Power Quality Enhancement Using VSI Based STATCOM for SEIG Feeding Non Linear Loads

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***Abstract*— This paper deals with the performance analysis of static compensator (STATCOM) based voltage regulator for self- excited induction generators (SEIGs) feeding non-linear single phase loads. 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 compensate the unbalanced current caused by single-phase loads that are connected across the two terminals of the three-phase SEIG under varying loads has been analyzed by using D-Q frame theory algorithm. This enables us to predict the behavior of the system under transient conditions. The simulated results shows that by using a STATCOM based voltage regulator the SEIG can balance the current; in addition to that the STATCOM is able to regulate the terminal voltage of the generator and suppresses the harmonic currents injected by non- linear loads.**

***Index Terms*—Self-excited induction generator (SEIG), single- phase synchronous D-Q frame theory, static synchronous compensator (STATCOM).**

I. Introduction

Distributed power generation has become a topic of interest in recent years to supply power to remote, rural and isolated regions. Need for standby power is also increasing rapidly due to unreliable utility supplies. Heavy distribution losses and investment in transmission lines compel one to seek autonomous power generation. Depletion of fossil fuels has turned our attention towards renewable energy sources. For power generation wind, small hydro and biomass are attractive options. Since they are exceptionally to be located in isolated regions, the technology must be simple, rugged and easy to maintain and operate. Suitable energy conversion system has to be developed for such applications. On the electrical side the generator and controller have to be appropriately chosen to meet the customer needs. Self-excited induction generator (SEIG) has been shown advantages for such applications. Such three-phase generators would often feed unbalanced loads due to the very nature of distributed load arrangement dictated by location of consumers. Engine and hydro turbine driven SEIG needs to have suitable controllers to satisfy proper power quality at consumer end. At varying loads, reactive power requirement has to change to provide the required voltage at the given prime mover speed and load pf. The unbalanced loads would pose additional problem on the design of controller that should not only provide needed VAR but also maintain the generator output voltage and current under balance in spite of unbalanced load. This paper addresses this issue and suggests a viable STATCOM based controller. The other suggested controllers in literature like switched capacitor, thyristor controlled inductor , saturable core reactor , and series capacitor do not meet such requirements. With rapid advances in power electronics and signal processing, static compensator (STATCOM) can be an attractive reactive power controller. While use of STATCOM for power systems and for self excited induction generator has been already reported under balanced condition, its applicability to SEIG under unbalanced conditions has not been explored.

An alternative method of feeding single-phase loads using a three-phase SEIG without de-rating the machine is proposed. In this method, a three-phase SEIG works in conjunction with a three-phase STATCOM and the single-phase loads are connected across two of the three terminals of the SEIG. The benefit of integrating a STATCOM in an SEIG based standalone power generation feeding single-phase loads is threefold—generator currents balancing; voltage regulation; and mitigates the harmonics injected by nonlinear loads. The STATCOM injects compensating currents to make the SEIG currents balanced and regulates the system voltage as well. Moreover, this method offers balanced voltages across the generator windings and ensures the sinusoidal winding currents while feeding nonlinear loads.

II. System Configuration and Principle of Operation

Fig. 1 shows the schematic diagram of the STATCOM-compensated three-phase SEIG feeding single-phase loads. The system consists of an SEIG driven by renewable energy-based prime mover. The single-phase consumer loads are connected across "*a*" and "*c*" phases of the SEIG. A two-level, three-leg insulated-gate bipolar transistor (IGBT)-based VSI with a self- sustaining dc-bus capacitor is used as a STATCOM. The STAT- COM is connected at point of common coupling (PCC) through filter inductors as shown in Fig. 1. The STATCOM regulates the system voltage by maintaining equilibrium among the reactive power circulations within the system. Moreover, the

