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Enhanced Voltage Regulation of SEIG with DVR Based Cyber Physical System Under Varying Load Conditions

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***Abstract*— This paper presents the design of a Dynamic Voltage Restorer (DVR)-based cyber-physical system for voltage control in a constant speed prime mover-driven Self-Excited Induction Generator (SEIG). SEIGs powered by biomass or biogas are commonly used in isolated renewable energy systems but suffer from poor voltage regulation. To address this issue, the DVR enhances voltage stability by compensating for voltage fluctuations. The DVR system offers advantages such as reduced rating, size, and cost of the voltage source converter (VSC) and the DC bus capacitor. The DVR controller is implemented using an Insulated Gate Bipolar Transistor (IGBT)-based VSC with a self-supported DC bus. A 7.5 kW, 415 V, 50 Hz SEIG-based generation system integrated with a DVR is modeled and simulated in the MATLAB environment. The study demonstrates the effectiveness of the proposed DVR system in maintaining voltage regulation in isolated renewable energy setups.**

Keywords- DVR, Isolated power Generation, Power Quality,SEIG, Voltage Controller.

I. INTRODUCTION

Renewable energy sources such as biogas, biomass, small hydro, and wind power play a significant role in reducing carbon emissions, one of today's most critical challenges. In isolated power generation systems, an asynchronous machine excited by a capacitor bank functions as a SEIG, also known as an IAG. SEIGs are favored for their low cost, low maintenance, ruggedness, and brushless construction. At no load, the excitation capacitor provides the required reactive power to maintain rated voltage. However, under load conditions, SEIGs struggle to maintain reactive power balance, leading to poor voltage regulation and underutilization of machine capacity. To address this, external reactive power compensation is essential. Previous studies have explored STATCOM- and SSSC-based solutions, though with limitations such as reliance on batteries and single PI controllers. This paper proposes a DVR-based series voltage controller with a capacitor-supported DC bus and dual PI controllers for effective voltage regulation under both linear and nonlinear load conditions.

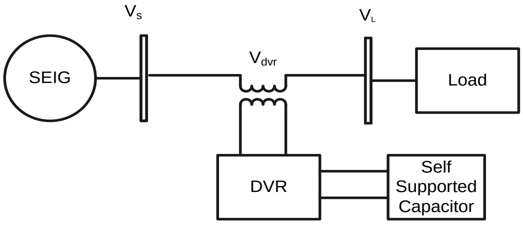

Figure 1 Schematic diagram of SEIG-DVR

The DVR is a power electronic device based on a VSC, consisting of an interfacing transformer, VSC, and a DC bus capacitor. It operates by injecting a reactive voltage component in series between the SEIG and the load to maintain a stable source and load voltage. The schematic of the SEIG integrated with a capacitor-supported DVR is illustrated in Fig. 1. This work investigates the performance of the SEIG equipped with a series voltage controller under three-phase linear load conditions. A hysteresis control strategy is implemented in the DVR to regulate the system voltage effectively. The entire system is designed, modeled, and simulated in the MATLAB environment. Simulation results demonstrate the effectiveness of the proposed DVR-based voltage control approach in enhancing the voltage regulation capability of the asynchronous generator while supplying three-phase linear loads.

II.SYSTEM CONFIGURATION AND CONTROL SCHEME

he system comprises a constant speed prime mover, such as a biogas or diesel engine, driving a SEIG equipped with a voltage controller. A 7.5 kW, 415 V, 50 Hz asynchronous machine, incorporating its magnetic saturation characteristics, is used as the generator. A 5 kVAR delta-connected excitation capacitor bank is employed to generate the rated voltage under no-load conditions. Under varying load conditions, the additional reactive power required is supplied by the DVR, which acts as both a source and sink of reactive power to maintain constant terminal voltage. Figure 2 illustrates the system configuration, including the SEIG, excitation capacitor bank, DVR (comprising a voltage source converter, transformer, capacitor, and filters), and the consumer load.

