Performance Analysis of Autonomous Micro Hydro Power Plant with Induction Generator
Sonam Singh
M.Tech Student
Department of Electrical Engineering
Madan Mohan Malaviya University of Technology, Uttar Pradesh, India

Abstract:
This paper based on simulation and result of the SEIG-ELC system that can be installed in the micro hydro power plant at off-grid locations and remotes areas to feed static loads. The steady state and transient performance characteristics of a three-phase self-excited induction generator with electronic load controller (ELC) under varying loading conditions have been presented. Experimental are performed to study and verify the proposed control schemes for the regulation of voltage and frequency of all overall generating system. This paper deals with simulation of SEIG-ELC based micro hydro power plant using the mathematical modelling of different components of it presented and verified experimentally for the loaded and unloaded conditions. Results which are inaccessible in the experimental setup have been predicted using the simulation.

Keywords: Micro-Hydro Power System, Sim Power System, Electronic load controller (ELC), IGBT, Induction Generator

1. INTRODUCTION

In the present circumstances of energy harnessing is a critical challenge due to increasing demand of energy with depletion in energy resources like coal, oil etc. Remote areas, islands, military equipment, ships, hilly areas, etc are the areas that are mainly isolated from the power system grid and require a generating system. However because of depletion of fossil fuels and global warming, the requirement of locally available natural sources has increased such as wind, small hydro, etc. So, the present interest is growing towards the renewable energy for the generation of electric power. In remote and under undeveloped areas consumers those who are far from distribution grid cannot access power or electricity. Thus one reliable solution to obtain power supply is provided by a micro hydro power system through induction machine installation. [1,2,3,4]. Most micro-hydro schemes are located in the mountainous regions of developing countries, such as the Andes and Hindu-Kush Himalayan Region, which includes Afghanistan, Bhutan, China, India, Myanmar, Nepal and Pakistan. By using appropriate designs, local skills and local manufacture these schemes can be more cost-effective than large hydro project. Micro hydro is a type of hydroelectric power that typically produces up to 100 kW of electricity using the natural flow of water. [3] For this micro hydro power plant power can be generated by using asynchronous generator or induction generator (IG) driven by the prime mover of the hydro. These installations can provide power to remote areas like home or small community. In this paper, an effort has been made for an analysis of autonomous micro hydro power plant with SEIG and its transient behavior has been analyzed by connection and disconnection of resistive load. The residual magnetism in the machine is in use into account in simulation process as it is necessarily required for the generator to self excite. The simulations have been carried out developing model in MATLAB/SIMULINK [2]. The paper has been well thought-out in different sections: section 2&3 describes SEIG mathematical model, section 4 describes SIMULINK model of SEIG with load. In section 5, results have been obtained for two cases of excitation under connection and disconnection of resistive load.

2. INDUCTION GENERATOR

Now-a-days induction generators are widely used in wind based power generation system and in micro hydro electric energy generation system. Mostly, induction machines that are available in the market are the induction motor. Three phase balanced power supply is given to the stator winding of a three phase induction motor by which three phase currents flow in the stator winding which produces a rotating magnetic field. To induced E.m.f.s in rotor, rotating flux wave cuts the stationary rotor conductors. As the rotor circuit is short circuited, this induced E.m.f.s give rise to current in the rotor conductors. The interaction of these rotor currents with rotating flux wave produces torque in the rotor of a three phase induction motor and as a result rotor begins to rotate. When the slip of machine is negative i.e. the rotor rotates with speed above synchronous speed then induction machines acts as a generator. When slip is negative, the rotor E.m.f., rotor current and power becomes negative.[21,22] Under this condition, the developed electric torque is negative (opposite to prime mover) and the machine delivers power to supply mains. Induction generator is also called asynchronous generator.

2.1 Classification of Induction Generators [1]

The induction machine plays a dual role like as either a motor or generator which provides several advantages for hydro and wind power plants. It has different application in different areas and depending upon them it has many classifications [1, 3, 11, 25].

2.2 Classification of IG on the basis of excitation process

As IG needs reactive power support from some external source, IGs are classified depending on the mode of excitation as:
A. Grid Connected Induction Generator
The grid connected induction generator takes its reactive power for excitation process from the grid supply, so it is called grid connected induction generator. It is also called autonomous system. In this system generator is driven by a prime mover above its synchronous speed and hence the slip is negative in case of grid connected induction generator. Fig. 1 shows a grid connected induction generator. The power factor of the grid connected induction generator is fixed by its slip and its equivalent circuit parameters and not affected by the load.