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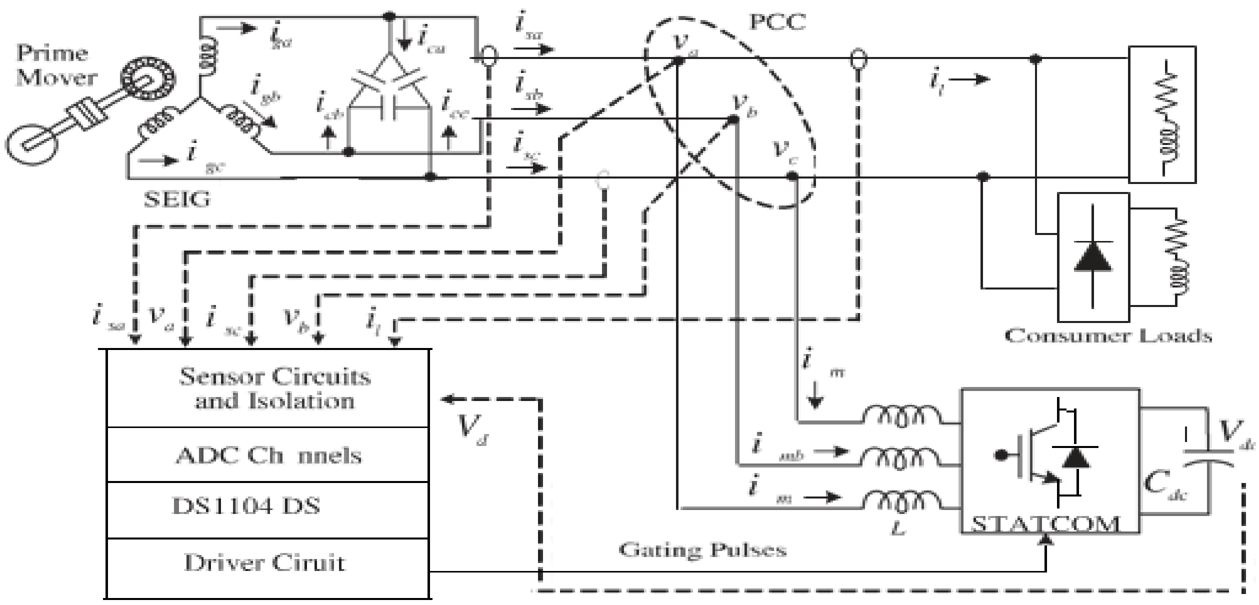

Fig. 1. Schematic diagram of the SEIG–STATCOM system feeding single-phase loads.

STATCOM suppresses harmonics injected by nonlinear loads and provides load balancing while feeding single-phase loads.

The unbalanced load currents in a three-phase system can be divided into two sets of balanced currents known as positive sequence components and negative sequence components. In order to achieve balanced source currents, the source should be free from the negative sequence components of load currents. Therefore, when the STATCOM is connected across PCC, it sup- plies the negative sequence currents needed by the unbalanced load or it draws another set of negative sequence currents which are exactly 180◦ out of phase to those drawn by unbalanced load so as to nullify the effect of negative sequence currents of unbalanced loads.

III. Control Algorithm of the STATCOM

Fig. 2 shows the block diagram of the proposed single-phase synchronous D-Q frame theory-based control algorithm for the three-phase STATCOM. The reference source currents (i^*_{sa} , i^*_{sb} , i^*_{sc}), for regulating the terminal voltage and current balancing are computed using a single-phase synchronous D-Q frame theory applied to the three-phase SEIG system.

A. *Single-Phase Synchronous Rotating D-Q Frame Theory*

It is simple to design a controller for a three-phase system in synchronously rotating D-Q frame because all the time-varying signals of the system become dc quantities and time-invariant. In case of a three-phase system, initially, the three-phase voltages or currents (in *abc* frame) are transformed to a stationary frame($\alpha-\beta$) and then to synchronously rotating D-Q frame. Similarly, to transform