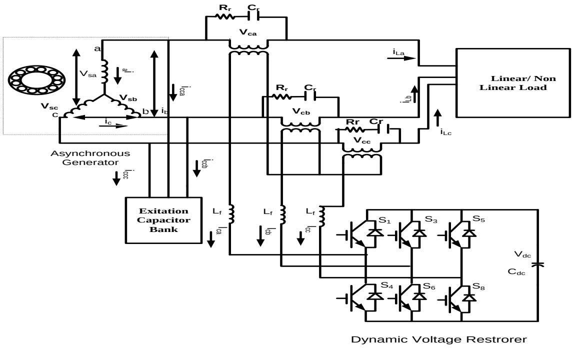

Figure 2 System Configuration of SEIG-DVR

1) Control scheme of DVR: Three-phase unit voltage templates (U_{sad}, U_{sbd}, U_{scd}) are derived in-phase with the supply currents (i_{sa}, i_{sb}, i_{sc}). The DC bus voltage of the DVR is regulated using a PI controller over the sensed (V_{dc}) and reference values (V_{dc}*) of DC bus voltages. This PI controller output is considered as the amplitude (V_{cd}*). The (V_{cd}*) is multiplied with unit voltage templates to generate in-phase component of the injection voltages (V_{Cad}*, V_{Cbd}*, V_{Ccd}*).The amplitude of sensed load voltage (V_{Lp}) and reference value (V_{Lp}*) of the load terminal voltage passes through another PI controller. The PI controller output V_{cq}* is multiplied with quadrature unit voltage vectors (U_{saq}, U_{sbq}, U_{scq}) to generate quadrature component of the injection voltages (V_{Caq}*, V_{Cbq}*, V_{Ccq}*) of the DVR. The algebraic sum of the in phase components (V_{Cad}*, V_{Cbd}*, V_{Ccd}*) and the quadrature components (V_{Caq}*, V_{Cbq}*, V_{Ccq}*) generate the reference signals (V_{La}*, V_{Lb}*, V_{Lc}*). The hysteresis controller is used over the reference load voltages (V_{La}*, V_{Lb}*, V_{Lc}*) and sensed load voltages (V_{La}, V_{Lb}, V_{Lc}) to generate gating signals for the IGBT's of the VSC.The control scheme of DVR is shown in fig.3.

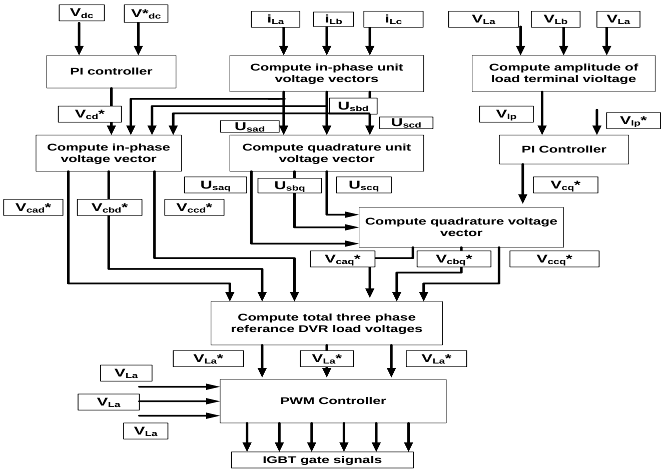

Figure 3 Control scheme of the DVR

III MODELING OF SEIG WITH DVR

1) *Modelling of Asynchronous Generator*

The asynchronous machine with self excitation capacitance is working as SEIG by providing torque through constant speed prime-mover. The d-q axis asynchronous machine model is used in stationary reference frame including saturation characteristic. Saturation characteristic is determined by conducting a synchronous speed test on the machine. The d-q axis flux state-space model equations of an asynchronous machine are described as:

$$p\phi_{ds} = v_{ds} - R_s i_{ds} \qquad (1)$$

$$p\phi_{qs} = v_{qs} - R_s i_{qs} \qquad (2)$$

$$p\phi_{dr} = v_{dr} - R_r i_{dr} - \omega_r \varphi_{qr} \qquad (3)$$

$$p\phi_{qr} = v_{qr} - R_r i_{qr} + \omega_r \varphi_{dr} \qquad (4)$$

The developed torque of IAG is given by

$$T_e = (3/4)\, p\, (\phi_{ds} i_{qs} - \phi_{qs} i_{ds}) \qquad (5)$$

The voltages of squirrel-cage rotor are

$$v_{dr} = v_{qr} = 0 \qquad (6)$$

These d-q axis flux linkages may be expressed in terms of their respective currents as