![Figure.1. Grid connected induction generator](http://ijesc.org/)

B. Self-excited Induction Generator
Self-excited induction generator (SEIG) employs cage rotor construction with shunt capacitors connected at its terminals for excitation. The shunt capacitors may be either constant or variable. In Fig. 2, a capacitor bank is connected across the stator terminals of a 3-phase IG in order to supply the reactive power for self excitement process [1,6,7,8,9,10].

![Figure.2. Self-excited induction generator](http://ijesc.org/)

3. ELECTRONIC LOAD CONTROLLER
In small hydro power scheme, the cost of hydraulic governor is a major fraction of the total system cost i.e. up to 30% and it is also technically complicated and requires trained maintenance. The provision of low cost stand-alone generation in small hydro applications (up to 500 kW), has a great significance. As the turbine operates at constant flow due to use of speed regulator that controls the amount of water enters in turbine then there is high mechanical stress, high mechanical constant and speed governing is required additional cost. Cost reduction may be obtained by utilizing electronic load controller (ELC) to regulate the supply frequency. [14] The goal of an ELC is to minimize the cost of a small hydro installation by using the hydraulic governor with an electronic circuit. Water flow to the turbine remains constant at a rate required to produce optimum power from the generator. No effort is made to adjust this flow once the initial setting has been done. [2,11,15,16,27] There are numerous of research paper has been published on voltage and frequency controllers for an IG driven by uncontrolled micro-hydro turbine for single-phase as well three phase power applications. Most of these controllers that have been proposed are reported as electronic load controllers (ELCs) which maintain the constant power to regulate constant voltage and frequency at the generator terminal. To generate the rated voltage at desired power the value of excitation capacitor is selected.[2] The basic principle for controlling the constant power at the generator terminal is done by employing an ELC and operates it in a way so that the total power (absorbed by the load controller and consumer load) is constant. If consumer demand is less, the balance of generated power is absorbed by the ELC. Change in consumer load, a ballast load is used so that the total load on the generator remains constant as:

\[ P_{out} = P_e + P_d \]

Where, \( P_{out} \) = Generated power of the generator (which should be constant), \( P_e \) = Consumer power, \( P_d \) = Dump load power.

4. SIMULINK MODEL OF PROPOSED SYSTEM AND THEIR RESULTS
Experimental are performed to study and verify the proposed control schemes for the regulation of voltage and frequency of all overall generating system in Fig 5. The simulation of SEIG-ELC based micro hydro power plant using the mathematical modelling of various components of it presented. The parameter of various components of the system are given in Appendix - A. [27]

4.1 MODELING OF ELC:
The considered ELC consists of an uncontrolled diode rectifier bridge, a control circuit, a solid-state switch (IGBT) operating as a chopper and the dump load (resistors) as shown in Fig. 3. The stator voltage is fed to the ELC circuit through a small value of source inductance (\( L_d \)) and resistance (\( R_d \)). A filtering capacitor (C) is connected across the rectifier output to filter out the ac ripples of the dc voltage [10, 11, 12, 18, 19]. The volt–current relation of the complete load controller system is:

\[ v_{max} = 2R_d i_d + 2L_d i_d + v_d \]  

(1)  
From which the derivative of ELC current (\( i_d \)) is defined as:

\[ p_{dc} = \frac{v_{max} - v_d - 2R_d i_d}{2L_d} \]  

(2)

Where, \( v_{max} \) is the maximum value of ac line voltages (\( v_a, v_b, v_c, -v_a, -v_b, -v_c \)) depending on which diode pair is conducting and \( v_d \) is the dc-link voltage. The ac dump load currents in the three phases (\( i_{d_a}, i_{d_b} \) and \( i_{d_c} \)) are obtained by using the magnitude of \( i_d \) and direction (sign) corresponding to conducting pairs of diodes.

Charging and discharging of the filter capacitor is expressed as:

\[ pv_d = \frac{c}{R_{d1}} (i_{d_a} - i_{d_c}) \]  

(3)

(with \( i_{d_a} = \frac{v_{d_a}}{R_{d1}} + S \frac{v_{d_b}}{R_{d2}} \))

Where, S is the switching function indicating the switching status of the IGBT switch. When the switch is closed, then \( S = 1 \) and when the switch is opened, then \( S = 0 \). The switching states of the IGBT (S = 1 or 0) depend on the output of Pulse Width Modulation (PWM) wave with the varying duty cycle which compares the output of Proportional Integral (PI) voltage controller with the saw tooth carrier wave as shown in fig.3.

