DESIGN AND CONTROL OF VOLTAGE REGULATORS FOR WIND DRIVEN SELF EXCITED INDUCTION GENERATOR

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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) supplying balanced/unbalanced and linear/non linear loads. 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 SEIG needs to maintain a constant terminal voltage under varying loads. A set of voltage regulators are designed and their performance is simulated using SIMULINK to demonstrate their capabilities as a voltage regulator, a harmonic eliminator, a load balancer and a neutral current compensator. It also discusses the merits and demerits, to select a suitable topology of the voltage regulator according to self excited induction generator. 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.*

I. INTRODUCTION

The rapid depletion and the increased cost of conventional fuels have given a thrust to the research on self excited induction generator as alternative power sources driven by various prime movers based on nonconventional energy sources[5]. These energy conversion systems are based on constant speed prime movers, constant power prime movers and variable power prime movers[6][15]. In constant speed prime movers (biogas, biomass, biodiesel etc) based generating systems; the speed of the turbine is almost constant therefore the frequency of the generated voltage remains constant. 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][12][16][25] like simplicity, being maintenance free, absence of DC, being brushless, etc. as compared to a conventional synchronous generator[8][11][13]. A major disadvantage of an SEIG is its poor voltage regulation [14][24][18]. 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), saturable-core reactors and short-shunt connections [6][9][19][21]. 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[2][23][17].

Basic topology of STATCOM consists of a 3-phase current controlled voltage source converter (VSC) and an electrolytic capacitor at its DC bus. The DC bus capacitor is used to self support a DC bus of STATCOM and takes very small active power from SEIG for its internal losses to provide sufficient reactive power as per requirements [3][10]. Here STATCOM is a source of leading or lagging current and can be designed in such a way to maintain constant voltage across the SEIG terminals with varying loads. In this paper various STATCOM based VR topologies are presented which are based on two leg VSC, three leg VSC for three phase three wire SEIG system[4][7][20].

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. Simulated results show that the SEIG-STATCOM system behaves as an ideal generating system under these conditions.

The brief description about this paper includes, Section2 discusses mainly about the various STATCOM controllers used in this paper with the diagrams. Section 3 includes the design of various STATCOM techniques included in this paper with the controlling strategies. Section 4 discusses the results obtained from the MATLAB/SIMULINK models for various STATCOM techniques applied to a self excited induction generator connected to a grid.Section 5 gives the conclusions of this paper.

The system we tested has the following components:

- a wind turbine
- a three-phase, 3-hp,slip ring induction generator driven by the wind turbine
- various sets of capacitors at stator terminals to provide reactive power to the induction generator
- a three-phase various STATCOM devices
- a three phase balanced/unbalanced grid

II. SYSTEM STATCOM CONTROLLERS

The VRs are classified as three phase three wire VRs and three phase four wire VRs. These VRs are based on the two leg VSC, three leg VSC, four leg VSC, three single phase VSC, three leg with midpoint capacitor based VSC and transformer based VRs. In the following section, detailed system description is presented for different STATCOM based voltage regulators.

2.1. Three Phase 3-wire voltage regulators

Mainly two types of VR topologies are discussed for three phase 3-wire self excited induction generator (SEIG). The first one is based on three leg voltage source converter (VSC) and another one is based on a two leg VSC with midpoint capacitor.

2.1.1. Two Leg Voltage Source Converter (VSC) Based Voltage Regulator

Figure 1 shows an isolated generating system which consists of a constant speed wind turbine, and self excited induction generator along with two leg VSC based VR Two legs of VSC are connected to each phase of the generator through interfacing inductors while the third phase of the generating system is connected to the midpoint of the capacitors. Midpoint capacitors require equal voltage distribution across both the capacitors and voltage rating at the DC link of the VSC is comparatively higher than the 3-leg VSC based topology. However switch counts are reduced in this topology of VR

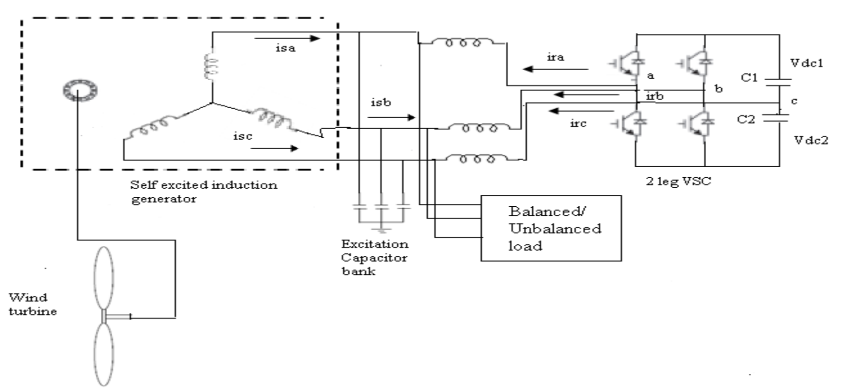


Fig1: Two leg VSC based VR for SEIG system feeding three phase three wire loads.

