage under a varying load. A three-phase insulated gate bipolar transistor (IGBT) based current controlled voltage source inverter (CC-VSI) known as STATCOM is used for harmonic elimination. It also provides the required reactive power an SEIG needs to maintain a constant terminal voltage under varying loads. A dynamic model of an SEIG-STATCOM system with the ability to simulate varying loads has been developed using a stationary d-q axes reference frame. This enables us to predict the behavior of the system under transient conditions. The simulated results show that by using a STATCOM based voltage regulator the SEIG terminal voltage can be maintained constant and free from harmonics under linear/non linear and balanced/unbalanced loads.

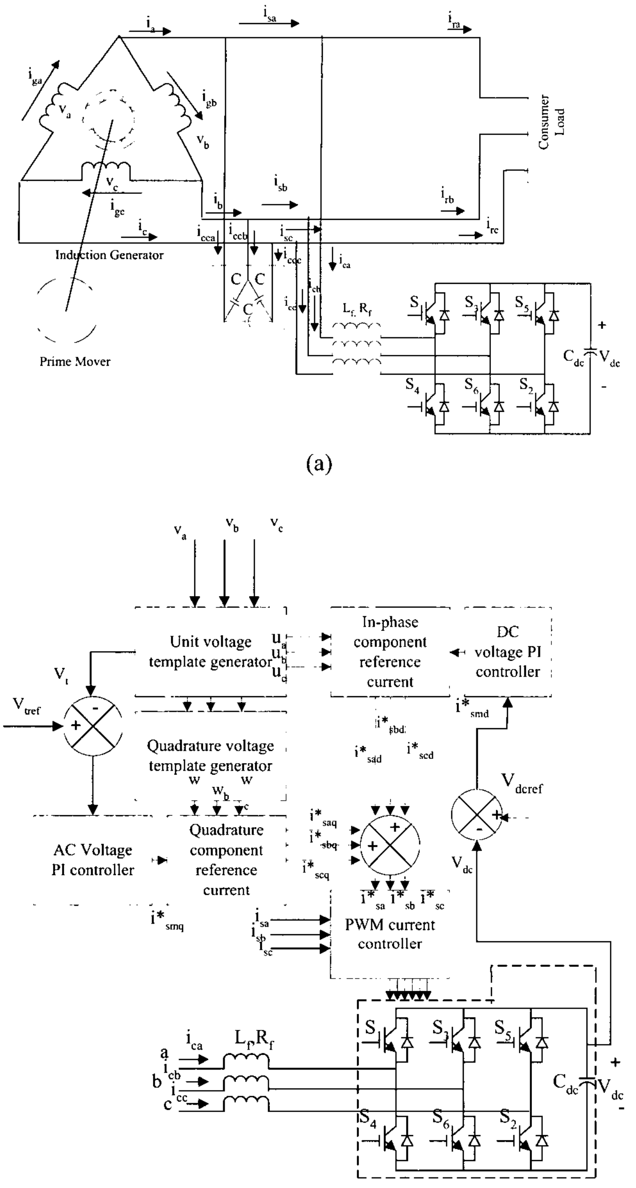
Keywords: Self-excited induction generator, static compensator, voltage regulation, load balancing, harmonic elimination.

1. Introduction

Due to global environmental concern, increased emphasis is being given to non-conventional energy sources to provide electricity. These non-conventional energy sources have great potential to act as prime movers for the generating systems. An externally driven induction machine operates as a self-excited induction generator (SEIG), with its excitation requirements being met by a capacitor bank connected across its terminals. The SEIG has advantages [1] like simplicity, being maintenance free, absence of DC, being brushless, etc. as compared to a conventional synchronous generator.

Considerable literature exists on steady state and transient analysis of SEIG's under balanced/unbalanced resistive, reactive and motor loads[1-5]. In[3-5] d-q axes modeling is reported for the transient analysis of an SEIG.

Manuscript received May14, 2004; revised January 20, 2005.
†Corresponding Author: bsingh@ee.iitd.ac.in, I. I.T. Delhi
Tel: +91-11-26591045, 91-9811502125, Fax: +91-11-26581606
*N.I.T., Dakshin Karnataka, India
**Dept. of Elec. Engg., I. I.T. Delhi, India



(a)

(b)

Fig. 1 Schematic Diagram of SEIG-STATCOM

Wang and Deng[6] have presented the transient performance of an SEIG under an unbalanced excitation system. Jain et al. [7] have given a generalized model for the transient analysis of an SEIG under symmetrical and asymmetrical conditions.

A major disadvantage of an SEIG is its poor voltage regulation. It requires a variable capacitance bank to maintain constant terminal voltage under varying loads. Attempts have been made to maintain constant terminal voltage using fixed capacitor and thyristor controlled reactors (TCR)[8], saturable-core reactors[9] and short-shunt connections[10]. The voltage regulation provided by these schemes is discrete but these inject harmonics into the generating system. However, with the invention of solid-state commutating devices, it is possible to make a static, noiseless voltage regulator which is able to regulate continuously variable reactive power to keep the terminal voltage of an SEIG constant under varying loads. This system, called STATCOM, has specific benefits compared to conventional SVC's[11]. Schauder and Mehta[12] have derived governing equations of STATCOM to determine its response to negative sequences and harmonic voltage components in the transmission line.

Singh and Shilpakar [13] have proposed an analysis of a solid-state voltage regulator for an SEIG with balanced loads. Miranda et al. [14] have proposed a static VAR compensator for an electrical pumping system driven by an induction generator. Kuo and Wang [15], [16] have described a method of voltage control of an SEIG under non-linear loads.

In general, electrical loads are linear in nature. However, due to the extensive use of solid-state controllers in different appliances, they draw harmonic current from AC sources and behave as non-linear loads. Adjustable speed drives used in pumps, compressors, air-conditioner and other domestic appliances such as TV's, computers, SMPS's, and UPS's consist of either three-phase or single-phase rectifiers at the front-end. These non-linear loads draw non-sinusoidal currents from the generating system, therefore injecting harmonics into the system. An SEIG is an isolated system, which is small in size, and the injected harmonics pollute the generated voltage. The STATCOM eliminates the harmonics, provides load balancing and supplies the required reactive power to the load and the generator. In this paper, the authors present a simple mathematical model for the transient analysis of the SEIG-STATCOM system under balanced/unbalanced, linear/non-linear loads (R, R-L and rectifier with capacitor filter and R load). Simulated results show that the SEIG-STATCOM system behaves as an ideal generating system under these conditions.