![Figure.3. Schematic diagram of ELC with Control circuit](http://ijesc.org/)
4.2. MODELING OF CONTROL SCHEME OF ELC

The closed-loop control is the heart of ELC and it plays a vital role in keeping the terminal voltage of the SEIG constant. The SEIG output voltage is sensed and converted to dc through a single-phase rectifier circuit for the feedback signal, as shown in Fig. 3. A small capacitor ($C_f$) is used to filter the ripples out from the rectified voltage to be used as the feedback signal ($v_{df}$) and it is compared with the reference voltage ($v_{ref}$) [24].

The error voltage is fed to a PI voltage controller. [14]. The output of the controller is compared with the sawtooth carrier waveform to result in the PWM signal to alter the duty cycle of the chopper. The single-phase rectifier circuit used in this feedback loop is modelled as

$$v_t = R_{ff}i_{df} + L_{ff}i_{df} + K v_{df} \quad (4)$$

Here, $v_t$ is the absolute value of the instantaneous value of the ac output voltage of the step-down transformer corresponding to the SEIG voltage ($v_e$ or -$v_e$) depending on which diode pair is conducting and $v_{df}$ is the dc voltage. $R_{ff}$ and $L_{ff}$ are the resistance and leakage inductance of the step-down transformer, respectively. K is a constant depending upon the tapping of the potentiometer.

From (4), the derivative of current ($i_{df}$) is given as

$$\frac{di_{df}}{dt} = \frac{v_e - v_{df} - R_{ff}i_{df}}{L_{ff}} \quad (5)$$

Charging and discharging of the filtering capacitor ($C_f$) at the output of the single-phase uncontrolled rectifier is as follows

$$\frac{dv_{df}}{dt} = \frac{I_{df} - R_{ff}i_{df}}{C_f K} \quad (6)$$

Voltage $v_{df}$ is used as the feedback voltage signal and compared with the reference signal. The resulting error is fed to the PI voltage controller. The analog PI voltage controller modeled as

$$v_{p} = K_1 \frac{v_{ref} - v_{df}}{v_{ref}} \quad (7)$$

$$v_{p2} = K_2(v_{ref} - v_{df}) \quad (8)$$

The output signal of the PI controller ($v_o$) is $v_o = v_{p1} + v_{p2}$.

Where $v_{ref}$ is the reference voltage, $K_1 = R_{ff}/R_1 = 34.55$ and $T_{ce} = R_{ff} C_f = 0.1935$ as $R_{ff} = 194 \Omega$, $R_1 = 5.6 k \Omega$, $C_f = 1 \mu F$, $R_{pa}$ and $R_{pb}$ are the input resistance, feedback resistance, and feedback capacitance used in the analog PI controller.

The output of the PI controller ($v_o$) is compared with the sawtooth PWM carrier waveform. The saw tooth waveform is defined as

$$v_{st} = \frac{A_{st} \cdot t}{T_p} \quad (9)$$

Where $A_{st}$ is an amplitude of the sawtooth carrier waveform (2.38 V), $t$ is time in microseconds, and $T_p$ is a time period (200μs) of the sawtooth PWM carrier wave. The PI controller output voltage ($v_o$) is compared with the sawtooth carrier waveform and output is fed to the gate of the chopper switch (IGBT), which is operated as:

$$S = 1, \quad \text{when} \quad v_{o} > v_{th}, \quad \text{and} \quad S = 0, \quad \text{when} \quad v_{o} < 0.$$  

Where $S$ is the switching function used for generating the gating signal of the IGBT of the chopper of the ELC.

The PWM signal is fed to an opto-isolator, which isolates the power circuit and the control circuit.[14,24] The opto-isolator inverts the signal at its output and hence a single stage transistor amplifier is used at its output, which again inverts the signal to regain the original signal. This signal is then fed to a push-pull amplifier, which drives the IGBT chopper with the appropriate duty cycle.

4.3 STATIC LOAD:

A schematic of three phase resistive load is shown in Fig. 4.