2.1.2 Three Leg Voltage Source Converter (VSC) Based Voltage Regulator

Figure 2 shows an asynchronous generator system based isolated generating system along with three leg VSC based STATCOM based voltage regulator. The VR consists of a three-leg IGBT (Insulated

Gate Bipolar Junction Transistor) based current controlled voltage source converter, DC bus capacitor and AC inductors. The output of the VSC is connected through the AC filtering inductor to the SEIG terminals. The DC bus capacitor is used as an energy storage device and provides self-supporting DC bus of VR This DC side capacitor supplies the real power difference between the load and SEIG during the transient period. In the steady state the real power supplied by the SEIG should be equal to the real power demand of the load plus a small power to compensate for the losses of the VR.Thus DC capacitor voltage is maintained at a reference value for its satisfactory operation.

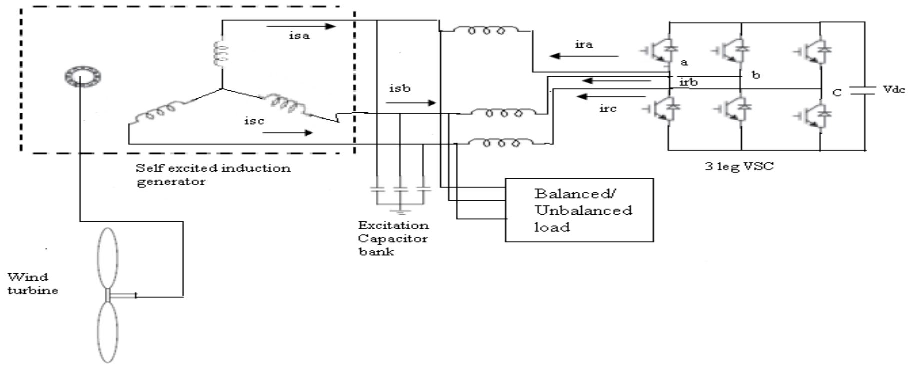


Fig2: Three leg VSC based VR for SEIG system feeding three phase three wire loads.

III. MODELING OF SEIG-STATCOM SYSTEM

The mathematical model of the SEIG-STATCOM system contains the modelling 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. are modelled as follows.

3.1.1. Control scheme of Two Leg Voltage Source Converter (VSC) Based Voltage Regulator

The block diagram of control scheme for two leg VSC based voltage regulator for a SEIG system is as shown in Fig.3

The control strategy of the two-leg voltage controller based VR is realized similar to three-leg VSC, through derivation of reference source currents (i_{sa}^{r}, i_{sb}^{r}) while main difference between two topology to derivation of active component of current as shown in Figure 3. Reference source currents consist of two components one is in phase or active power component (i_{da}^{r}, i_{db}^{r}) for the self supporting DC bus of VSC while the other one is in quadrature or reactive power component (i_{qa}^{r}, i_{qb}^{r},) for regulating the terminal voltage. The amplitude of active power component of the source current (I_{dm}) is estimated using two PI controllers among which, one is used to control the voltage of DC bus of VSC while another one is used for equal voltage distribution across the midpoint DC bus capacitors. The output of the first PI controller is estimated by comparing the reference DC bus voltage (V_{dcref}) with the sensed DC bus voltage (V_{dx}).The output of the second P1 controller is estimated by comparing the voltages across both capacitors (V) and (Va). This voltage error signal is processed using this second PI controller The sum of output of both PI controllers (I_{dm1}) and (I_{dm2}) gives the active power current component (I_{dm}) of the reference source current. The multiplication of I_{dm} with in phase unit amplitude templates (u_{ad},u_{bd}) yields the in-phase component of instantaneous reference source currents. These (u_{ad},u_{bd}) templates are sinusoidal functions, which are derived by unit templates of in-phase with line voltages (u_{ab},u_{bc},u_{ca}). These templates (u_{ab},u_{bc},u_{ca}) are derived by dividing the AC voltages V_{ab},V_{bc},$V_{ca}$by their amplitude V_t. To generate the quadrature contponent of reference source currents, another set of sinusoidal quadrature unity amplitude templates (u_{aq},,u_{bq}, u_{cq}) is obtained from in-phase unit templates (u_{abd},u_{bcd},u_{cad}). The multiplication of these components (u_{aq},u_{bq}) with output of the PI (Proportional Integral) AC voltage controller (I_{qm}) gives the quadrature, or reactive power component of reference source currents. The sum of instantaneous quadrature and inphase component of source currents is the reference source currents (i_{sa}^{r},i_{sb}^{r}) and each phase source current is compared with thecorresponding reference source current to generate the PWM switching signal for VSC of the controller.