$$\phi_{ds} = L_s i_{ds} + L_m i_{dr}\,, \qquad \phi_{qs} = L_s i_{qs} + L_m i_{qr} \qquad (7)$$

$$\phi_{dr} = L_s i_{dr} + L_m i_{ds}\,, \qquad \phi_{qr} = L_s i_{dr} + L_m i_{qs} \qquad (8)$$

$$L_s = L_{ls} + L_m, \qquad L_r = L_{lr} + L_m \qquad (9)$$

Subscripts *s, r, l* and *m* denote stator, rotor, leakage and magnetizing quantities respectively in *d* and *q* axis.The magnetizing inductance L_m is calculated from synchronous speed test on asynchronous machine that presented in form of polynomial as:

$$L_m = a + bI_m + cI^2_m + dI^3_m \qquad (10)$$

Where *a,b,c* and *d* are constant. The magnetizing current of IAG is computed as:

$$I_m = \{(i_{ds} + i_{dr})^2 + (i_{qs} + i_{qr})^2\}^{1/2}/\sqrt{2} \qquad (11)$$

The prime mover torque speed characteristic is given as:

$$T_{sh} = K_1 - K_2\omega_r \qquad (12)$$

Where K_1 and K_2 are constants given in Appendix and ω_r is rotor speed. The relation between excitation capacitance (C_e), current through (i_e) and stator voltages of IAG (v_s) is as follows:

$$C_e\, p[v_s] = [i_e] \qquad (13)$$

2) Modeling of control scheme of SEIG-DVR system for feeding three phase load is given as follows.

Three phase load currents of SEIG feeding load considered as a sinusoidal and hence their amplitude is computed as:

$$i_{Lmag} = [2/3(i_{La}^2 + i_{Lb}^2 + i_{Lc}^2)]^{1/2} \qquad (14)$$

The in phase unit voltage vectors are computed by divide individual load current by their amplitude.

$$U_{sad} = i_{La}/i_{Lmag};\ \ U_{sbd} = i_{Lb}/ i_{Lmag};\ \ U_{scd} = i_{Lc}/ i_{Lmag} \qquad (15)$$

The quadrature unit voltage templates may be derived using a quadrature transformation of in-phase unit vector.

$$U_{saq} = -U_{sbd}/\sqrt{3} + U_{scd}/\sqrt{3} \qquad (16)$$

$$U_{sbq} = \sqrt{3}U_{sad}/2 + (U_{sbd} - U_{scd})/2\sqrt{3} \qquad (17)$$

$$U_{scd} = -\sqrt{3}U_{sad}/2 + (U_{sbd} - U_{scd})/2\sqrt{3} \qquad (18)$$

A. Quadrature component of voltage vectors

The amplitude of load terminal voltages is computed as:

$$V_{Lp} = [2/3(V_{La}^2 + V_{Lb}^2 + V_{Lc}^2)]^{1/2} \qquad (19)$$

This amplitude of load terminal voltage V_{Lp} is compared with the reference value V_{Lp}^* of load terminal voltage and generate error signal. The AC load voltage terminal error $V_{er(n)}$ at n^th^ sampling instant is :

$$V_{er(n)} = V_{Lp(n)}^* - V_{Lp(n)} \qquad (20)$$

The output of the PI controller $V_{cq}(n)^*$ for maintaining AC load terminal voltage constant at n^th^ sampling instant is expressed as :

$$V_{cq(n)}^* = V_{cq(n-1)}^* + K_{pa}\{V_{er(n)}-V_{er(n-1)}\} + K_{ia}V_{er(n)} \qquad (21)$$

Where K_{pa} and K_{ia} are the proportional and integral gain constant of the proportional integral (PI) controller and $V_{cp(n-1)}^*$ is the amplitude of quadrature component of the reference load voltage at (n-1)th instant. The quadrature components of reference load voltage are computed as;

$$V_{caq}^* = V_{cq}^*U_{saq};\ \ V_{cbq}^* = V_{cq}^*U_{sbq};\ \ V_{ccq}^* = V_{cq}^*U_{scq} \qquad (22)$$