2. System Configuration and Control Scheme

The schematic diagram of an SEIG with excitation capacitor, STATCOM, load and control scheme is shown in Fig.1. Excitation capacitors are selected such that the SEIG generates rated voltage at rated speed under no load. The additional demand for reactive power is fulfilled using the STATCOM under varying loads. The STATCOM acts as a source of lagging or leading current to maintain the constant terminal voltage despite variations in load. The STATCOM consists of a three-phase IGBT based current controlled voltage source inverter, a DC bus capacitor and AC inductors. The output of the inverter is connected through the AC filtering inductor to the SEIG terminals. The DC bus capacitor is used as an energy storage device and provides the self-supporting DC bus of the STATCOM.

The control technique is used to regulate the terminal voltage of the SEIG is based on the generation of source currents. (They have two components, in-phase and quadrature, with AC voltage.) The in-phase unit vectors (u_a, u_b and u_c) are three-phase sinusoidal functions, computed by dividing the AC voltages v_a, v_b and v_c by their amplitude V_t. Another set of quadrature unit vectors (w_a, w_b and w_c) are sinusoidal functions obtained from in-phase vectors (u_a, u_b and u_c). To regulate the AC terminal voltage (V_t), it is sensed and compared with the reference voltage. The voltage error is processed in the PI controller. The output of the PI controller (I_{smq}*) for the AC voltage control loop determines the amplitude of the reactive current to be generated by the STATCOM. Multiplication of quadrature unit vectors (w_a, w_b and w_c) with the output of the PI based AC voltage controller (I_{smq}*) yields the quadrature component of the reference source currents (i_{saq}*, i_{sbq}* and i_{scq}*). To provide a self-supporting DC bus for STATCOM, its DC bus voltage is sensed and compared with the DC reference voltage. The error voltage is processed in another PI controller. The output of the PI controller (I_{smd}*) determines the amplitude of the active current. Multiplication of in-phase unit vectors (u_a, u_b and u_c) with the output of the PI controller (I_{smd}*) yields the in-phase component of the reference source currents (i_{sad}*, i_{sbd}*and i_{scd}*). The instantaneous sum of quadrature and in-phase components gives the reference source currents (i_{sa}*, i_{sb}* and i_{sc}*), which are compared with the sensed line current (i_{sa}, i_{sb} and i_{sc}). These current error signals are amplified and compared with the triangular carrier wave. If the amplified current error signal is equal to or greater than the triangular carrier wave, the lower device of the inverter phase is turned on and the upper device turned off. If the amplified current error signal is equal to or less than the triangular carrier wave the lower device of the inverter phase is turned off and the upper device turned on.

A non-linear load draws non-sinusoidal currents which causes harmonics to be injected into the generating system. Under unbalanced load conditions, SEIG currents may be unbalanced which may cause the machine to be derated. STATCOM is able to filter out the harmonics and balance the unbalanced load resulting in balanced and sinusoidal currents and voltages in the generator.

3. Modeling of SEIG-STATCOM System

The mathematical model of the SEIG-STATCOM system contains the modeling of an SEIG and STATCOM as follows.

3.1 Modeling of control scheme of STATCOM

Different components of the SEIG-STATCOM system shown in Fig. 1 are modeled as follows.

From the three-phase voltages at the SEIG terminals (v_a, v_b and v_c), their amplitude (V_t) is computed as:

$$V_t = \{ (2/3) (v_a^2 + v_b^2 + v_c^2) \}^{1/2} \tag{1}$$

It (V_t) is filtered to eliminate ripples if there are any present.

The unit vector in phase with v_a, v_b and v_c are derived as:

$$u_a = v_a/V_t; \quad u_b = v_b/V_t \quad ; \quad u_c = v_c/V_t \tag{2}$$

The unit vectors in quadrature with v_a, v_b and v_c may be derived using a quadrature transformation of the in-phase unit vectors u_a, u_b and u_c as:

$$w_a = -u_b / \sqrt{3} + u_c / \sqrt{3} \tag{3}$$

$$w_b = \sqrt{3}\, u_a / 2 + (u_b - u_c) / 2\sqrt{3} \tag{4}$$

$$w_c = -\sqrt{3}\, u_a / 2 + (u_b - u_c) / 2\sqrt{3} \tag{5}$$

3.1.1 Quadrature component of reference source currents

The AC voltage error $V_{er(n)}$ at the n^{th} sampling instant is:

$$V_{er(n)} = V_{tref(n)} - V_{t(n)} \quad (6)$$

where $V_{tref(n)}$ is the amplitude of the reference AC terminal voltage and $V_{t(n)}$ is the amplitude of the sensed three-phase AC voltage at the SEIG terminals at the n^{th} instant. The output of the PI controller ($I^*_{smq(n)}$) for maintaining constant AC terminal voltage at the n^{th} sampling instant is expressed as:

$$I^*_{smq(n)} = I^*_{smq(n-1)} + K_{pa} \{ V_{er(n)} - V_{er(n-1)} \} + K_{ia} V_{er(n)} \quad (7)$$

where K_{pa} and K_{ia} are the proportional and integral gain constants of the proportional integral (PI) controller. $V_{er\,(n)}$ and $V_{er(n-1)}$ are the voltage errors at the n^{th} and $(n-1)^{th}$ instant and $I^*_{smq(n-1)}$ is the amplitude of the quadrature component of the reference source current at the $(n-1)^{th}$ instant. The quadrature components of the reference source currents are computed as:

$$i^*_{saq} = I^*_{smq}\, w_a; \quad i^*_{sbq} = I^*_{smq}\, w_b; \quad i^*_{scq} = I^*_{smq}\, w_c \quad (8)$$