**Figure 4. Three phase resistive load**

For the three-phase delta connected resistive load as shown in Fig. 4, the line currents are given by the following relations:

$$i_{al} = i_{pa} - i_{pc} = \left( \frac{v_e}{R_{pa} + R_{pb}} \right) - \left( \frac{v_e}{R_{pa} + R_{pb}} \right) \quad (10)$$

$$i_{bl} = i_{pb} - i_{pa} = \left( \frac{v_e}{R_{pa} + R_{pb}} \right) - \left( \frac{v_e}{R_{pa} + R_{pb}} \right) \quad (11)$$

$$i_{cl} = i_{pc} - i_{pb} = \left( \frac{v_e}{R_{pa} + R_{pb}} \right) - \left( \frac{v_e}{R_{pa} + R_{pb}} \right) \quad (12)$$

4.4 SIMULINK MODEL OF SEIG-ELC SYSTEM WITH RESISTIVE LOAD

The developed SIMULINK MODEL of SEIG-ELC system supplying three phase resistive load.

**Figure 5. SIMULINK Model of SEIG-ELC system with Resistive load**

4.5 SIMULATION RESULTS

The objective of the work is to simulate a self excited induction generator (SEIG) with electronic load controller (ELC) under various transient conditions. The complete MATLAB Simulink model is developed with the help of SimPower systems block sets.

Following cases are taken for study:

1. Process of Self-excitation and Voltage build up,
2. Sudden application and removal of resistive load.

4.3. Process of Self-excitation and Voltage Build up

In this case, SEIG built up process of the stator voltage when the rotor of the induction machine is driven at 1575 rpm under no-load conditions has been shown in Fig[4]. To accelerate the Induction machine above its synchronous speed with uncontrolled prime mover and then connect a suitable capacitor bank at its leads. Initially the induction generator electromagnetic force is zero due to lack of excitation after capacitor are connected machine will absorb reactive power to
develop its magnetic field and Emf will gradually increase until the steady-state regime is achieved.

**Figure 6. Transient waveforms of SEIG line voltages Va, Vb, Vc (Volt) during the voltage build up**

Capacitor banks provide the necessary magnetizing current to start the voltage build up process which is determined by feeding the induction machine without load and measuring the current as a function of the terminal voltage variation. The value of each self excitation capacitors is fixed to 170 μF per phase is started at no load.

**Figure 7. Transient waveforms of SEIG capacitor line currents Ica, Icb, Icc (Amp) during the voltage buildup**

**Figure 8. Frequency f(Hz) of generated voltage**

**Figure 9. Electromagnetic torque Te (N-m)**

**Figure 10. Rotor speed Nr (rpm) developed in SEIG**

The simulation results show that self excitation can be established and speeds on self-excitation examine. It can be observed from these results that the voltage builds up starts early as the speed increases up to 1575 rpm around 0.4 s to attain the steady state voltage of the SEIG. Figs. 6 to 10 show voltage build up for all three lines at SEIG terminals, capacitor currents, Electromagnetic torque, Rotor speed and frequency of generated voltage, respectively.

### 4.6. Sudden Application and Removal of Resistive Load

Two topologies used, sudden application and sudden removal of resistive load of 1500 W are considered.

**Figure 11. Schematic diagram of SEIG feeding resistive load**

Schematic diagram of 3-phase SEIG with ELC feeding resistive load is shown in the Fig11.

#### 1. Sudden Connected of Resistive Load

Initially SEIG is operated at no load. At t = 1 sec., ELC is connected at SEIG terminals and at t=1.2 sec., a resistive load of 1500 W is suddenly connected to the SEIG terminals. Figs11 show the sudden application of resistive load. It is found that the line-A voltage and frequency of generated voltage at SEIG terminals remain almost unchanged, this ensuring high degree stability for the proposed configuration.

**Figure 12. Voltage and current waveforms of line-A at the SEIG terminals due to sudden application of resistive load**

In fig 12 shows Voltage and current (Va & Ia) waveforms of line-A at the SEIG terminals during sudden switching resistive load. After load connected at t=1.2 Voltage decreases around 528 V, the ELC-DC voltage decreases voltage regulator reacts diminishing the amount power dissipated by dump load. The current through the IG remains stable at 8.2 Amp and active power delivered by IG circulates through the ELC thus converter carries current.

**Figure 13. show the waveforms of capacitor currents of line-A at SEIG terminals sudden application of resistive load**

Fig.13: show the waveforms of capacitor currents of line-A at SEIG terminals sudden application of resistive load.

**Figure 14. Waveforms of main load current of line-A due to sudden application of resistive load.**
In the beginning as there is no load connected at IG leads, the active flows through the ELC and consumed by dump load resistance. Fig.14 represent the main load current and ELC current of line-A, respectively.

Figure.15. Waveforms of ELC current of line-A due to sudden application of resistive load
Fig.15 shows the variation in electromagnetic torque, rotor speed due to switching of resistive load, respectively.