$$V_t=\sqrt{\frac{2}{3}(V_a^2+V_b^2+V_c^2)} \qquad (1)$$

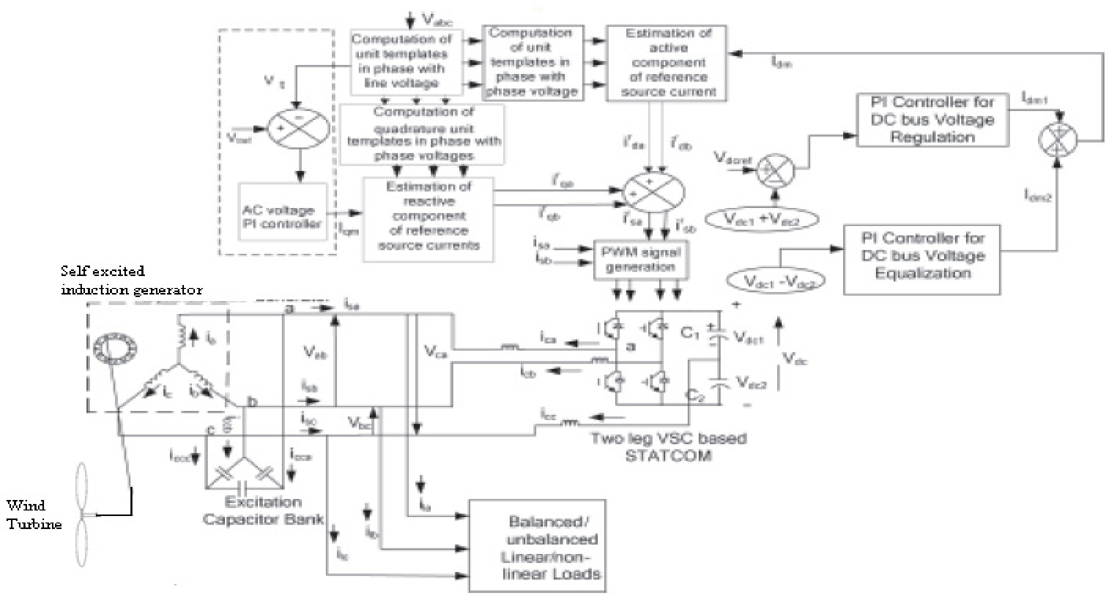


Fig.3. Block diagram of control scheme for Two leg VSC based voltage regulator for a SEIG system

3.1.1.1. Design of Two Leg Voltage Source Converter (VSC) Based Voltage Regulator

This section presents the detailed design of two-leg VSC based VRs for a SEIG driven by a constant speed wind turbine. The two leg VSC and its voltage waveforms are shown in Figure 4.

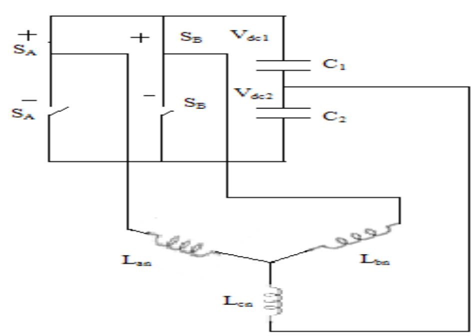


Fig.4.Two leg VSC

The design procedure is focused on, to determine the value of interfacing inductors, DC link capacitors and the voltage across the DC link capacitors along with the rating of the devices. The design of the inductor and capacitor depends upon the voltage and current ripples.

3.1.1.2. Design of the Interfacing Inductor

In PWM switching of the converter, $V_{controlA}$,$V_{controlB}$ and $V_{controlc}$ can be assumed to be constant to be constant during one switching frequency time period.At the zero crossing of $V_{controlA}$ therefore,

$$\left.\begin{aligned} &V_{controlA}=0 \\ &V_{controlB}=m_aV_{tri}\sin(120)= m_a\frac{\sqrt{3}}{2} \end{aligned}\right\} \qquad (2)$$

$V_{controlC}=m_a V_{tri}\sin(240)=-\ m_a\frac{\sqrt{3}}{2}$

When m_a is the modulation index and the converter AC terminal voltage vector is defined from the line to neutral voltages V_{an}, V_{bn}, V_{cn} which can be calculated as follows:

$$\left.\begin{aligned} V_{an} &= V_{aN}-V_{Nn}=V_{aN}-\tfrac{1}{3}(V_{aN}+V_{bN}+V_{cN}) \\ V_{bn} &= V_{bN}-V_{Nn}=V_{bN}-\tfrac{1}{3}(V_{aN}+V_{bN}+V_{cN}) \\ V_{cn} &= V_{cN}-V_{Nn}=V_{cN}-\tfrac{1}{3}(V_{aN}+V_{bN}+V_{cN}) \end{aligned}\right\} \qquad (3)$$

Where V_{aN}, V_{bN} and V_{cN} are the converter pole voltages against the midpoint of the DC capacitor and V_{Nn} is the voltage between the neutral point(n) and the midpoint of the DC capacitor(N,C).