3.1.2 In-phase component of reference source currents

The error in the DC bus voltage of the STATCOM ($V_{dcer(n)}$) at the n^{th} sampling instant is:

$$V_{dcer(n)} = V_{dcref(n)} - V_{dc(n)} \quad (9)$$

where $V_{dcref(n)}$ is the reference DC voltage and $V_{dc(n)}$ is the sensed DC link voltage of the STATCOM. The output of the PI controller for maintaining the DC bus voltage of the STATCOM at the n^{th} sampling instant, is expressed as:

$$I^*_{smd(n)} = I^*_{smd(n-1)} + K_{pd} \{V_{dcer(n)} - V_{dcer(n-1)}\} + K_{id} V_{dcer(n)} \quad (10)$$

$I^*_{smd(n)}$ is considered to be the amplitude of the active source current. K_{pd} and K_{id} are the proportional and integral gain constants of the DC bus PI voltage controller. The in-phase components of the reference source currents are computed as:

$$i^*_{sad} = I^*_{smd}\, u_a; \quad i^*_{sbd} = I^*_{smd}\, u_b; \quad i^*_{scd} = I^*_{smd}\, u_c \quad (11)$$

3.1.3 Total reference source currents

The total reference source currents are the sum of the in-phase and quadrature components of the reference source currents as:

$$i^*_{sa} = i^*_{saq} + i^*_{sad} \quad (12)$$

$$i^*_{sb} = i^*_{sbq} + i^*_{sbd} \quad (13)$$

$$i^*_{sc} = i^*_{scq} + i^*_{scd} \quad (14)$$

3.1.4 PWM current controller

The total reference currents (i^*_{sa}, i^*_{sb} and i^*_{sc}) are compared with the sensed source currents (i_{sa}, i_{sb} and i_{sc}). The ON/OFF switching patterns of the gate drive signals to the IGBTs are generated from the PWM current controller. The current errors are computed as:

$$i_{saerr} = i^*_{sa} - i_{sa} \quad (15)$$

$$i_{sberr} = i^*_{sb} - i_{sb} \quad (16)$$

$$i_{scerr} = i^*_{sc} - i_{sc} \quad (17)$$

These current error signals are amplified and then compared with the triangular carrier wave. If the amplified current error signal is greater than the triangular wave signal switch S_4 (lower device) is ON and switch S_1 (upper device) is OFF, and the value of the switching function SA is set to 0. If the amplified current error signal corresponding to i_{saerr} is less than the triangular wave signal, switch S_1 is ON and switch S_4 is OFF, and the value of SA is set to 1. Similar logic applies to the other phases.

3.2 Modeling of STATCOM

The STATCOM is a current controlled VSI and is modeled as follows:

The derivative of its DC bus voltage is defined as:

$$pv_{dc} = (i_{ca}\, SA + i_{cb}\, SB + i_{cc}\, SC)/\, C_{dc} \quad (18)$$

Where SA, SB and SC are the switching functions for the ON/OFF positions of the VSI bridge switches S_1-S_6.

The DC bus voltage reflects the output of the inverter in the form of the three-phase PWM AC line voltage e_{ab}, e_{bc} and e_{ca}. These voltages may be expressed as:

$$e_{ab} = v_{dc}\,(SA - SB) \quad (19)$$

$$e_{bc} = v_{dc}\,(SB - SC) \quad (20)$$

$$e_{ca} = v_{dc}\,(SC - SA) \quad (21)$$

The volt-amp equations for the output of the voltage source inverter (STATCOM) are:

$$v_a = R_f\, i_{ca} + L_f\, pi_{ca} + e_{ab} - R_f\, i_{cb} - L_f\, pi_{cb} \quad (22)$$

$$v_b = R_f\, i_{cb} + L_f\, pi_{cb} + e_{bc} - R_f\, i_{cc} - L_f\, pi_{cc} \quad (23)$$

$$i_{ca} + i_{cb} + i_{cc} = 0 \quad (24)$$

The value of i_{cc} from eqn (24) is substituted into eqn. (23) which results in:

$$v_b = R_f\, i_{cb} + L_f\, pi_{cb} + e_{bc} + R_f\, i_{ca} + L_f\, pi_{ca} + R_f\, i_{cb} + L_f\, p\, i_{cb} \quad (25)$$

Rearranging the eqn. (22) and eqn. (25) results in:

$$L_f\, pi_{ca} - L_f\, pi_{cb} = v_a - e_{ab} - R_f\, i_{ca} + R_f\, i_{cb} \quad (26)$$

$$L_f\, pi_{ca} + 2\, L_f\, pi_{cb} = v_b - e_{bc} - R_f\, i_{ca} - 2\, R_f\, i_{cb} \quad (27)$$

Hence, the STATCOM current derivatives are obtained by solving eqns. (26) and (27) as:

$$pi_{ca} = \{(v_b - e_{bc}) + 2\, (v_a - e_{ab}) - 3\, R_f\, i_{ca}\}/(3L_f) \quad (28)$$

$$pi_{cb} = \{(v_b - e_{bc}) - (v_a - e_{ab}) - 3\, R_f\, i_{cb}\}/(3L_f) \quad (29)$$

3.3 Modeling of SEIG

The dynamic model of the three-phase SEIG is developed a using stationary d-q axes references frame, whose voltage-ampere equations with usual notation are [3]:

$$[v] = [R]\, [i] + [L]\, p\, [i] + w_g\, [G]\, [i] \quad (30)$$

from which, the current derivatives can be expressed as:

$$p[i] = [L]^{\ 1} \{ [v] - [R]\, [i] - w_g\, [G]\, [i] \} \quad (31)$$

where $[v] = [v_{ds}\ v_{qs}\ v_{dr}\ v_{qr}]^T$; $[i] = [i_{ds}\ i_{qs}\ i_{dr}\ i_{qr}]^T$

$[R] = \text{diag}\ [\ R_s\ R_s\ R_r\ R_r]$

$$[L]=\begin{bmatrix} L_{ss} & 0 & L_m & 0 \\ 0 & L_{ss} & 0 & L_m \\ L_m & 0 & L_{rr} & 0 \\ 0 & L_m & 0 & L_{rr} \end{bmatrix} \quad [G]=\begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & -L_m & 0 & L_{rr} \\ L_m & 0 & L_{rr} & 0 \end{bmatrix} \quad (32)$$