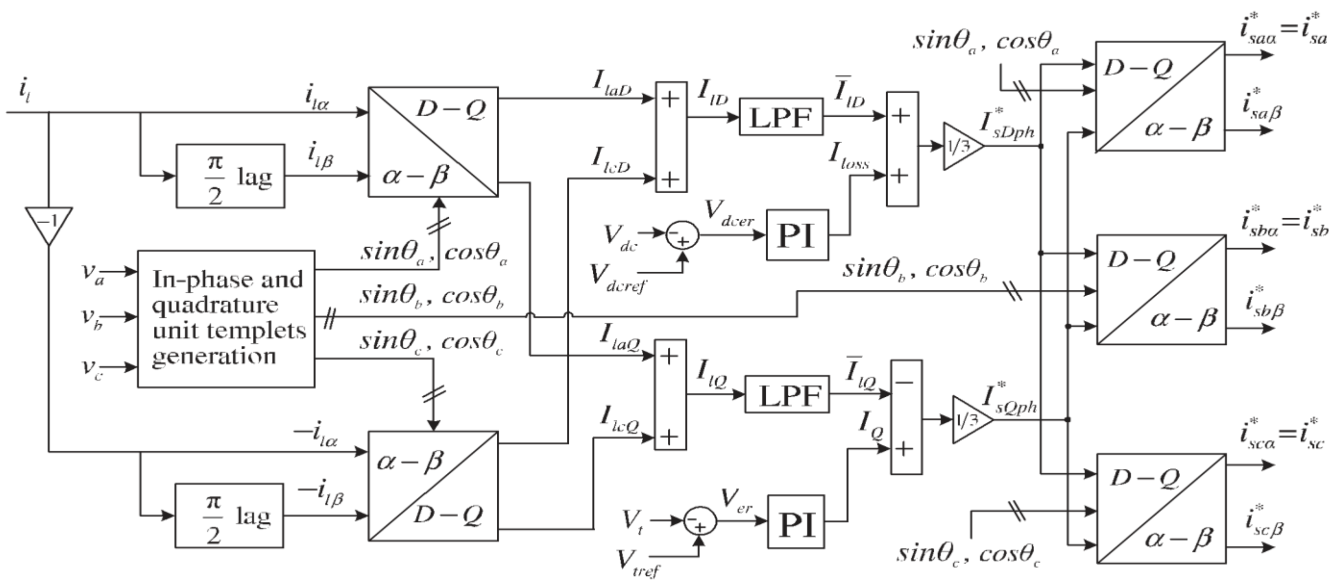

Fig. 2. Block diagram of the single-phase synchronous D-Q theory control algorithm for the STATCOM.

an arbitrary signal "$x(t)$" of a single-phase system into a synchronously rotating D-Q frame, initially that variable is transformed into a stationary $\alpha-\beta$ frame using the single-phase p-q theory and then to a synchronously rotating D-Q frame. Therefore, to transform a signal into a stationary $\alpha-\beta$ frame, at least two phases are needed. Hence, a pseudo second phase for the arbitrary signal $x(t)$ is created by giving 90° lag to the original signal. The original signal represents the component of α-axis and 90° lag signal is the β-axis component of stationary reference frame. Therefore, an arbitrary periodic signal $x(t)$ with a time period of "T" can be represented in a stationary $\alpha-\beta$ frame as

$$x_\alpha(t) = x(t); x_\beta(t) = x\ t\text{-}(T/4) \quad \text{-------}(1)$$

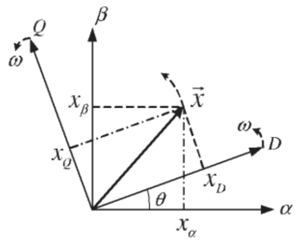

Fig. 3. Stationary $\alpha-\beta$ frame and synchronously rotating D-Q frame repre- sentation of vector $x(t)$.

For a single-phase system, the concept of the stationary $\alpha-\beta$ frame and synchronously rotating D-Q frames relative to an arbitrary periodic signal $x(t)$ is illustrated in Fig. 3. The signal $x(t)$ is represented as vector x, and the vector x can be decomposed into two components x_α and x_β. As the x vector rotates around the center, its components x_α and x_β which are the projections on the α- β axes vary in time accordingly. Now, considering that there are synchronously rotating D-Q coordinates that rotate with the same angular frequency and direction as x, then the position of x with respect to its components x_D and x_Q is same regardless of time. Therefore, it is clear that the x_D and x_Q do not vary with time and only depend on the magnitude of x and its relative phase with respect to the D-Q rotating frame. The angle θ is the rotating angle of the D-Q frame and it is defined as

$$\theta = {}_0\int^t \omega dt \text{ ------ } (2)$$

where ω is the angular frequency of the arbitrary variable x. The relationship between stationary and synchronous rotating frames can be derived from Fig. 3. The components of the arbitrary single-phase variable $x(t)$ in the stationary reference frame are transformed into the synchronously rotating D-Q frame using the transformation matrix "C" as

$$\begin{pmatrix} x_D \\ x_Q \end{pmatrix} = C \begin{pmatrix} x_\alpha \\ x_\beta \end{pmatrix} \text{ -------- } (3)$$

Where

$$C = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \text{ ----------- } (4)$$