Peak to peak inductor current ripple is

$$I_{Lripple} = \frac{1}{L_{am}}\int_0^{\frac{T_s}{2}} V_{am}\,dt = \frac{\text{Area A}}{L_{an}} \qquad (4)$$

The interfacing inductor L_{an}, L_{bn} and L_{cn} can be calculated as follows:

$$L_{an}=L_{bn}=\frac{V_{dc}}{12}\left(\frac{1}{k_L f_s i_{Lripple}}\right)\left(m_a\frac{\sqrt{3}}{2}+1\right) \qquad (5)$$

By substituting the values of all parameters, the value of the inductor can be calculated as given in table shown in Fig.5.

Parameter	Expression	Calculated	Selected
L_{an}	$\left(\frac{V_d}{12}\right)\left(\frac{1}{K_L f_s i_{Lripple}}\right)\left(1+m_a\frac{\sqrt{3}}{2}\right)$	8.8mH	8mH
L_{bn}	$\left(\frac{V_d}{12}\right)\left(\frac{1}{K_L f_s i_{Lripple}}\right)\left(1+m_a\frac{\sqrt{3}}{2}\right)$	8.8mH	8mH
L_{cn}	$\left(\frac{V_d}{6}\right)\left(\frac{1}{K_L f_s i_{Lripple}}\right)\left(1+m_a\frac{\sqrt{3}}{4}\right)$	5.2mH	5mH
V_{dc1}, V_{dc2}	$2\sqrt{2}\left(\frac{\left(\frac{V}{\sqrt{3}}\right)}{m_a}\right)$	677V	700V
C_{dc1}, C_{dc2}	$\frac{I_{avg}}{2\omega V_{dc}}$	1655µF	4000µF
V_{sw}	$V_{sw} = (V_{dc}+V_d)$	1833V	3300V
I_{sw}	$I_{sw}=1.25(i_{ripple(pp)}+I_{s(peak)})$	30A	60A

Fig.5.Calculation and selection of various components of two leg VSC based VR

3.1.2.1. Design of the midpoint D.C link capacitor and its voltage

Voltage across each capacitor must be more than the peak voltage for satisfactory PWM control as

$$V_{dc1}=V_{dc2}=\frac{2\sqrt{2}\,V}{\sqrt{3}m_a} \qquad (6)$$

Where m_a is the modulation index normally with maximum value 1.The current which flows through the phase connected to the midpoint capacitor is equal to the flow through the capacitors. Therefore the ripple in the capacitor voltage can be estimated as:

$$V_{dc1\text{-}ripple}=\frac{1}{C_{dc1}}\int i_c\,dt = \frac{I_{avg}}{2\omega C_{dc1}} \qquad (7)$$

$$I_{avg} \approx 0.9\ I_s \quad (8)$$

Where I_{avg} is the average current which flows through the DC bus capacitor (C_{dc1}) and $I_s$is the required rms compensator current rating of the devices. The voltage rating (V_{sw}) of the device can be calculated under dynamic condition as:

$$V_{sw} = (V_{dc}+V_d) \quad (9)$$

Where V_d is 10% overshoot in the DC link voltage under dynamic conditions.

Rated current which flows through the two leg VSC is I_s.The peak value of the current flows through the VR considering the safety factor of 1.25 the maximum device current can be calculated as:

$$I_{sw} = 1.25(i_{ripple(pp)}+I_{s(peak)}) \quad (10)$$

From this voltage(V_{sw}) and current rating(I_{sw}) of the IGBT switches can be estimated.Here one design example for a two-leg VSC based VR is carried out for feeding 0.8p.f lagging reactive load,SEIG requires reactive power of 140-160% of rated generated power.Therefore the additional reactive power required from no load to full load at 0.8 lagging p.f load and it is calculated as:

$$\text{Additional VAR}(Q_{AR})=\sqrt{3}VI_s \quad (11)$$

Where V is SEIG line voltage and $I_s$is VR line current.

3.1.2. Control scheme of Three Leg Voltage Source Converter (VSC) Based Voltage Regulator

The block diagram of control scheme for two leg VSC based voltage regulator for a SEIG system is as shown in Fig.6.