Where $L_{ss} = L_{ls} + L_m$ and $L_{rr} = L_{lr} + L_m$

The electromagnetic torque balance equation of the SEIG is defined as:

$$T_{\text{shaft}} = T_e + J\, (2/P)\, p\, w_g \quad (33)$$

The derivative of the rotor speed of the SEIG from eqn. (33) is:

$$pw_g = \{P/(2J)\}\, (T_{\text{shaft}} - T_e) \quad (34)$$

where the developed electromagnetic torque of the SEIG is expressed as [3]:

$$T_e = (3P/4)\, L_m\, (i_{qs}\, i_{dr} - i_{ds}\, i_{qr}) \quad (35)$$

The shaft torque of the prime mover is considered a function of speed as:

$$T_{\text{shaft}} = (k_1 - k_2\, w_g) \quad (36)$$

where T_{shaft} is the shaft torque which is decided by the drooping characteristic of the prime-mover. Constants k_1(3370) and k_2 (10) are fixed for a particular type of prime mover. The SEIG operates in the saturation region and its magenetizing characteristic is non-linear in nature. Therefore, the magnetizing current should be calculated at each step of integration in terms of the stator and the rotor dq axes currents as:

$$I_m = \{(i_{ds} + i_{dr})^2 + (i_{qs} + i_{qr})^2\}^{1/2} / \surd 2 \quad (37)$$

Magnetizing inductance is calculated from the magnetization characteristic expressed using the curve between L_m and I_m. The relation between L_m and I_m is obtained by a synchronous speed test for the SEIG under test [13] and can be written as:

$$L_m = 0.205 + 0.0053 I_m - 0.0023\, I_m^2 + 0.0001 I_m^3 \quad (38)$$

3.4 AC Line Voltage at the Point of Common Coupling

Direct and quadrature axis currents of the SEIG (i_{ds} and i_{qs}) are converted into three-phases (a, b and c). The derivative of the AC terminal voltage of the SEIG is defined as:

$$p\, v_a = \{(i_a - i_{ra} - i_{ca}) - (i_b - i_{rb} - i_{cb})\} / (3\, C) \quad (39)$$

$$p\, v_b = \{(i_a - i_{rc} - i_{ca}) + 2\, (i_b - i_{rb} - i_{cb})\} / (3\, C) \quad (40)$$

$$v_a + v_b + v_c = 0. \quad (41)$$

where i_a, i_b and i_c are the SEIG stator line currents, i_{ra},

i_{rb} and i_{rc} are the 3-phase load line currents and i_{ca}, i_{cb} and i_{cc} are the STATCOM currents. C is the per phase excitation capacitor, which is connected across the SEIG terminals.

3.5 Modeling of Loads

The mathematical modeling of linear and non-linear loads is divided into the following three categories.

3.5.1 Three-phase resistive load

The line currents i_{ra}, i_{rb} and i_{rc} in delta connected loads are obtained as:

$$i_{ra} = (v_a - v_c)/R_L \tag{42}$$

$$i_{rb} = (v_b - v_a)/R_L \tag{43}$$

$$i_{rc} = (v_c - v_b)/R_L \tag{44}$$

3.5.2 Three-phase resistive-inductive load

The derivative of phase currents of the delta connected resistive-inductive loads are defined as:

$$p\ i_{pa}=(v_a-R_L i_{pa})/L_L \tag{45}$$

$$p\ i_{pb}=(v_b-R_L i_{pb})/L_L \tag{46}$$

$$p\ ipc=(vc-RLipc)/LL \tag{47}$$

From these load phase currents, the line currents of this delta connected resistive-inductive load are:

$$i_{ra} = (i_{pa} - i_{pc});\quad i_{rb} = (i_{pb} - i_{pa});\quad i_{rc} = (i_{pc} - i_{pa}); \tag{48}$$

3.5.3 Three-phase rectifier with capacitive filter and resistive load

In a practical uncontrolled diode bridge rectifier, an electrolytic capacitor is used at the DC output for filtering to feed DC load. An uncontrolled diode bridge rectifier has two operating modes: conducting and non-conducting. Small source impedance (R_{sL}, L_{sL}) is considered at the input of the rectifier. When the diodes are in conduction, the line-line voltage of the AC source is connected to the load and the basic DC side equation is given by:

$$v_s = 2\, R_{SL} i_d + 2\, L_{SL} p i_d + v_d \tag{49}$$

In the current derivative form, the above equation can be expressed as:

$$p\ i_d = (v_s - v_d - 2\, R_{SL} i_d) / (2L_{SL}) \tag{50}$$

where v_d and i_d are the diode rectifier output DC voltage and current, voltage v_s is the input line voltage segment which is determined by the conducting diode pair of the rectifier.

The AC load currents in all three phases (i_{ra}, i_{rb} and i_{rc}) of the AC source are calculated by using the magnitude of i_d and the direction (sign) corresponding to the conduction pairs of diodes, which is the same as shown in Table1.

Moreover, the charging/discharging equation of the DC load filter capacitor is expressed as:

$$pv_d = (i_d - i_r) / C_{RL} \tag{51}$$

Where C_{RL} is the load capacitance on the DC side, v_s is the maximum line voltage of the generator (v_a,v_b,v_c, $-v_a$, $-v_b$ and $-v_c$), v_d is the instantaneous voltage across the capacitor and i_r is the resistive load current (v_d /R_{RL}). When neither of the diode pair is conducting then the charged capacitor would discharge through the load resistance (R_{RL}).