B. reference source currents estimation using single-phase synchronous rotating d-q frame theory

The main objective of employing a three-phase STATCOM in three-phase SEIG-based standalone power generating system feeding single-phase consumer loads is to balance the generator currents so that the generator can be loaded to its full capacity without de-rating. The control structure of the STATCOM employs an ac voltage PI controller to regulate the system voltage and a dc bus voltage PI controller to maintain the dc bus capacitor voltage constant and greater than the peak value of the line voltage of PCC for successful operation of the STATCOM. The PCC voltages (v_a , v_b , v_c), source currents (i_{sa} , i_{sb} , i_{sc}), load current (i_l), and dc bus voltage (V_{dc}) are sensed and used as feedback signals. Considering PCC voltages as balanced and sinusoidal, the amplitude of the PCC voltage (or system voltage) is estimated as

$$V = \sqrt{\left(\frac{2}{3}\right)(v_a^2 + v_b^2 + v_c^2)} \text{ ------------- } (5)$$

Consider one of the three phases at a time and then trans- form the voltages and currents of that particular phase into a stationary $\alpha-\beta$ frame, then the PCC voltages and load current in stationary $\alpha-\beta$ frame are represented as

$$v_{a\alpha}(t) = v_a(t);\ v_{b\alpha}(t) = v_b(t);\ v_{c\alpha}(t) = v_c(t) \text{ ----- } (6)$$

$$v_{a\beta}(t) = v_a\ (t\text{-}(T/4)) \text{ ---------------------- } (6a)$$

$$v_{b\beta}(t) = v_b\ (t\text{- }(T/4)) \text{ ---------------------- } (6b)$$

$$v_{c\beta}(t) = v_c\ (t\text{- }(T/4)) \text{ -------------------- } (6c)$$

$$i_{l\alpha}(t) = i_l(t);\quad i_{l\beta}(t) = i_l\ (t\text{- }(T/4)) \text{ ------ } (7)$$

The sinusoidal signal filters based on a second-order generalized integrator or a sinusoidal signal integrator (SSI) can be used for creating β-axis signals which are lagging the original signals. In the present investigation, a filter based on SSI is used. The SSI filters generate quadrature signals using system frequency information. Since the system frequency fluctuates under load perturbations, a PLL is used to continuously estimate the system frequency, and the estimated frequency is fed to SSI filters which makes the proposed control adaptive to frequency fluctuations, thereby avoids the loss of synchronization of the STATCOM.

Now consider a synchronously rotating D-Q frame for phase "a" which is rotating in the same direction as $v_a(t)$, and the projections of the load current $i_l(t)$ to the D-Q axes give the D and Q components of the load current. Therefore, the D-axis and Q-axis components of the load current in phase "a" are estimated as

$$\begin{pmatrix} I_{l\alpha D} \\ I_{l\alpha Q} \end{pmatrix} = \begin{pmatrix} \cos\theta_\alpha & \sin\theta_\alpha \\ -\sin\theta_\alpha & \cos\theta_\alpha \end{pmatrix} \begin{pmatrix} I_{l\alpha} \\ I_{l\beta} \end{pmatrix} \text{ ---------- } (8)$$

where $\cos\theta a$ and $\sin\theta a$ are estimated using $va\alpha$ and $va\beta$ as follows:

$$\begin{pmatrix} \cos\theta_\alpha \\ \sin\theta_\alpha \end{pmatrix} = \frac{1}{\sqrt{v_{a\alpha}^2 + v_{a\beta}^2}} \begin{pmatrix} v_{a\alpha} \\ v_{a\beta} \end{pmatrix} \text{------------------- } (9)$$

Ila D represents the active power component of the load current as the signals belong to the same axis are multiplied and added to estimate the D-axis component, whereas *Ila Q* represents the reactive power component of the load current as the orthogonal signals are multiplied and added to derive the Q-axis component.

Similarly, the D-axis and Q-axis components of the load current in phase "c" are estimated as

$$\begin{pmatrix} I_{l\alpha D} \\ I_{l\alpha Q} \end{pmatrix} = \begin{pmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{pmatrix} \begin{pmatrix} -I_{l\alpha} \\ -I_{l\beta} \end{pmatrix} \text{-------- (10)}$$

The negative sign of currents in eq(10) indicates that the load current in phase "*c*" is equal to phase "*a*" but 180◦ out of phase. As the single-phase load is connected across the phases "*a*" and "*c*," D-axis and Q-axis components for phase "*b*" are not estimated.