Figure.16. Electromagnetic torque and rotor speed in SEIG due to sudden application of resistive load

Figure.17. Frequency of generated voltage due to sudden application of resistive load.
Fig.17 shows frequency of generated voltage due to switching of resistive load, respectively the frequency will decreases 48.6 Hz after load connected, but return almost instantly to rated value of 50 Hz. The above simulation results demonstrated when the consumer load is applied, controller responds and current flowing through ELC is reduced to control total generated power at generator terminal constant. Accessibility of sufficient excitation capacitor keeps constant voltage at generator terminals.

II. Sudden Disconnected of Resistive Load
Initially SEIG-ELC system is operated with 1500 W resistive load. Suddenly resistive load of 1500 W is removed at t= 3 sec from the SEIG terminals. When a resistive load of 1500 W is suddenly removed across the SEIG terminals, it is seen that peak value of the ELC input current of line-A increases. Fig.18 shows ELC current of line-A. The duty cycle of the chopper switch is increased. This indicates that the power is transferred from main load to the dump load and accordingly, the total power supplied by the SEIG remains unchanged. Thus the terminal voltage of the SEIG is maintained constant.

Figure.18. Voltage and current waveforms of line-A at the SEIG terminals due to sudden removal of resistive load
The waveforms due to the removal of resistive load of 1500 W at t=3 sec. are shown in Figs.18 to23. In this case, the line voltages and currents and the output voltage of the SEIG remain same after removal of resistive load.

Figure.19. Capacitor current of line-A at due sudden removal of resistive load

Figure.20. Waveforms of main load current of line-A due to sudden removal of resistive load.

Figure.21. Waveforms of ELC current of line-A due to sudden removal of resistive load

Figure.22. Rotor speed and Electromagnetic torque and in SEIG due to sudden removal of resistive load

Figure.23. Frequency of generated voltage due to sudden removal of resistive load
Fig.12to Fig.23 shows the transient waveforms of SEIG voltages, SEIG current, consumer load current, ELC current, and capacitor current at the application under sudden resistive load (1.5 kW) and removal of sudden load.

5. CONCLUSIONS
This paper present a work, on the control system which consist of a voltage source inverter (VSI) to stabilize the frequency and a dump load (DL) to deal with voltage regulation for an autonomous micro hydro power plant locate with induction generator. It has been observed that the ELC is capable of handling the transients caused by load switching. The performance of the SEIG with load controller has been simulated for transient conditions such as process of self-excitation, voltage build up, and switching of resistive load. For resistive main load, the stator line voltages of the SEIG remain same before and after application of main load. The performance analysis of SEIG has been indomitable for two different cases. It is observed that the performance of
SEIG under connection and disconnection of resistive load, excitations, the stator voltage, stator currents, load currents and capacitor currents are balanced. In this case the voltage build up is quite fast because of balanced excitation. Under unbalanced excitation the electromagnetic torque is having oscillations.

Appendix A.
(A)Parameters of SEIG [15]:
For simulating SEIG, an Induction machine rated: P= 3.7 kW, 3-phase, 4-pole, 50 Hz,V= 415 V, I= 7.6 A, Y-

connected induction machine is used with following parameters:
\[ R_s = 0.6833 \, \Omega \], \[ R_r = 0.606 \, \Omega \], \[ L_m = 0.004152 \, \text{H} \], \[ L_p = 0.004152 \, \text{H} \]
The magnetizing inductance \( L_m \) is related to the magnetizing current as \( L_m = 0.015486 \, \text{H} \)
The moment of inertia of the induction machine including the prime mover coupled on its shaft is 0.166 kg·m²

(B)Parameters of Prime-mover Characteristics
The following parameters are used for simulating the characteristics of prime mover:
\[ k_1 = 600 \] and \[ k_2 = 3.5 \]

(C) Parameters of Electronic Load Controller and Control Circuit [25] :
For ELC and its control circuit, values of different parameters are as follows:
\[ R_L=84 \, \Omega \], \[ C_a=380 \, \mu \text{F} \], \[ R_i = 1 \, \Omega \], \[ L_i = \frac{0.001}{1} \, \text{H} \]
\[ R_b=194 \, k \, \Omega \], \[ R_f=5.6k \, \Omega \], \[ C_f=1 \, \mu \text{F} \]
\[ R_g=1 \, \Omega \], \[ L_{ef}=0.0085 \, \text{H} \]
\[ C_s=40 \, \mu \text{F} \], \[ R_{lf}=40 \, k \, \Omega \]

(d) Parameters of Resistive load-1500kw.

6. REFERENCES