Table 1 Three-phase non-linear AC load currents

S. No.	Maximum voltage	i_{ra}	i_{rb}	i_{rc}
1	v_a	i_d	$-i_d$	0
2	$-v_a$	$-i_d$	i_d	0
3	v_b	0	i_d	$-i_d$
4	$-v_b$	0	$-i_d$	i_d
5	v_c	$-i_d$	0	i_d
6	$-v_c$	i_d	0	$-i_d$

3.5.4 Single-phase rectifier with resistive-capacitive load

The single-phase rectifier with capacitive filter and resistive load has two operating modes: conducting and non-conducting. When the diodes are conducting, the AC source is connected to the load and the basic equation is expressed as:

$$v_s = R_{SL} i_d + L_{SL} p i_d + v_d \tag{52}$$

In the current derivative form, the above equation can be expressed as:

$$p\ i_d = (v_s - v_d - R_{SL} i_d) / (L_{SL}) \tag{53}$$

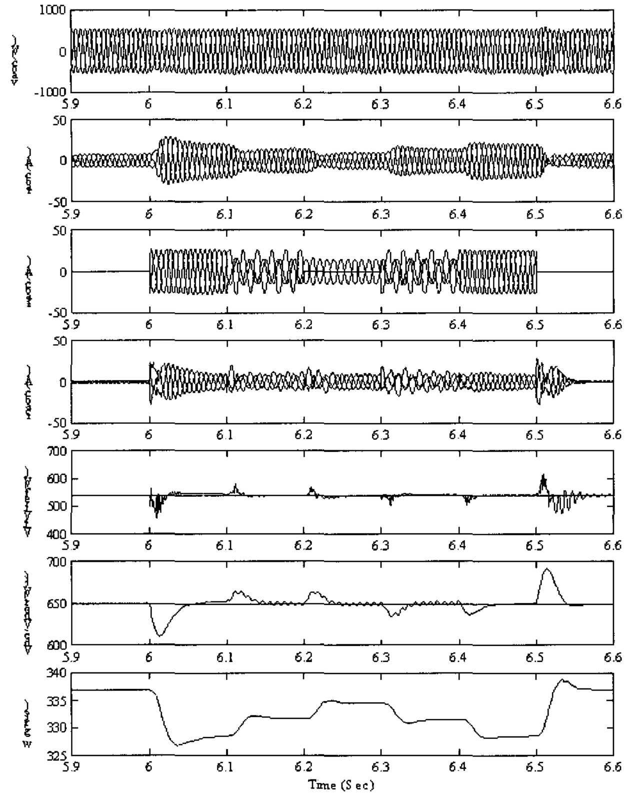


Fig. 2 Transient waveforms of three-phase SEIG-STATCOM system supplying resistive load at no-load to 3-ph(15kW) to 2-ph(10kW) to 1-ph(5kW)to 2-ph(10kW) to 3-ph(15kW) to no load

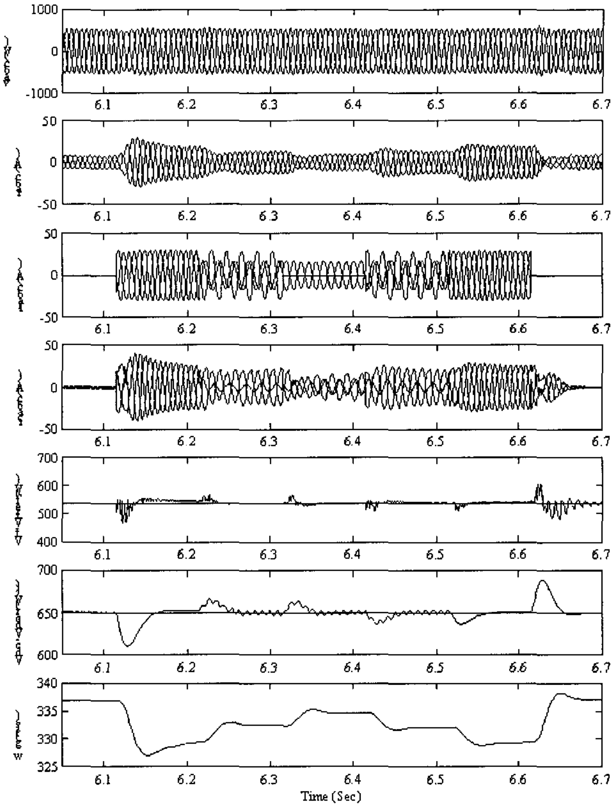


Fig. 3 Transient waveforms of three-phase SEIG-STATCOM system supplying lagging(0.8) pf load at no-load to 3-ph(15kW) to 2-ph(10kW) to 1-ph(5kW) to 2-ph(10kW) to 3-ph(15kW) to load

and the charging /discharging equation of the DC load filter capacitor is:

$$pv_d = (i_d - i_r) / C_{RL} \qquad (54)$$

When neither of the diode pair is conducting then the charged capacitor would discharge through the load resistance (R_{RL}). The rectifier AC currents will be the same as mentioned in Table 1 and they will be zero in the non-conducting phase.

4. Results and Discussion

The SEIG-STATCOM system feeding linear/non-linear and balanced/unbalanced loads are simulated and results are shown in Figs. 2-6. For this study, a 15 kW, 381/440V, 30A, 4-pole machine was used as a generator and the parameters of the generator are given in the Appendix.

4.1 Performance of SEIG-STATCOM System Feeding Resistive Loads

A resistive load is considered to be a linear load. Fig. 2 shows the transient waveforms of the 3-phase generator voltages (v_{abc}), generator currents (i_{abc}), three-phase load currents (i_{ra}, i_{rb} and i_{rc}), three-phase STATCOM currents (i_{ca}, i_{cb} and i_{cc}), the amplitude of the SEIG terminal voltage and its reference value (V_t-V_{tref}), the DC bus voltage and its reference value (V_{dc}- V_{dcref}) and the generator speed (w_g). It demonstrates the response of the STATCOM for regulating the SEIG terminal voltage while a pure resistive load is being applied. At 0.6 sec a three-phase 15 kW resistive load is switched on. A dip in the prime mover speed of the SEIG is observed at the sudden application of the 15 kW load due to the drooping characteristic of the prime mover. A small dip in the DC bus voltage of STATCOM is also observed, but it recovers quickly due to the corrective action of the PI controller. At 6.1-sec.