The D-axis components of the load current in phases "*a*" and "*c*" are added together to obtain an equivalent D-axis current component of total load on the SEIG as

$$IlD = Ila\ D + Ilc\ D \quad \text{--------------------------} \quad (11)$$

Similarly, an equivalent Q-axis current component of total load on the system is estimated as

$$IlQ = Ila\ Q + Ilc\ Q \quad \text{----------------------------} \quad (12)$$

The equivalent D-axis and Q-axis current components of total load are decomposed into two parts namely fundamental and oscillatory parts as

$$I_{lD} = \overline{I_{lD}} + \widetilde{I_{lD}} \text{--------(13)}$$

$$I_{lQ} = \overline{I_{lQ}} + \widetilde{I_{lQ}} \text{-------(14)}$$

The reason for the existence of the oscillatory part is due to the nonlinear and single-phase nature of connected loads in the system. Even if the connected loads are linear in nature,
The reason for the existence of the oscillatory part is due to the nonlinear and single-phase nature of connected loads in the system. Even if the connected loads are linear in nature,

single-phase loads. To ensure the power quality, the reference D-axis and Q-axis components of source currents must be free from these oscillatory components.

To maintain the dc-bus capacitor voltage of the STATCOM at a reference value, it is sensed and compared with the reference Hence, the signals I_{lD} and I_{lQ} are passed through low-pass filters (LPFs) to extract the fundamental (or dc) components as shown in Fig. 2. value and then the obtained voltage error is processed through a PI controller. The dc-bus voltage error of the STATCOM V_{dcer} at k^{th} sampling instant is expressed as

$$V_{\mathrm{dcer}}(k) = V_{\mathrm{dcref}}(k) - V_{\mathrm{dc}}(k) \text{-------} \quad (15)$$

where $V_{\mathrm{dc\ re\ f}}(k)$ and $V_{\mathrm{dc}}(k)$ are the reference and sensed dc-bus voltages of the STATCOM at k^{th} sampling instant, respectively. In the present investigation, the dc-bus voltage reference is set to 400 V.

The output of the PI controller for maintaining a constant dc bus voltage of the STATCOM at *k*th sampling instant is expressed as

$$Iloss\ (k) = Iloss\ (k-1) + Kpd\ \{Vd\ cer\ (k) + Vd\ cer\ (k-1)\} + Kid\ Vd\ cer\ (k) \text{-------} (16)$$

The output of the PI controller for maintaining the PCC voltage at the reference value in *k*th sampling instant is expressed as

$$I_Q(k) = I_Q(k-1) + K_{pa}\{V_{er}(k) + V_{er}(k-1)\} + K_{ia} V_{er}(k) \text{ --(17)}$$