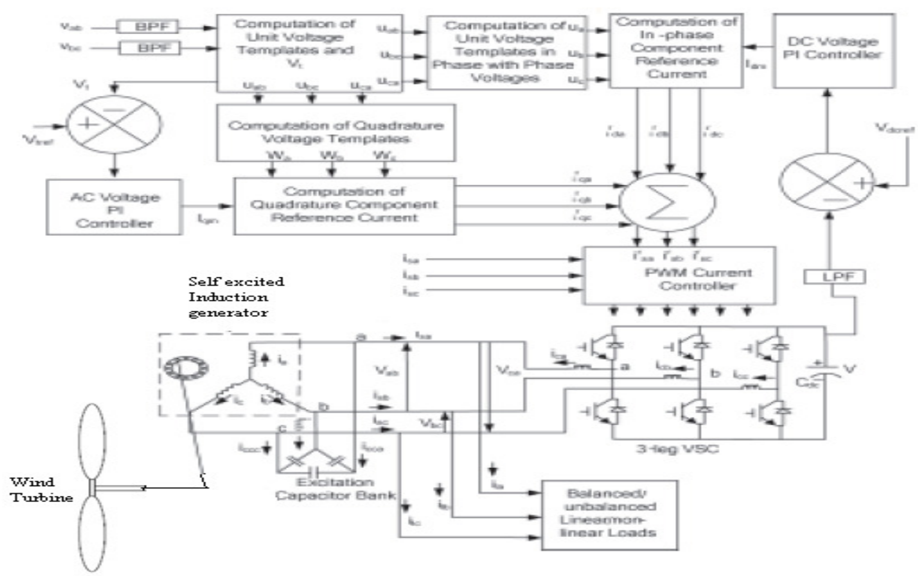


Fig.6. Block diagram of control scheme for three leg VSC based voltage regulator for a SEIG system

3.1.2.1. Modelling of control scheme of STATCOM

Different components of the SEIG-STATCOM system shown in Fig.6 are modelled 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:

$$V_t=\sqrt{\frac{2}{3}(V_a^2+V_b^2+V_c^2)} \quad (12)$$

The unit vector in phase with V_a,V_b and V_c are derived as:

$$u_a=\frac{V_a}{V_t};u_b=\frac{V_b}{V_t}\quad ; \qquad u_c=\frac{V_b}{V_t} \quad (13)$$

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:

$$\left.\begin{aligned} w_a &= \frac{-u_b}{\sqrt{3}} + \frac{u_c}{\sqrt{3}} \\ w_b &= \frac{\sqrt{3}}{2} u_a + \frac{(u_b - u_c)}{2\sqrt{3}} \\ w_c &= -\frac{\sqrt{3}}{2} u_a + \frac{(u_b - u_c)}{2\sqrt{3}} \end{aligned}\right\} \quad (14)$$

3.1.2.2. Quadrature component of reference source currents

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

$$V_{er(n)} = V_{tref(n)} - V_{t(n)} \quad (15)$$

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 ($I^*_{smq(n)}$) is used for maintaining constant AC terminal voltage at the n^{th} sampling instant.
The qudrature components of the reference source currents are computed as:

$$i^*_{saq} = I^*_{smq} w_a \; ; \quad i^*_{sbq} = I^*_{smq} w_b \; ; \; i^*_{scq} = I^*_{smq} w_c \quad (16)$$

3.1.2.3.In-phase component of reference source currents

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

$$V_{dcr(n)} = V_{dcref(n)} - V_{dc(n)} \quad (17)$$

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 is used for maintaining the DC bus voltage of the STATCOM at the n^{th} sampling instant.
The in-phase components of the reference source currents are computed as:

$$\left.\begin{aligned} i^*_{sad} &= I^*_{smd} u_a \\ i^*_{sbd} &= I^*_{smd} u_b \\ i^*_{sad} &= I^*_{smd} u_c \end{aligned}\right\} \quad (18)$$

3.1.2.4. 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 :.

$$\left.\begin{aligned} i^*_{sa} &= i^*_{saq} + i^*_{sad} \\ i^*_{sb} &= i^*_{sbq} + i^*_{sbd} \\ i^*_{sc} &= i^*_{scq} + i^*_{scd} \end{aligned}\right\} \quad (19)$$

3.1.2.5. 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:

$$\left.\begin{aligned} i_{saerr} &= i^*_{sa} - i_{sa} \\ i_{sberr} &= i^*_{sb} - i_{sb} \\ i_{scerr} &= i^*_{sc} - i_{sc} \end{aligned}\right\} \quad (20)$$

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.

3.1.2.6.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:

$$pV_{dc} = \frac{i_{ca}SA + i_{cb}SB + i_{cc}SC}{C_{dc}} \tag{21}$$

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:

$$\left.\begin{aligned} e_{ab} &= V_{dc}(SA-SB) \\ e_{bc} &= V_{dc}(SB-SC) \\ e_{ca} &= V_{dc}(SC-SA) \end{aligned}\right\} \tag{22}$$

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

$$\left.\begin{aligned} V_a &= R_f i_{ca} + L_f\, pi_{ca} + e_{ab} - R_f i_{cb} - L_f pi_{cb} \\ V_b &= R_f i_{cb} + L_f pi_{cb} + e_{bc} - R_f i_{cc} - L_f pi_{cc} \end{aligned}\right\} \tag{23}$$

$$i_{ca} + i_{cb} + i_{cc} = 0 \tag{24}$$

The value of icc from above eqn (24) is substituted into eqn.(23) which results in:

$$V_b = R_f i_{cb} + L_f pi_{cb} + e_{bc} + R_f i_{ca} + L_f pi_{ca} + R_f i_{cb} + L_f pi_{cb} \tag{25}$$