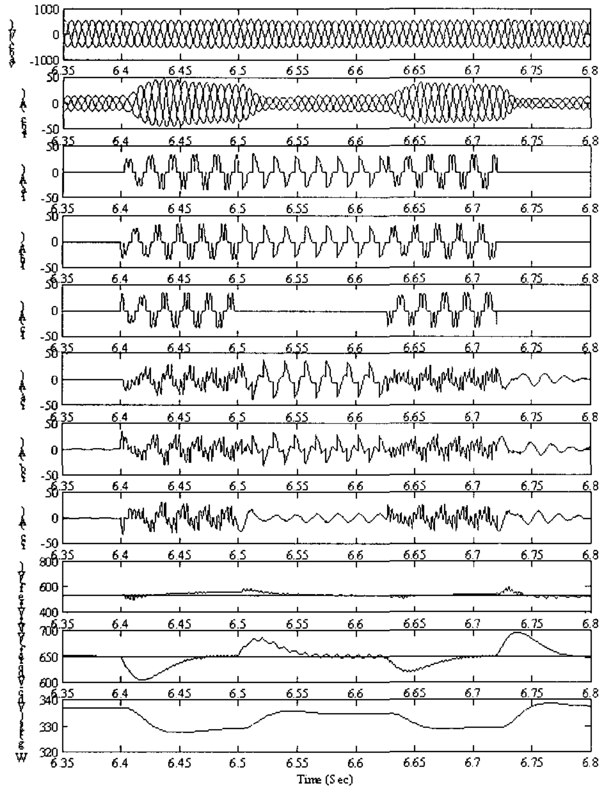


Fig. 4 Transient waveforms of three-phase SEIG-STATCOM system supplying non-linear load at no-load to 3-ph(15kW) to 1-ph(5.8kW) to 3-ph to no load

Table 2 Generator voltage and current and load current THD under three-phase and single-phase loads

Type of Load	Generator Voltage	Generator Current	Load Current
Three-phase R load	0.167%	0.084%	0.05%
Single-phase R load	0.375%	0.433%	0.143%
Three-phase R-L load	0.285%	0.151%	0.10%
Single-phase R-L load	0.336%	1.09%	0.11%
Three-phase rectifier load	0.185%	0.197%	56.37%
Single-phase rectifier load	0.80%	1.024%	51.81%

one-phase of the load is disconnected from the generator and the generated power is reduced to 10 kW. It is observed that the STATCOM is able to regulate the SEIG terminal without any surge. At 6.2-sec. two phases of the load are disconnected from the generator (resulting in only 5kW generated power). When the load phases are disconnected from the generator, its currents decrease to show the lesser burden on the SEIG. At 6.3-sec. one-phase of the load is connected to the SEIG-STATCOM system and at 6.4-sec. the second phase of the load is connected. At 6.5-sec the three-phase load is disconnected from the SEIG-STATCOM system. An over-shoot and an under-shoot in the DC bus voltage are observed, respectively, at the disconnecting and connecting of the load. Charging and discharging of the DC bus capacitor of the STATCOM is clearly observed when the load is unbalanced. This shows the load balancing aspect of the STATCOM. The total harmonic distortion (THD) of the generator voltage and current, as shown in Table 2, is below 5% for both a three-phase and even a single-phase (severely unbalanced) resistive load.

4.2 Performance of SEIG-STATCOM System Feeding Resistive-inductive Loads

A resistive-inductive load is considered to be another linear load. Fig.3 shows the transient waveforms of a three-phase SEIG-STATCOM system supplying lagging pf (0.8) load. The three-phase generator voltages (v_{abc}), generator currents (i_{abc}), three-phase load currents (i_{rabc}), three-phase STATCOM currents (i_{cabc}), amplitude of the SEIG terminal voltage and its reference value (V_t-V_{tref}), the DC bus voltage and its reference value (V_{dc}-V_{dcref}) and the generator speed (w_g) are illustrated in the figure to show the voltage regulation and load balancing concept. At 6.115-sec. a three-phase lagging pf load of 15 kW is applied resulting in increased generator currents, load currents, and STATCOM currents due to supplying active and reactive power to the load. At 6.215-sec. one-phase of the load is disconnected from the generator and at 6.315-sec. the second phase is disconnected; the generated power is reduced to 10 kW and 5 kW, respectively. The total harmonic distortion (THD) of the generator voltage and current for the three-phase balanced case and the single-phase unbalanced case is mentioned in Table 2 and it is observed that the THD is less than 5%. At 6.415-sec. one phase of the load is reconnected and at 6.515-sec. the second phase is reconnected. At 6.615-sec. the total three-phase load is removed from the SEIG terminals. It is

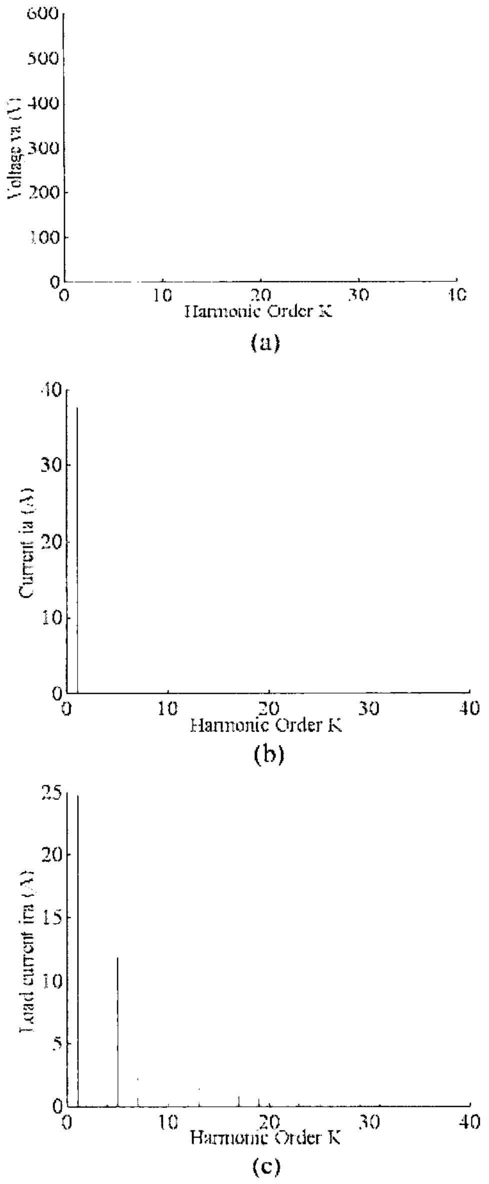


Fig. 5 Harm onic spectrum of generator voltage, cureent and three-phase nonlinear load current