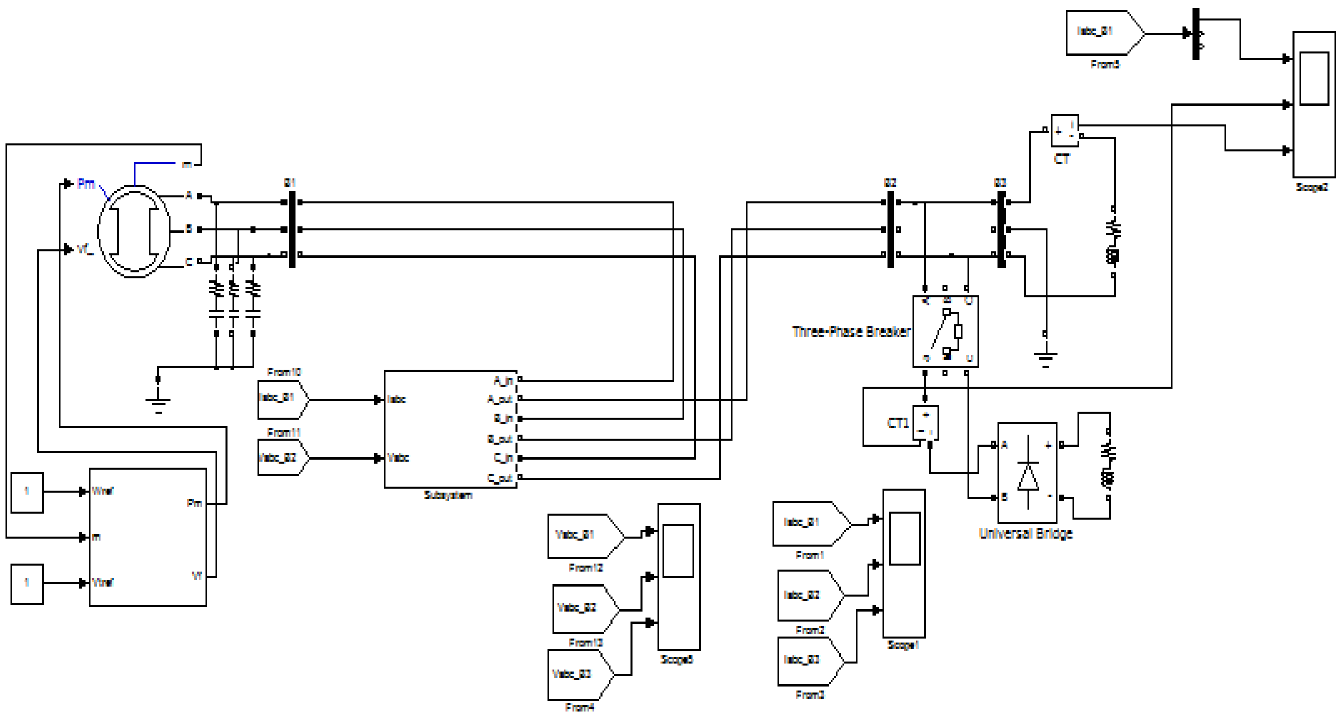

Fig – 4 : simulation implementation of SEIG-STATCOM feeding single phase load

the D and Q components estimated in (12) and (13) would still contain oscillatory parts due to the unbalance caused by

where K_{pa} and K_{ia} are the proportional and integral gain con- stants of the PI controller, $V_{er}(k)$ and $V_{er}(k-1)$ are the voltage errors at *k*th and $(k-1)$th instants, respectively. $IQ(k)$ is the equivalent Q-axis component (or reactive power component) of the current to be supplied by the STATCOM to meet the reac- tive power requirements of both the load and SEIG, thereby it maintains the PCC voltage at the reference value.

The per phase Q-axis component of the reference source current required to regulate the system voltage is defined as

$$I^*_{sQph} = \frac{I_Q}{3} + \frac{\overline{I_{lQ}}}{3} \quad \text{-------(18)}$$

I^*_{sQph} indicates the magnitude of the reactive power component of the current that should be supplied to each phase of the source (i.e., SEIG) to achieve the reference terminal voltage. The value of I^*_{sQph} can be either positive or negative based on loading conditions. Using the D-axis and Q-axis components of currents derived in (18), the phase "*a*," *α*- axis and *β*-axis components of the reference source current can be estimated as

$$\begin{pmatrix} i^*_{sa\alpha} \\ i^*_{sa\beta} \end{pmatrix} = \begin{pmatrix} \cos\theta_a & \sin\theta_a \\ -\sin\theta_a & \cos\theta_a \end{pmatrix} \begin{pmatrix} -I^*_{sDph} \\ -I^*_{sQph} \end{pmatrix} \text{-------(19)}$$

In the above matrix, the *α*-axis current represents the reference source current of actual phase "*a*," and the *β*-axis current rep resents the current that is at *π*/2 phase lag which belongs to the fictitious phase.

Therefore, one can have

$$i^*_{sa} = I^*_{sDph} \cos\theta_a - I^*_{sQph} \sin\theta_a \quad \text{------- (20)}$$

Similarly, reference source currents for phases "*b*" and "*c*" are estimated as

$$i^*_{sb} = I^*_{sDph} \cos\theta_b - I^*_{sQph} \sin\theta_b \quad \text{--------- (21)}$$

$$i^*_{sc} = I^*_{sDph} \cos\theta_c - I^*_{sQph} \sin\theta_c \quad \text{-------- (22)}$$

Three-phase reference source currents (i^*_{sa}, i^*_{sb} , i^*_{sc}) are compared with the sensed source current (i_{sa} , i_{sb} , i_{sc}) and the current errors aer computed as

$$ia\ \text{err} = isa - isa \quad \text{--------------------- (23)}$$

$$i_b\ \text{err} = i_{sb} - i_{sb} \quad \text{--------------- (24)}$$

$$ic\ \text{err} = isc - isc \quad \text{----------------------- (25)}$$

These current error signals are fed to the current-controlled PWM pulse generator for switching the IGBTs of the STATCOM. Thus, the generated PWM pulses are applied to the STATCOM to achieve sinusoidal and balanced source currents along with desired voltage regulation.