Rearranging the equation results in:

$$L_f pi_{ca} - L_f pi_{cb} = V_a - e_{ab} - R_f i_{ca} + R_f i_{cb} \tag{26}$$

$$L_f pi_{ca} + 2L_f pi_{cb} = V_b - e_{bc} - Rfica - 2R_f i_{cb} \tag{27}$$

Hence, the STATCOM current derivatives are obtainedby solving eqns. and as:

$$pi_{ca} = \frac{\{(V_b - e_{bc}) + 2(V_a - e_{ab}) - 3R_f i_{ca}\}}{3L_f} \tag{28}$$

$$pi_{cb} = \frac{\{(V_b - e_{bc}) - (V_a - e_{ab}) - 3R_f i_{cb}\}}{3L_f} \tag{29}$$

3.1.2.7. AC Line Voltage at the Point of CommonCoupling

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:

$$\left.\begin{aligned} pV_a &= \frac{\{(i_a - i_{ra} - i_{ca}) - (i_b - i_{rb} - i_{cb})\}}{3C} \\ pV_b &= \frac{\{(i_a - i_{rc} - i_{ca}) + 2(i_b - i_{rb} - i_{cb})\}}{3C} \end{aligned}\right\} \tag{30}$$

$$V_a+V_b+V_c = 0 \quad (31)$$

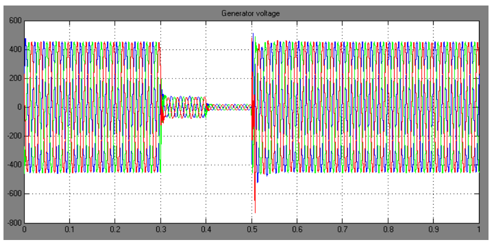
Where i_a ,i_b and i_c are the SEIG stator line currents, i_{ra},i_{rb} and $i_{rc}$are the three phase load line currents and i_{ca},i_{cb} and i_{cc} are the STATCOM currents. C is the per phase excitation capacitor, which is connected across the SEIG terminals.

IV. Results and Discussions

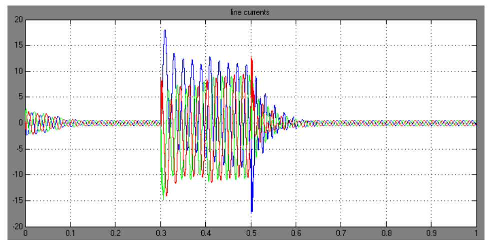
The SEIG-STATCOM system feeding linear/non-linear and balanced/unbalanced loads are simulated and results are shown in Figs.7-8 . For this study, a 3.5 kW, 440V,7.5A, 4-pole machine was used as a generator and the parameters of the generator are given in the Appendix.

4.1. Performance of two Leg voltage Regulator for a SEIG System

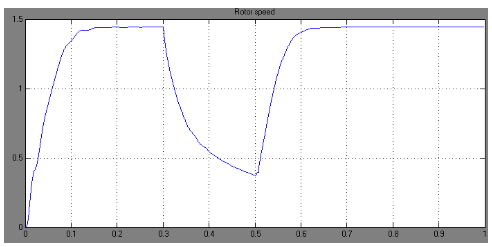
Here performance of two leg voltage source converter with mid point capacitor based VR topology has been simulated using MATLAB/SIMULINK and verified for self excited induction generator driven by wind turbine.