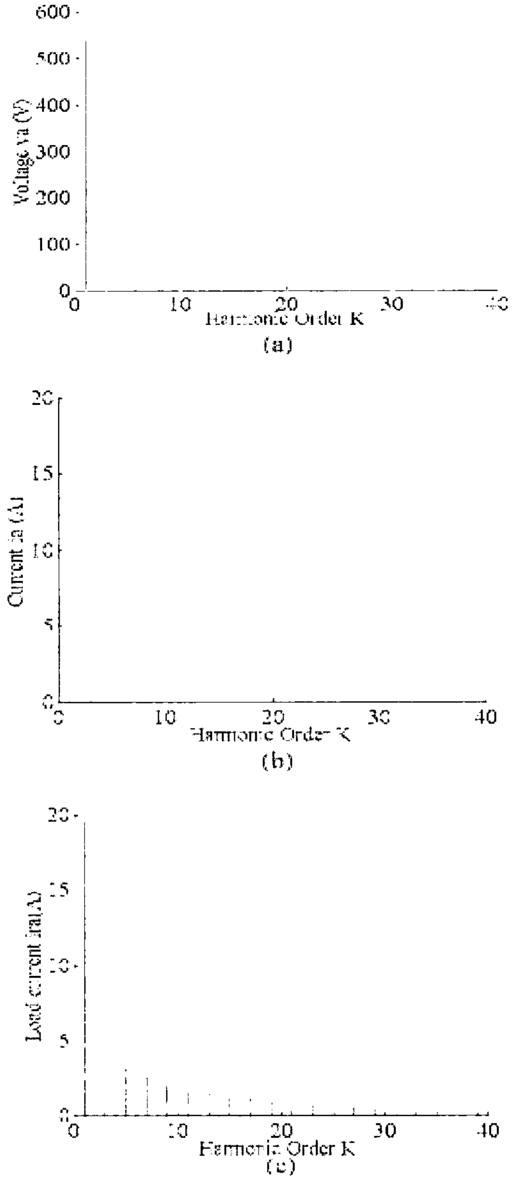


Fig. 6 Harm onic spectrum of generator voltage, cureent and single-phase nonlinear load current

observed that the generator voltage remains constant under balanced and even unbalanced lagging pf loads. Variations in generator speed are observed with the change in load due to the drooping characteristic of the prime mover.

4.3 Performance of SEIG-STATCOM Feeding Non-Linear load

Three-phase and single-phase rectifiers with capacitive filter and resistive load are considered as non-linear loads. Fig.4 shows the transient waveforms of all the performance quantities of the three-phase SEIG-STATCOM system supplying three-phase rectifier with capacitive filter and DC load. At 6.4 sec it is changed to a single-phase rectifier load. In the case of a single-phase rectifier, due to the DC link capacitor of the rectifier, the AC current of the rectifier is highly discontinuous. The discontinuous AC current injects harmonics into the system. The STATCOM eliminates harmonics so that the generator voltages and currents are free from harmonics as can be observed from Figs. 5-6 and Table-2. Figs. 5a, 5b and 5c show the harmonic spectrum of the generator voltage, current and load current, respectively, under a three-phase rectifier load. Fig. 6a, Fig. 6b and Fig. 6c show the harmonic spectrum of the generator voltage, current and load current under a single-phase rectifier load. It is observed from the harmonic spectrum shown in Figs. 5-6 and Table-2 that the THD in the generator voltage and current is less than 5% in spite of the 52% THD of the rectifier load current. The generator voltage and current remain constant and sinusoidal under three-phase and single-phase rectifier loads. Therefore, in this case, STATCOM is acting as a voltage regulator, load balancer and harmonic eliminator. Under the single-phase rectifier load, the generator speed of the SEIG is higher, which shows the light load on the generator.

5. Conclusion

It is observed that the developed dynamic model of the three-phase SEIG–STATCOM is capable of simulating its performance while feeding linear/non-linear, balanced / unbalanced loads under transient conditions. From these results, it is found that the SEIG terminal voltage remains constant and sinusoidal under a three-phase or a single-phase rectifier load. When a single-phase rectifier load is connected, the STATCOM balances these unbalanced load currents so that the generator currents and voltages remain sinusoidal, balanced and constant and, thus, STATCOM acts as a load balancer. A rectifier based non-linear load generates harmonics, which are also eliminated by STATCOM. Therefore, it is concluded that the STATCOM acts as a voltage regulator, a load balancer and a harmonic eliminator. Although different aspects of uncontrolled rectifiers have been modeled as non-linear loads here, the developed model can easily be modified to simulate a compensating controlled rectifier as a non-linear load.

Appendices

1) STATCOM Control Parameters

L_f= 1.2 mH, R_f = 0.045 Ω and C_{dc} = 4000μF.

AC voltage PI controller: K_{pa} =0.05, K_{ia} = 0.04.

DC bus voltage PI controller K_{pd} = 0.7, K_{id} =0.1

Carrier frequency = 20 kHz

2) Parameters of Rectifier Load

Three-phase rectifier L_{SL}=0.1mH, R_{SL} = 1 Ω, R_{RL} = 22 Ω, and C_{RL} = 470μF.

Single-phase rectifier L_{SL}=0.1mH, R_{SL} = 1 Ω, R_{RL}=75 Ω and C_{RL}=150μF

3) Machine Parameters

The parameters of the 15 kW, 381/440V, 30A, 50 Hz, 4-pole induction machine are given below.

R_s = 0.69 Ω, R_r = 0.74Ω, L_{ls} = L_{lr} = 1.1 mH, J = 0.23 kg/m^2, L_{ss} = L_{ls} + L_m and L_{rr} = L_{lr} + L_m.

4) Terminal capacitor

C = 57 μF/ phase

References

[1] S. S. Murthy, O. P. Malik and A. K. Tandon, “Analysis of self-excited induction generator,” IEE Proc., Vol. 129, Pt. C, No. 6, pp. 260-265, November 1982.

[2] S. S. Murthy, Bhim Singh, Sushma Gupta and B. M. Gulati, “General steady state analysis of three-phase self-excited induction generator feeding three-phase unbalanced load/single-phase load for stand-alone applications,” IEE Proc.-Gener. Transm. Distrib., Vol. 150, No. 1, pp. 49-55, January 2003.

[3] C. Grantham, D. Sutanto and B. Mismail, “Steady state and transient analysis of self-excited induction generator,” IEE Proc., Vol. 136, Pt. B. No. 2, pp. 61-68, March 1989.