IV SIMULATION IMPLIMENTATION

Fig.4 shows the VSI based STATCOM-compensated SEIG system feeding single-phase loads. A 8.1 -kW, 400-V, 50-Hz, Y-connected induction generator has been used to simulate the performance while feeding single-phase loads.

A Y-connected 4-kVAR capacitor bank is connected across the SEIG terminals to provide self-excitation. A diesel engine drive is used to realize the prime mover for the SEIG. A three-phase two-level IGBT- based VSI has been used as the STATCOM. The STATCOM is connected across the PCC through filter inductors *Lf* . Both linear and nonlinear loads are considered for testing the system. A single-phase uncontrolled diode bridge rectifier feeding a series *R*–*L* load is used as a nonlinear load. The source currents of phases "*a*" and "*c*." are used to compute the dq frame. The current in phase "*b*" is estimated under the assumption that the sum of instantaneous currents in three phases is zero. Three phase voltages v_a , v_b , and the dc-bus capacitor voltage of the STATCOM (*V*dc) is also used to compute the dq frame control algorithm and to generate the switching pulses to the STATCOM. A fixed step sampling time of 55 *µ*s has been used for processing the control algorithm.

V. RESULTS AND DISCUSSION

A simulation model of the proposed SEIG–STATCOM system has been developed and tested experimentally at different loads. The experimental results presented in Figs. 5–8 demonstrate the performance of the developed system under steady state as well as dynamic conditions.