B. In- phase component of voltage vectors

The error in DC bus voltage V_{dcer} (n) of DVR at nth sampling Instant is:

$$V_{dcer(n)} = V_{dc(n)}^* - V_{dc(n)} \qquad (23)$$

Where $V_{dc}(n)^*$ is the reference DC voltage and $V_{dc}(n)$ is the sensed DC link voltage of the DVR. The output of PI controller for maintaining DC bus voltage of the DVR at the nth sampling instant is expressed as;

$$V_{cd(n)}^* = V_{cd(n-1)}^* + K_{pd}\{V_{dcer(n)}-V_{dcer(n-1)}\} + K_{id}V_{dcer(n)} \qquad (24)$$

Where K_{pd} and K_{id} are the proportional and integral gain constant of the proportional integral (PI) controller and $V_{cd}(n-1)^*$ is the amplitude of In-phase component of the reference load voltage at (n-1)th instant. The In-phase components of the reference load voltage are computed as ;

$$V_{cad}^* = V_{cd}^*U_{sad};\ \ V_{cbd}^* = V_{cd}^*U_{sbd};\ \ V_{ccd}^* = V_{cd}^*U_{scd} \qquad (25)$$

C. Reference Load Voltages

Total three phase reference load voltages are the sum of in-phase and quadrature components of the load voltages as;

$$V_{La}^* = V_{Cad}^* + V_{Caq}^* \qquad (26)$$

$$V_{Lb}^* = V_{Cbd}^* + V_{Cbq}^* \qquad (26)$$

$$V_{Lc}^* = V_{Ccd}^* + V_{Ccq}^* \qquad (27)$$

These reference load voltages signals are compared with sensed load voltages V_{La}, V_{Lb}, V_{Lc} and generate error signals which are passing through a hysteresis controller to generate gating pulses switch the IGBT's of the VSC of DVR.

4) Modeling of VSC (Voltage Source Converter)

The DVR is a current controlled VSC. The derivative of its dc voltage is defined as:

$$pv_{dc} = (i_{ca}S_A + i_{cb}S_B + i_{cc}S_C)/C_{dc} \qquad (28)$$

Where $p = d/dt$ and S_A, S_B and S_C are the switching function for the on/off positions of the VSC Bridge switches S_1-S_6. The dc bus voltage reflects at the output of the inverter in the form of three phase ac line voltage e_a, e_b and e_c which are expressed as:

$$e_a = v_{dc}(S_A-S_B),\ e_b = v_{dc}(S_B-S_C),\ e_c = v_{dc}(S_C-S_A) \qquad (29)$$

The volt-current equations of the output of VSI of DVR are:

$$v_a = R_f i_{ca} + L_f p i_{ca} + e_a - R_f i_{cb} - L_f p i_{cb} \qquad (30)$$

$$v_b = R_f i_{cb} + L_f p i_{cb} + e_a - R_f i_{cc} - L_f p i_{cc} \qquad (31)$$

$$i_{ca} + i_{cb} + i_{cc} = 0 \tag{32}$$

The value of i_{cc} from (32) is substituted into (31) which result in:

$$v_b = R_f i_{cb} + L_f p i_{cb} + e_a + R_f i_{ca} + L_f p i_{ca} + R_f i_{cb} + L_f p i_{cb} \tag{33}$$

By rearranging (30) and (33), these result in

$$L_f p i_{ca} - L_f p i_{cb} = v_a - e_a - R_f i_{ca} + R_f i_{cb} \tag{34}$$

$$L_f p i_{ca} + 2L_f p i_{cb} = v_b - e_b - R_f i_{ca} - 2R_f i_{cb} \tag{35}$$

Hence, the DVR current derivatives are obtained by solving (34) and (35) as:

$$p i_{ca} = \{ (v_b - e_b) + 2(v_a - e_a) - 3 R_f i_{ca} \}/ (3L_f) \tag{36}$$

$$p i_{cb} = \{ (v_b - e_b) + (v_a - e_a) - 3R_f i_{ca} \}/ (3L_f) \tag{37}$$

5) Modelling of transformer

The currents of DVR produce magnetic flux ф in transformer, which induced voltages V_{ca1}, V_{cb1} and V_{cc1} across DVR side

$$V_{ca1} = 1.414\, f\, \phi_{ca}\, N_1 \tag{38}$$

Where N_1 is number of turns and f is frequency. The transformer injected voltages in the SEIG-DVR system are

V_{ca}, V_{cb} and V_{cc}.(V_{ca}/V_{ca1})

$$= (V_{cb}/V_{cb1}) = (V_{cc}/V_{cc1}) = (N_2 / N_1) \tag{39}$$

N_2 is the number of turns of transformers across system side.