[4] K. E. Hallenius, P. Vas and J. E. Brown, “The analysis of saturated self-excited asynchronous generator,” IEEE Trans. on Energy Conversion, Vol. 6, No. 2, pp. 336-341, June 1991.

[5] M. H. Salama and P. G. Holmes, “Transient and steady-state load performance of a stand-alone self-excited induction generator,” IEE Proc. Electr. Power Appl. Vol. 143, No. 1, pp. 50-58, January 1996.

[6] L. Wang and R. Y. Deng, "Transient performance of an isolated induction generator under unbalanced excitation capacitors," IEEE Trans. on Energy Conversion, Vol. 14, No. 4, pp. 887-893, Dec. 1999.

[7] S. K. Jain, J. D. Sharma and S. P. Singh, “Transient performance of three-phase self-excited induction generator during balanced and unbalanced faults,” IEE Proc. Gener. Transm. Distrib., Vol. 149, No. 1, pp. 50-57, January 2002.

[8] M. B. Brennen and A. Abbondati, "Static exciter for induction generator," IEEE Trans. on Industry Applications, Vol. 13, No. 5, pp. 422-428, 1977.

[9] R. K. Mishra, Bhim Singh and M. K. Vasantha, "Voltage regulator for an isolated self-excited cage induction generator," Electric Power System Research, Vol. 24, No. 1, pp. 75-83, July 1992.

[10] L. Shridhar, Bhim Singh and C. S. Jha, "Transient analysis of the self regulated short shunt self excited induction generator," IEEE Trans. on Energy Conversion, Vol. 10, No. 2, pp. 261-267, June 1995.

[11] E. Larsen, N. Miller, S. Nilsson and S. Lindgren, "Benefits of GTO-based compensation systems for electric utility applications," IEEE Trans. on Power Delivery, Vol. 7, No. 4, pp. 2055-2064, October 1997.

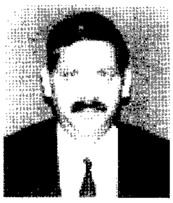
[12] C. Schauder and H. Mehta, "Vector analysis and control of advanced static VAR compensator," IEE Proc.-C, Vol. 140, No. 4, pp.299-306, July 1993.

[13] Bhim Singh and L. B. Shilpakar, "Analysis of a novel solid state voltage regulator for a self-excited induction generator," IEE Proc. Gener. Transm. Distrib., Vol. 145, No. 6, pp. 647-655, November 1998.

[14] M. S. Miranda, R. O. C. Lyra and S. R. Silva, "An alternative isolated wind electric pumping system using induction machines," IEEE Trans. on Energy Conversion, Vol. 14, No. 4, pp. 1611-1616, December 1999

[15] S. C. Kuo and L. Wang, "Analysis of voltage control for a self-excited induction generator using a current-controlled voltage source inverter (CC-VSI)," IEE Proc. Gener. Transm. Distrib., Vol. 148, No. 5, pp. 431-438, September 2001.

[16] S. C. Kuo and L. Wang, "Analysis of isolated self-excited induction generator feeding a rectifier load," IEE Proc. Gener. Transm. Distrib., Vol. 149, No. 1, pp. 90-97, January 2002.



Bhim Singh was born in Rahamapur, U. P., India in 1956. He received B. E. (Electrical) degree from the University of Roorkee, India in 1977 and M. Tech. and Ph. D. degrees from the Indian Institute of technology (IIT), New Delhi, in 1979 and 1983, respectively. In 1983, he joined as a Lecturer and in 1988 became a Reader in the Department of Electrical Engineering, University of Roorkee. In December 1990, he joined as an Assistant Professor, became an Associate Professor in 1994 and full Professor in 1997 at the Department of Electrical Engineering, IIT Delhi. His field of interest includes power electronics, electrical machines and drives, active filters, static VAR compensator, analysis and digital control of electrical machines. Prof. Singh is a Fellow of Indian National Academy of Engineering (INAE), Institution of Engineers (India) (IE (I)) and Institution of Electronics and Telecommunication Engineers (IETE), a Life Member of Indian Society for Technical Education (ISTE), System Society of India (SSI) and National Institution of Quality and Reliability (NIQR) and Senior Member IEEE (Institution of Electrical and Electronics Engineers).

S.S. Murthy was born in Karnataka, India, in 1946. He received his B.E, M.Tech. and Ph.D.degrees respectively from Bangalore University, Indian Institute of Technology (IIT)Bombay, and IIT Delhi.

He has been with IIT Delhi since 1970 and was the Chairman of the Department of Electrical Engineering from 1998-2001. He has held assignment in University of New castle, UK, University of Calgary Canada, ERDA Barodra and Kirloskar Electric, Banglore. He holds 4 patents on the SEIG, Micro Hydel Applications and a novel-braking scheme. He has also transferred technology of self-excited and grid connected induction generators to industry for low-and medium-power generation under standalone or grid connected mode. He has completed several industry sponsored research and constancy projects dealing with electrical machines, drives, and energy systems. Recently, he was instrumental in establishing start-of-the-art energy audit and energy conservation facilities at IIT under World Bank funding. His areas of interest include electric machines, drives, special machines, power electronic applications, renewable energy systems, energy efficiency and conservation.

Dr. Murthy has received many awards notable being-ISTE/Maharashtra Govt. Award for outstanding research and IETE/Bimal Bose Award for contribution in Power Electronics. He has made significant contributions to professional societies, including being General Chair of the 1st IEEE International Conference on Power Electronics, Drive and Energy Systems (PEDES' 96) held in January 1996 in New Delhi. He is a Senior Member of IEEE, Fellow of IEE Life Fellow of the Institution of Engineers (India), and Life Member of ISTE.

Sushma Gupta was born in Lalitpur, U. P., India in 1971. She received the B. E. degree in 1993 and M. E. in 1999 from Barakatullah University Bhopal. She was Lecturer in Electronic Engineering Department at Government Engineering College, Rewa, M. P. India. She is a currently Research Scholar in Electrical Engineering Department in Indian Institute of Technology, Delhi India. Her main research interests are power electronics, machines, digital electronics microprocessor and self excited induction generator.