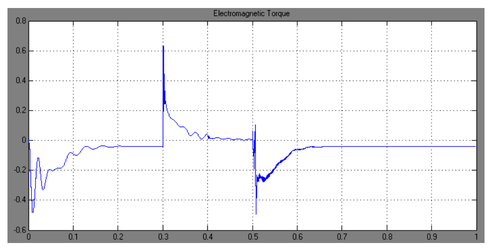
Generated voltage



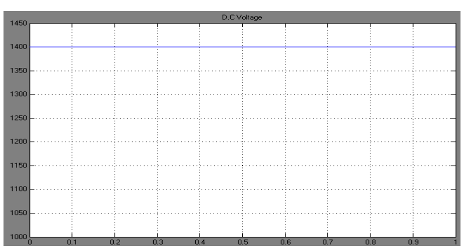
Line current



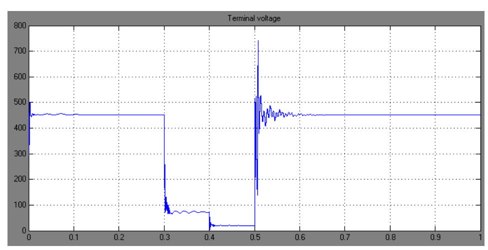
Rotor speed



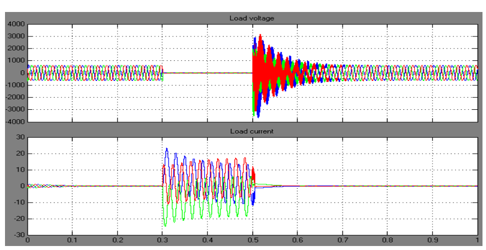
Electromagnetic Torque



D.C voltage



Terminal Voltage



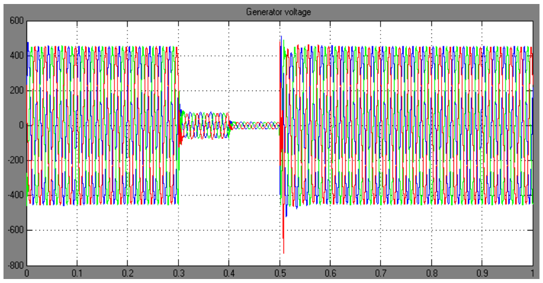
Load voltage and load current

Fig.7.Performance of two leg VSC based VR for a SEIG system feeding 3-phase balanced/unbalanced grid

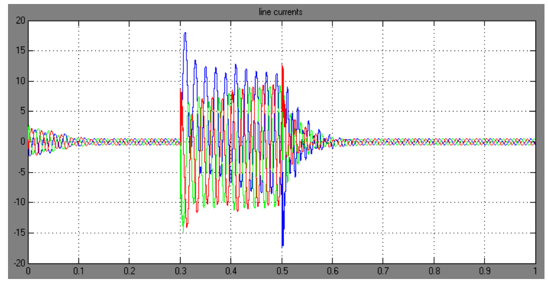
Figure 7 shows the transient waveforms of three-phase generator voltages (v_{abc}), generator currents (i_{abc}), speed, electromagnetic torque, D.C voltage, terminal voltage, load voltage and load current respectively demonstrating the response regulating the SEIG terminal voltage while supplying a grid.
At 0.3seconds, three-phase nonlinear load is applied and it is found that with application of the sudden load, there is increased generator currents, load currents, STATCOM currents and decrease in supply voltage due to supplying active and reactive power to the load.The voltage is 75volts and current is 10A.
Along with this, short circuit occurs at 0.4seconds,with this there is further increased generator currents, load currents, STATCOM currents and decrease in supply voltage due to supplying active and reactive power to the load.The voltage is 20volts and current is 15A.
At 0.5seconds the STATCOM is connected to the system. Due to this the voltage is reached to the required voltage. It is observed that the generator voltage remains constant underbalanced and even unbalanced lagging pf loads. Variations in generator speed are observed with the change in load due to the drooping characteristic of the wind turbine.
The STATCOM is disconnected from the system at 0.55seconds after it reaches the required voltage. At 0.6 seconds short circuit is removed and at 0.7 seconds is removed from the load. Now the machine is working under steady state conditions.
The total harmonic distortion (THD) of the generator voltage and current for the three-phase balanced case are observed.It is observed that the THD is less than 5%.
With the application of the three phase nonlinear loads and short circuits it is found that Voltage regulator responds in a desirable manner and maintains constant voltage at the generator terminal. Along with this, the DC link voltage and voltage across both midpoint capacitors of voltage regulators also remain equal and constant.
The STATCOM eliminates harmonics so that the generator voltages and currents are free from harmonics a scan be observed

4.2. Performance of three Leg voltage Regulator for a SEIG System

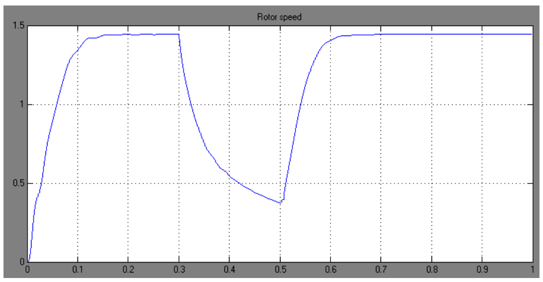
Here performance of three leg voltage source converter with a capacitor based VR topology has been simulated and verified for self excited induction generator driven by wind turbine.
Figure 8 shows the transient waveforms of three-phase generator voltages (v_{abc}), generator currents (i_{abc}), speed, electromagnetic torque, D.C voltage, terminal voltage, load voltage and load current respectively demonstrating the response regulating the SEIG terminal voltage while supplying a grid.
At 0.3seconds, three-phase nonlinear load is applied and it is found that with application of the sudden load, there is increased generator currents, load currents, STATCOM currents and decrease in supply voltage due to supplying active and reactive power to the load.The voltage is 75volts and current is 10A.
Along with this, short circuit occurs at 0.4seconds, with this there is further increased generator currents, load currents, STATCOM currents and decrease in supply voltage due to supplying active and reactive power to the load.The voltage is 20volts and current is 15A.
At 0.5seconds the STATCOM is connected to the system. Due to this the voltage is reached to the required voltage. It is observed that the generator voltage remains constant underbalanced and even unbalanced lagging pf loads. Variationsin generator speed are observed with the change in loaddue to the drooping characteristic of the wind turbine.
The D.C voltage obtained here is having fewer ripples compared with the two leg voltage regulator for a SEIG system. Due to these transients there is even change in the variation of the speed and the torque.



