Abstract—This paper describes the mathematical modelling of self-excited induction generators (SEIGs) with are improved electronic load controller (IELC) for microhydel applications supplying variety of loads. In small hydro plants, governor unit of turbine can be eliminated using IELC, which is simple and cost effective. The improved electronic load controller is a combination of a three-phase insulated gate bipolar transistor (IGBT) based current controlled voltage source inverter (CC-VSI) and a high frequency DC chopper which keeps the generated voltage and frequency constant in spite of change of balanced/unbalanced loads. A dynamic model of the SEIG- IELC suppling different types of loads using stationary d-q axes reference frame is developed for predicting the behavior of the system under transient conditions. The simulation is carried out for compensation of balanced/unbalanced loading conditions. The simulated results show that generated frequency and voltage remain constant with change in load. The proposed IELC acts as reactive power compensator, harmonic eliminator, load balancer and load controller.

Key Words: Self-excited induction generator, improved electronic load controller, Microhydel, Voltage and Frequency Regulation.

I. INTRODUCTION

In hilly and isolated areas plenty of hydro potential is available. These hydro potentials can be used to drive hydro turbine to generate the electricity. However, induction machine can be used as a generator provided its reactive power requirement is fulfilled by capacitor banks, is called self-excited induction generator (SEIG). The SEIG has advantages like simplicity, low cost, rugged, maintenance free, absence of DC, brushless etc. as compared to the conventional synchronous generator.

The analysis of the SEIG is complicated because its operation depends on the prime-mover speed, capacitor and load. Capacitance requirement with load and speed for the SEIG is reported in the literature [1-3]. Considerable literature is also reported on the transient analysis of the SEIG under balanced/unbalanced resistive, reactive and motor loads. In the literature [4-6], d-q axes modeling are reported for the transient analysis of SEIG under balanced and unbalanced excitation system. Jain et al. [7] have given a generalized model for the transient analysis of SEIG under symmetrical and unsymmetrical conditions.

In hydro plants, a turbine is used with governor to control power generation. In micro hydel application, water is available free of cost then a turbine without governor can be used as prime mover and capacitors are connected across the SEIG according to the rated power and the constant voltage can be maintained by electronic load controller (ELC) [8-14]. Thus electronic load controller (ELC) keeps the load constant on the SEIG under balanced and unity pf load. But in case of unbalanced loads, SEIG currents and voltage are unbalanced and at lagging PF loads SEIG voltage drops down because SEIG and load demands the reactive power, which is not fulfilled by the ELC. Most of the reported electronic load controllers are based on controlled and uncontrolled rectifier with DC chopper, which injects the harmonics in the SEIG. Due to harmonics injection, SEIG is derated and voltage and current of SEIG are non-sinusoidal. In case of unbalanced load, SEIG is further derated due to presence of positive and negative sequence component. The current controlled voltage source inverter with self-supporting DC bus employed as static compensator (STATCOM) can be used for filtering the harmonics and balancing the load. In the reported literature [15-19] STATCOM acts as a voltage regulator to maintain constant voltage for the SEIG. Larsen et al [15] have mentioned the advantage of the STATCOM. Marra and Pomilio [19] have given the VS-PWM bi-directional converter for SEIG, which can regulate the frequency and voltage in case of balanced and linear load. However, there is hardly any attempts on the voltage and frequency regulation under unbalanced and non-linear loads.

In this paper, an improved electronic controller (IELC) is presented which is the combination of CC-VSI and DC chopper. The IELC consists of current controlled voltage source inverter, which acts as a voltage regulator, and a DC chopper at DC bus of VSI keeps the rated power on the SEIG. A control technique is developed such that SEIG generates the constant power. In microhydel applications, turbine speed is kept constant and for a constant value excitation capacitor SEIG generates constant voltage, frequency and power, which is known as single point operation. Connecting the capacitor across the SEIG according to the balanced and unity PF power can reduce the rating of the CC-VSI. In this case, load balancing, reactive power compensation and harmonic elimination should be provided for the load by the CC-VSI. A mathematical model is developed for the transient analysis of IELC under the resistive, reactive and nonlinear loads with balanced/unbalanced conditions. The improved electronic load controller acts as a voltage and frequency regulator, harmonic eliminator, and load balancer.

II. SYSTEM CONFIGURATION AND CONTROL SCHEME

The schematic diagram of SEIG with excitation capacitor, improved electronic load controller ((CC-VSI)+DC chopper),
The consumer load and control scheme is shown in Fig. 1. Excitation capacitors are selected to generate the rated voltage of SEIG at no load. The reactive power requirement of SEIG and load is fulfilled by the CC-VSI with self-supporting DC bus. The SEIG generates constant power and when consumer power changes then DC chopper of IELC dumps the difference power (generated - consumed) by consumers in the IELC. Thus, generated voltage and frequency are not affected by the application and removal of the consumer load.