6) Modelling of the consumer loads

Linear loads of 7.5*kW* unity power factor and 7.5*kW*, 0.8pf are modeled using available resistive and reactive element. The resistive load line currents equations are defined as follows:

$$i_{La} = (V_{La}/R_{La}) – (V_{Lc}/R_{Lc}) \tag{40}$$

$$i_{Lb} = (V_{Lb}/R_{Lb}) – (V_{La}/R_{La}) \tag{41}$$

$$i_{La} = (V_{Lc}/R_{Lc}) – (V_{Lb}/R_{Lb}) \tag{42}$$

The reactive load volt- current equations are as follows:

$$V_{La} = R_{La}\, i_{pa} + L_{La}\, p\, i_{pa} \tag{43}$$

$$V_{Lb} = R_{Lb}\, i_{pb} + L_{Lb}\, p\, i_{pb} \tag{44}$$

$$V_{Lc} = R_{Lc}\, i_{pc} + L_{Lc}\, p\, i_{pc} \tag{45}$$

The phase current derivatives of reactive loads are:

$$P i_{pa} = (V_{La} – R_{La}\, i_{La})/L_{La} \tag{46}$$

$$P i_{pb} = (V_{Lb} – R_{Lb}\, i_{Lb})/L_{Lb} \tag{47}$$

$$P i_{pc} = (V_{Lc} – R_{Lc}\, i_{Lc})/L_{Lc} \tag{48}$$

The line currents of are defined in terms of phase currents as:

$$i_{La} = i_{pa} – i_{pc} \tag{49}$$

$$i_{Lb} = i_{pb} - i_{pa} \tag{50}$$

$$i_{Lc} = i_{pc} - i_{pb} \tag{51}$$

IV DESIGN OF DVR

1) Design of DVR: The design of DVR includes voltage rating of VSC (voltage source converter) of DVR, current rating of VSC of DVR, the KVA rating of VSC of DVR. Injection transformer rating, dc bus voltage, dc bus capacitance, ac interfacing inductance and the ripple filter in case of linear and nonlinear loads.

The voltage rating of VSC of DVR depends on the maximum voltage to be injected in linear load condition. Consider a voltage fluctuate up to 25% of phase voltage hence maximum sag in the source terminal voltage is calculated as 239.6*0.75 = 179.7 V and the injected voltage (V_c) is as:

$$V_c = \sqrt{(V_s^2 – V_L^2)} \tag{52}$$

$$= \sqrt{(239.6^2 – 179.7^2)} = 158.4 \text{ V}$$

In case of nonlinear load the design of voltage of DVR depends on the dc bus voltage of the three phase rectifier load. The DVR is eliminating harmonics in the source current and it injects only harmonics component of load voltage. Hence the fundamental component is as:

$$V_{LL} = (\sqrt{6}/\pi)\, V_d = 0.779 * V_d \tag{53}$$

Where V_{LL} is the line voltage of 415 V, the V_d is 532.7 V. The voltage rating of the DVR is obtained from the difference of source terminal and load voltage. Hence the DVR voltage is calculated as:

$$V_{C(rms)}^2 = \frac{1}{\pi}\left[\left\{2\int_0^{\pi/3}(415\sqrt{2}\sin\theta - 0)\right\} + \left\{\int_0^{2\pi/3}(415\sqrt{2}\sin\theta - 532.7)\right\}\right]d\theta \tag{54}$$

$V_{C(rms)}$ = 145.56 V is the voltage rating of VSC in nonlinear load. Then optimum value of voltage rating of VSC for combination of linear and nonlinear load is V_c = 158.4 V.