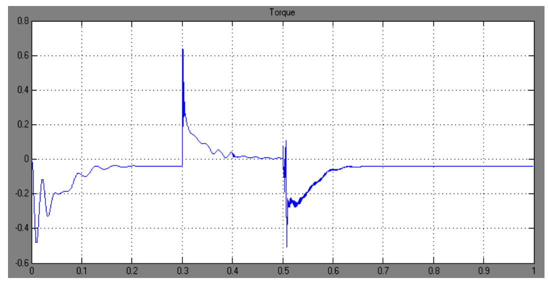
Generated voltage



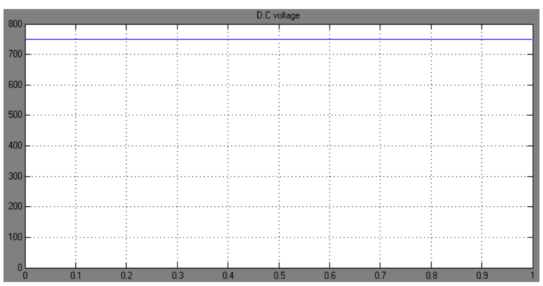
Line current



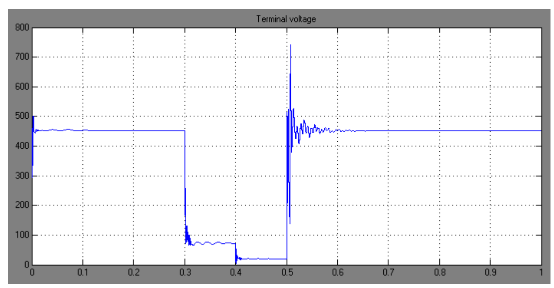
Rotor speed



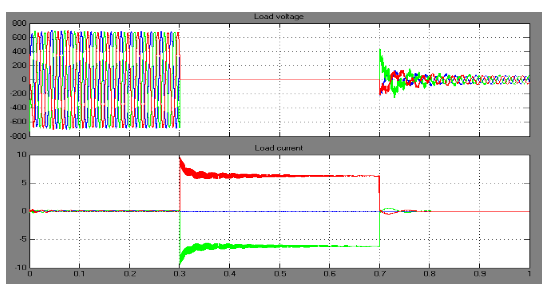
Electromagnetic torque



D.C voltage



Terminal voltage



Load voltage and load current

Fig.8.Performance of three leg VSC based VR for a SEIG system feeding 3-phase balanced/unbalanced grid

V. CONCLUSIONS

A set of VRs have been designed and their performance have been studied for SEIG system. For three-phase three-wire SEIG system two topologies of VR have been demonstrated one is based on three leg VSC while another one is based on the two leg VSC. A topology which is based on the two leg VSC, requires higher voltage rating of the switches and equal voltage distributed DC link, however less number of switching devices are required compared to three leg VSC based topology of VR. In three phase three wire SEIG system there are a number of configurations of the VRs for a three phase four wire SEIG system . 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 modelled as non-linear loads here, the developed model can easily be modified to simulate a compensating controlled rectifier as a nonlinear load. For future work they may develop the various STATCOM techniques by considering the neutral line and can develop the 3-leg and 4-leg wire systems.

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APPENDIX

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} = 22Ω, and C_{RL} = 470μF.
Single-phase rectifier L_{SL}=0.1mH, R_{SL} = 1 Ω, R_{RL}=75Ω and C_{RL}=150Mf
3. Machine Parameters
The parameters of the 3.5 kW,440V, 7.5A, 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 = 0.23kg/m2,
$L_{ss} = L_{ls} + L_m$ and $L_{rr} = L_{lr} + L_m$.
4. Terminal capacitor
C = 15 μF/ phase
5. Air gap voltage:
The piecewise linearization of magnetization characteristic of machine is given by:

$E_1=0$	$X_m \geq 260$
$E_1=1632.58-6.2X_m$	$233.2 \leq X_m \leq 260$
$E_1=1314.98-4.8X_m$	$214.6 \leq X_m \leq 233.2$
$E_1=1183.11-4.22X_m$	$206 \leq X_m \leq 214.6$
$E_1=1120.4-3.9.2X_m$	$203.5 \leq X_m \leq 206$
$E_1=557.65-1.144X_m$	$197.3 \leq X_m \leq 203.5$
$E_1=320.56-0.578X_m$	$X_m \leq 197.3$

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