The IELC consists of a three-phase IGBT based current controlled voltage source inverter, DC bus capacitor, DC chopper 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 self-supporting DC bus. DC Chopper is used to control dump power in IELC due to change in the consumer load.

The control technique to regulate the terminal voltage, load balancing, and harmonic elimination of the SEIG is based on the controlling of source currents (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. Another set of quadrature unit vectors (w_a, w_b, and w_c) is sinusoidal function obtained from in-phase vectors (u_a, u_b, and u_c). To regulate AC terminal voltage (V), 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^P') for AC voltage control loop decides the amplitude of reactive current to be generated by the CC-VSI. Multiplication of quadrature unit vectors (w_a, w_b, and w_c) with the output of PI based AC voltage controller (I^P') yields the quadrature component of the source reference currents (i_a, i_b, and i_c). For self-supporting DC bus of CC-VSI, its DC bus voltage is sensed and compared with DC reference voltage. The error voltage is processed in another PI controller. The output of the PI controller (I^P') decides the amplitude of active current. Multiplication of in-phase unit vectors (u_a, u_b, and u_c) with output of PI controller (I^P') yields the in-phase component of the source reference currents (i_a, i_b, and i_c). 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, lower device of the inverter phase is turned on and upper device turned off. If the amplified current error signal is equal to or less than the triangular carrier wave lower device is turned off and upper device is turned on.

The generated power by the SEIG is maintained constant by the third PI controller. The generated power is compared with the reference rated power. The PI controller processes output error of the comparator. The output of the PI controller is compared with triangular wave. If output of PI controller is more than the triangular wave, gate pulse of chopper switch (IGBT) is made high and its current increases through chopper switch so that SEIG experience same load. If controller output is less than PWM carrier triangle wave, gate pulse of IGBT is low and chopper switch is made open.

HI. MODELLING OF SEIG-IELC SYSTEM

The schematic diagram is shown in Fig. 1, which consists of SEIG, IELC, its control scheme and loads. The mathematical modelling of each component is as follows.

A. Modelling of control scheme of IELC

Three-phase voltages at the SEIG terminals (v_a, v_b, and v_c) are considered sinusoidal and hence their amplitude is computed as:

\[ V = \left\{ \frac{2}{3} (v_a^2 + v_b^2 + v_c^2) \right\}^{1/2} \quad (1) \]

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

\[ u_a = \frac{v_a}{V}; \quad u_b = \frac{v_b}{V}; \quad u_c = \frac{v_c}{V}. \quad (2) \]

The unit vectors in phase 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 \( u_c \) [17] as:

\[ w_a = \frac{u_a}{V} + \frac{u_a}{V} \]

Fig. 1 Schematic and power diagram of the improved SEIG-IELC system.
is the amplitude of reference AC terminal sampling instant is:

\[ V_{er(n)} = V_{ref(n)} \]

Where \( V_{er(n)} \) is the amplitude of reference AC terminal voltage and \( V_{ref(n)} \) is the amplitude of the sensed three-phase AC voltage at the SEIG terminals at \( n \text{nt} \) instant. The output of the PI controller \( (V_{cm}^*) \) for maintaining AC terminal voltage constant at the \( n \text{nt} \) sampling instant is expressed as:

\[ V_{cm}^* = 1 \cdot W \cdot + \cdot Kp, \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \cdot \·...
D. Modelling of SEIG

The dynamic model of the three-phase SEIG is developed using stationary d-q axes references frame, whose voltage-amper equation are [17]:

\[ [v] = [L] [i] + [L] [i] + [H] [G] [i] \]  \tag{39}

from which, current derivatives can be expressed as:

\[ \dot{[i]} = [L]^{-1} [v] - [R] [i] - \text{co} G [i] \]  \tag{40}

Where \([v] = [i], [v] = [i], [v] = [i] \) and \([v] = [i], [v] = [i], [v] = [i] \).

The electromagnetic torque balance equation of SEIG is:

\[ T_M = T_M + J(\omega) \]  \tag{42}

The derivative of rotor speed of the SEIG from eqn. (42) is:

\[ \dot{\omega} = \frac{T_M}{J} - \frac{T_M}{J} = \frac{P}{2J} \]  \tag{43}

The SEIG operates in the saturation region and its magnetizing characteristics is non-linear in nature. Therefore the magnetizing current should be calculated in each step of integration in terms of stator and rotor currents as:

\[ I_m = \frac{V(\delta, + \delta) + (i_m + i_e)}{1} \]  \tag{45'}

Magnetizing inductance is calculated from the magnetizing characteristics between \(L_m\) and \(L_m\). Relation between \(L_m\) and \(L_m\) is obtained by synchronous speed test [17] and can be written as:

\[ L_m = 0.1407 + 0.0014 L_m - 0.00012 L_m + 0.000048 L_m^3 \]  \tag{47}

E. AC line voltage at the point of common coupling

From direct and quadrature axis currents of the SEIG (\(i_d\) and \(i_q\)) are converted to in three-phase (a, b and c). The derivative of AC terminal voltage of the SEIG is defined as:

\[ P V_v = \frac{(i_d - i_a + \omega - (\omega - i_a) - i_b)}{3C} \]  \tag{48}

\[ P V_v = \frac{(i_d - i_a + \omega) + 2(i_b - i_a - i_c)}{3C} \]  \tag{49}

\[ v_a + v_b + v_c = 0 \]  \tag{50}

where \(i_a, i_b\) and \(i_c\) are SEIG stator line currents, \(i_m, i_q\) and \(i_k\) are 3-phase load currents and \(i_m, i_q\) and CC-VSI currents. C is per phase no load excitation capacitor value connected parallel to SEIG.

IV. RESULTS AND DISCUSSION

The SEIG system with IELC feeding resistive and reactive balanced/unbalanced loads is simulated and results are shown in Figs. 2-4. For the simulation, a 7.5 kW, 230V, 15.6 A, 4-pole machine has been used as a generator and parameters of the generator are given in Appendix.

A. SEIG-IELC System behaviour Feeding Three-phase resistive load

**Fig.2** Performance waveforms of three-phase SEIG-IELC system supplying resistive load (7.5 kW)
on SEIG. At application of load and under steady state, generator speed remains constant, which shows that generated voltage and frequency are constant. Under three-phase load on the SEIG, IELC current decreases which shows power on the SEIG remains constant. Load currents, generator currents and voltages are sinusoidal and harmonic free.

B. SEIG-IELC system behavior Feeding Three-phase Reactive load

Fig. 3 shows the transient waveforms of the three-phase SEIG-IELC supplying reactive load (0.8 PF). At 5.2-sec one phase load is disconnected from the SEIG consequently IELC current of one-phase increases to balance the SEIG system. At 5.3-sec. two-phases of load is disconnected from the load and hence IELC currents of two phases increase for balancing the SEIG system. At 5.4-sec. one-phase and 5.5-sec. two-phases of load are reconnected on the SEIG. In this case, IELC currents decrease because SEIG system is balanced. Chopper current also increases and decreases when consumer load decreases and increases respectively which shows that the generated power of the SEIG remains constant in spite of variation in consumer load. In reactive load, generator voltage constant and perfectly sinusoidal which shows that IELC is acting as a voltage regulator and load balancer. The speed of SEIG remains constant, which shows that the generator is delivering constant voltage, frequency and power.

SEIG-IELC system behavior Feeding Three-phase Non-Linear load

Fig. 4 Transient waveforms of three-phase SEIG-IELC system supplying non-linear load
Fig. 4 shows the SEIG-IELC system behavior supplying the non-linear load. A three-phase rectifier with R load and capacitive filter is taken as a non-linear load. At 6.5-sec loading on the rectifier load increases because of that load current increases. It is observed from the figure that generator voltages and currents remain constant and sinusoidal. At 6.75-sec, loading on the rectifier load is decreased consequently rectifier load currents decrease however the SEIG voltages and currents remain constant and sinusoidal which shows that IELC is acting as a harmonic eliminator. The SEIG speed remains constant in complete duration, which proves that it is generating constant frequency, voltage and power.

V. CONCLUSION

The developed mathematical model of three-phase SEIG-IELC system has been found an appropriate tool to study the behavior of SEIG with IELC at different types of loads under transient conditions. Simulations have been carried out and simulated results show that SEIG terminal voltage and frequency remain constant while supplying the resistive, reactive and non-linear loads with balanced/unbalanced conditions. When unbalancing of load takes place then IELC generates compensating currents and balances the generator currents and voltage thus IELC acts as load balancer. In case of variation in consumer load, chopper of IELC operates accordingly and generated power of the generator remains constant. The SEIG generates constant voltage and frequency as it is operating at constant power. Therefore, improved electronic load controller acts as voltage regulator, frequency regulator, load balancer and harmonic eliminator.

VI. APPENDICES

A. STATCOM control parameters

\[ U = 1.5 \text{ rad/H}, \quad R_e = 0.05 \quad \text{SI} \quad \text{and} \quad C_{pi} = 4000 \mu \text{F}. \]

AC voltage PI controller: \( K_{pi} = 0.05, \quad K_{pi} = 0.4 \).  
DC bus voltage PI controller: \( K_{pi} = 0.04, \quad K_{pi} = 0.005 \).
Carrier frequency = 20 kHz
Power PI controller \( K_{pi} = 0.4 \quad K_{pi} = 0.05 \).

B. Machines parameters

The parameters of the induction machines are given below.

\[ R_s = 1.0Q, R_r = 0.77Q, X_{1p} = X_{1q} = 1.0 \quad Q, \quad J = 0.1384 \text{ kg/m}^2 \]

VII. REFERENCES