The current rating of VSC depends on the connected load on the above system. For 7.5kW unity pf (power factor) and 0.8 pf loads, the currents are calculated as:

$$\sqrt{3}\, V_s I_s = 7500/pf \tag{55}$$

Where, I_s and V_s are the line current and line voltage respectively. For V_s = 415 V and unity pf, the current rating of VSC is I_s = 10.43A and for 0.8 pf, the current rating of VSC is I_s = 13.043A.

In case of 7.5kW nonlinear load connected through uncontrolled rectifier and three phase load voltage V_L = 415 V, then current rating of VSC is calculated as:

$$I_s = P/(\sqrt{3} V_L) = 13.043A \tag{56}$$

The R_L is equivalent resistance of the dc load, calculated as

$$P_{dc} = (V_d^2/R_L) \tag{57}$$

For P_{dc} = 7.5kW and V_d = 532.7 V, the R_L = 37.84 Ω

The KVA rating of VSC of DVR is calculated as:

$$kVA = 3\ V_c\ I_s/1000 \qquad (58)$$

$$= (3*158.4*13.043)/1000 = 6.198\text{kVA}$$

The kVA rating of the injection transformer is same as kVA rating of VSC.

$$\text{kVA} = 3\ V_c\ I_s/1000 = (3*158.4*13.043)/1000 = 6.198\ \text{kVA}$$

Hence the rating of the injection transformer is 6.198 kVA, 158/158

The dc capacitor voltage is depend of the VSC side voltage of the injection transformer voltage $V_{C(s)} = 158$ V

$$V_{dc} > 2\sqrt{2}\ V_{C(s)} = 446.8\ V \qquad (59)$$

Hence $V_{dc} = 450$ V is selected for DVR. The dc bus capacitance selection is depending on the transient energy required during change in load condition. Consider the energy store in capacitor equal to the energy demand of the load for a fraction of power cycle.

$$(1/2)\ C_{dc}\ (V_{dc}^2 – V_{dc1}^2) = 3\ V_{ph}*I_{ph} * t \qquad (60)$$

Where V_{dc} is the rated dc bus voltage, V_{dc1} is the drop in dc bus voltage allowing in transient and t is the time for which support is required. Considering t = 400µsec, $V_{dc} = 450$ V, $V_{dc1} = 450 – 2\%$ of 450 = 441 V and C_{dc} is dc bus capacitance.

$$1/2 * C_{dc}\ (450^2 – 441^2) = 3*239.6*13.043*0.40\ \text{ms}$$

$C_{dc} = 0.935$ mF, hence a dc bus of 1000µF, 450V is selected for DVR.

The design of ripple filter is dependent on the switching frequency. The capacitor is offered a low impedance path for switching ripple and series inductor is provided high impedance path for switching ripple. The reactance provided by the capacitor and inductor at half of switching frequency (f_r = 5kHz) is calculated as:

$$X_{Cr} = 1/\ (2*\pi*f_r*C_r) \qquad (61)$$

$$= 1/\ (2*3.14*5000*C_r)$$

$$X_{Lr} = 2*\pi*f_r*L_r \qquad (62)$$

$$= 2*3.14*5000*L_r$$

For $X_{Cr} = 3\Omega$, $C_r = 10.61\mu F$ and for $X_{Lr} = 100\Omega$, $L_r = 3.18$ mH

Calculation for the rating of IGBT of DVR: The maximum rms current rating through DVR is 13.043 A. The maximum current through the switching devices is $I_{SD} = 1.25\ (I_{cripple(p-p)} + I_{cpeak}) = 1.25(0.05*\sqrt{2}*13.043 + \sqrt{2}*13.043) = 24.2$ A

Where $I_{cripple(p-p)}$ is the peak to peak ripple current. I_{cpeak} is the peak line current and 1.25 is the safety margin taken for design consideration. The voltage rating of the switching device is decided by the DC-link voltage whose maximum value is 450 V. Taking 125% margin the voltage rating of switching devices, should be $V_{SD} = 1.25 * 450 = 562.5$ V

V RESULT AND DISCUSSION

The SEIG with excitation capacitor is generating rated voltage at no load condition. When SEIG is feeding resistive and inductive loads at 0.8 second without voltage controller, source voltage (V_s) and source current (i_s) goes down as shown in fig. 4