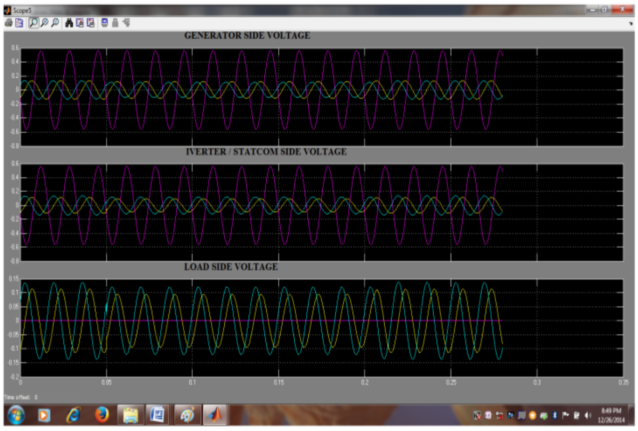

Fig-5 voltage waveforms of sending end, STATCOM side & receiving end

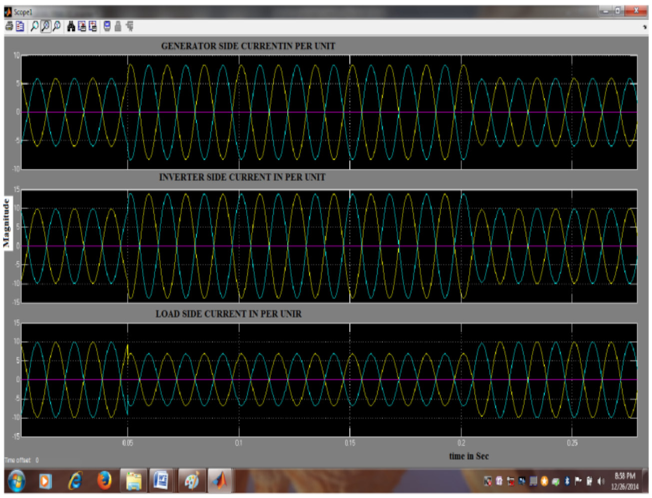

Fig - 6 : Current waveforms of sending end, STATCOM side & receiving end

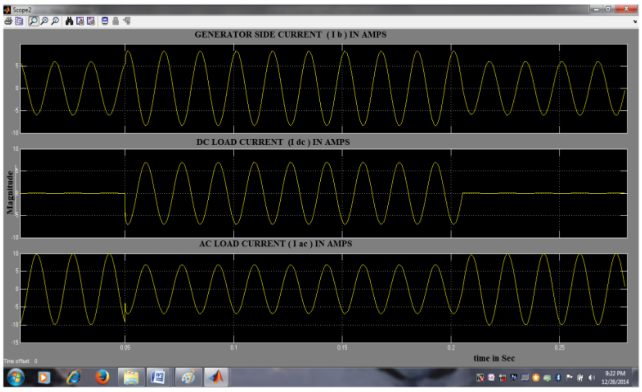

Fig.- 7 : Current waveforms of sending end, DC load & AC load

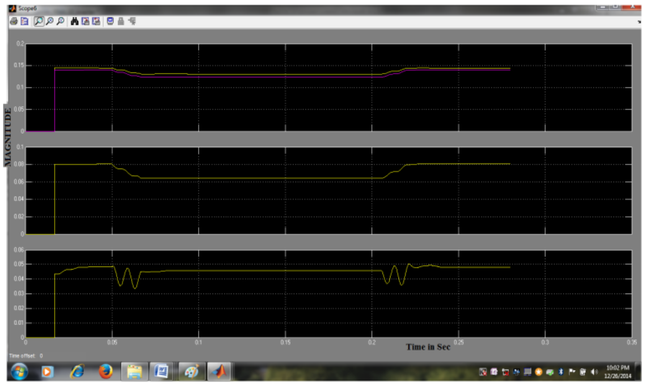

Fig- 8 : Real and Reactive power waveforms at load side

TABLE I

Performance of the SEIG at different terminal voltages and rated winding current

V_b (V)	I_g (A)	P_{gn} (kW)	Q_n (KVA)	S_{gn} (KVA)	F	i_l (A)	P_{ld} (kW)
240	14.53	3.48	4.99	6.05	0.58	12.53	3.02
230	14.53	3.7	4.44	5.75	0.64	14.06	3.23
220	14.58	3.84	3.98	5.5	0.7	15.16	3.35
210	14.57	3.89	3.66	5.31	0.73	16.21	3.42
200	14.56	3.91	3.26	5.06	0.77	16.66	3.37
	14.56	3.86	2.84	4.76	0.81	17.06	3.24
		3.74	2.61	4.53	0.83	17.3	3.11
		3.57	2.43	4.29	0.83	17.25	2.96

VI. CONCLUTION

The proposed method of feeding single-phase loads from a three-phase SEIG and VSI based STATCOM combination has been simulated and it has been proved that the SEIG is able to feed single- phase loads up to its rated capacity. A single-phase synchronous D-Q frame theory-based control of a three-phase STATCOM has been proposed, discussed and implemented for current balancing of the SEIG system. Simulation results have demonstrated effective current balancing capability of the proposed single-phase synchronous D-Q frame-based control using the VSI based STATCOM. In addition to current balancing, the STATCOM is able to regulate the terminal voltage of the generator and suppresses the harmonic currents injected by non- linear loads. The performance of the SEIG at different voltages has been simulated to identify the terminal voltage corresponding the maximum power output. It has been observed that when the SEIG is operated at lower instead of the rated voltage, the generator is able to deliver rated power without exceeding the rated winding current. The satisfactory performance demonstrated by the developed VSI based STATCOM–SEIG combination promises a potential application for isolated power generation using renewable energy sources in remote areas with improved power quality.

APPENDIX

SYSTEM PARAMETERS

1) *Parameters of 3.7-kW, 230-V, 50-Hz, Y-Connected, Four-Pole Induction Machine Used as the SEIG*
R_s = 0.39 Ω, R_r = 0.47 Ω, L_{ls} = 0.00633 H, L_{lr} = 0.00789 H, L_m = 0.2408 H at the rated voltage.
2) *STATCOM Parameters:*
Three-Leg IGBT VSI, L_f = 3 mH, R_f = 0.1Ω, and C_{dc}= 1650 μF.
ac voltage PI controller: K_{pa} = 0.2, K_{ia} = 0.3 dc voltage PI controller: K_{pd} = 1, K_{id} = 0.65.
3) *Load Parameters:*
A single-phase resistive load of a resistance 14.5 Ω con- nected across phases "*a*" and "*c*" is used as linear load. Nonlinear loads: Single-phase bridge rectifier feeding *R*–*L* load are used as nonlinear loads.
R = 14Ω, L = 250 Mh

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