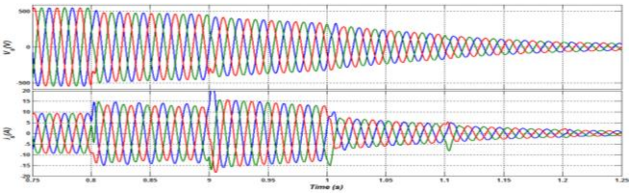

Figure 4 SEIG feeding resistive and inductive loads without voltage controller

The performance of SEIG-DVR feeding three phase linear loads with constant speed prime-mover application is simulated in MATLAB environment. Waveforms of generated source voltage (V_s) and current (i_s), excitation current (i_{cc}), load voltage (V_L), DVR compensated voltage (V_c), load current (i_L), DC link voltage (V_{dc}) and mechanical speed (ω_m) are shown in fig 5. The fig. 5 shows performance of SEIG-DVR system with different loads of 7.5 kW resistive during 0.8 - 0.9 seconds, 10.5 kW resistive during 0.9 – 1.0 seconds, 7.5 kW 0.85 power factor (pf) reactive during 1 - 1.1 seconds, 7.5kW 0.8 pf reactive during 1.1 – 1.2 second and 6.9 kW 0.85 pf reactive during 1.2 -1.3 seconds. The DVR improve capability of SEIG with improvement in voltage regulation and power quality of source voltage (V_s) and source current (i_s) for all above load's conditions. DVR maintaining constant source voltage, load voltage and DC link voltage for constant speed power generation with different load conditions. The fig. 6 shows injected compensation voltage (V_c) is lagging approximately 90^0 from load current (i_L) for provide leading kVAR to maintain constant source and load voltage. The SEIG-DVR systems are also capable to deliver more than rated power with maintains constant source voltage and corresponding increased current. The ratings SEIG-DVR systems are shown in table 1. The DVR require reduce rating and cost of IGBT based voltage source converter for same power generation. The 7.5 kW, 415V, 4 poles SEIG has been used.

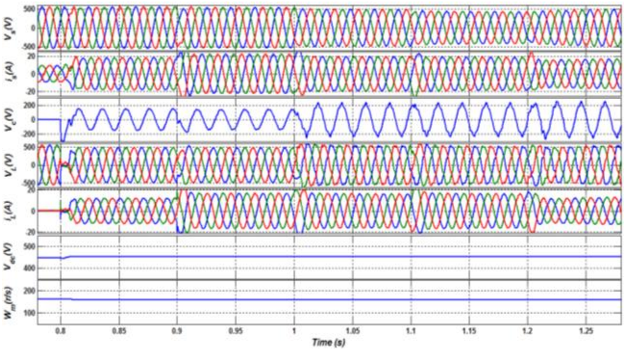

Figure 5 SEIG-DVR with change in resistive and inductive loads

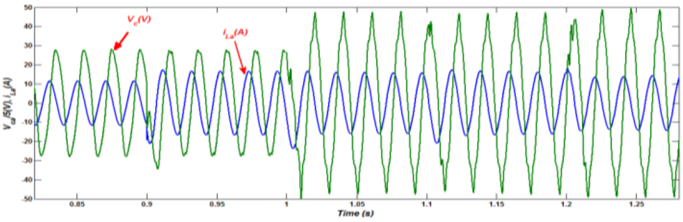

Figure 6 Compensation voltage (V_c) and load current (i_L) for SEIG-DVR with change in resistive and inductive loads

VI CONCLUSION

The performance of the SEIG-DVR system has been demonstrated for supplying both three-phase linear and nonlinear loads in isolated power generation driven by a constant speed prime mover. A 7.5 kW, 415 V, 50 Hz, Y-connected Self-Excited Induction Generator (SEIG) integrated with a DVR-based series voltage controller has been designed, modeled, and simulated using the MATLAB environment. The simulation results confirm the effective operation of the DVR in maintaining voltage regulation and improving power quality under varying load conditions. The proposed DVR controller ensures stable voltage at the load terminals, even in the presence of nonlinear loads, by effectively managing reactive power. Additionally, the system achieves this with reduced ratings, size, and cost of the IGBTs used in the VSC, making it a cost-effective solution for isolated renewable energy-based power generation systems. The approach enhances system reliability and power quality without the need for bulky compensation devices.

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