

Self-Excited Induction Generators (SEIG) Simulation and Behavioral Analysis for Application in Microgrid Hydro Power Generation

Anil Gupta^{1*}, Manisha Dubey²

¹Ph.D. Scholar Electrical Engineering Department, MANIT, Bhopal, India

²Prof. Electrical Engineering Department, MANIT, Bhopal, India

¹anilrgpv@gmail.com, ²manishadubey6@gmail.com

HOW TO CITE:

Anil Gupta, Manisha Dubey
(2026). Self-Excited Induction
Generators (SEIG) Simulation and
Behavioral Analysis for Application
in Microgrid Hydro Power
Generation.
International Journal of Special
Education, 41(16s), 1258-1270

ABSTRACT:

Integration of Renewable Energy Sources into Microgrids has attracted much research interest because of the high demand for green and sustainable sources of electricity production. In this research paper, simulation and behavioral analysis of Self-Excited Induction Generators (SEIG) used for power generation purposes along with microgrid hydro turbine generators is presented. The performance behavior of the self-excited induction generator is analyzed in terms of dynamic performance in the process of voltage building up, during steady state and during load changes. In order to perform analysis of the performance behavior, a detailed model of the self-excited generator is created using the d-q reference theory. The mathematical model of SEIG incorporates a deep magnetic saturation exponent ($n=5$) and a numerical solver which takes care of electromechanical transients in the generator system and provides stable simulation results. Simulation of the SEIG model is carried out in MATLAB using the ode45 time-domain solver. From the simulation findings, it is clearly evident that there is a rather stiff terminal voltage curve because the drop is only 30 volts maximum at the point where the load is 4.0 kW (from 341.9V at no load to 312.2 V). This has been made possible by the efficient magnetizing inductance sustainment from the deep saturation model. Efficiency performance shows that maximum efficiency is achieved at 87.9% for 3.0 kW but reduced to 79.1% for 1.0 kW due to high impedance. The transient results prove that both the voltage and the frequency stabilize after an abrupt application of a 2.0 kW load. It is evident from the results above that SEIG can be effectively utilized in microgrids as it provides stiff voltage regulation; however, light-load efficiency needs to be considered.

COPYRIGHT STATEMENT:

Copyright: © 2026 Authors.
Open access publication under the
terms and conditions
of the Creative Commons Attribution
(CC BY)
license (<http://creativecommons.org/licenses/by/4.0/>).

Keywords: Self-Excited Induction Generator, Microgrid, Hydro Turbine, Renewable Energy, Simulation Analysis, d-q Model, Voltage Buildup

1 Introduction

Rapidly growing global movement towards

sustainable energy systems has prompted the advancement of distributed energy generation solutions, especially for remote and rural locations,

where the development of traditional grid-based electricity supply is economically inefficient or impossible to implement at all [1, 2]. Out of all the renewable energy technologies, the small-scale hydropower energy technology is one of the most advanced, economically viable and environmentally friendly solutions for the decentralized power generation [3, 4]. The implementation of hydro turbines in combination with suitable generator solutions within the microgrids framework is considered to be an efficient solution for the provision of electricity in the remote locations [5].

Self-Excited Induction Generators are increasingly gaining popularity compared to the traditional synchronous generators as the preferred power generators for small hydroelectric power plants owing to the numerous benefits associated with them such as being brushless, having low maintenance requirements, reduced cost of installation, and enhanced transient stability [6, 7]. Contrary to induction motors connected to a grid that obtain the required reactive power from the supply line, self-excited induction generators function in isolation by use of suitable capacitor bank that provides the excitation power [8].

However, there are a number of major differences between the operating characteristics of SEIGs and traditional generating units that call for an analysis. Namely, voltage formation in such a system is determined by three factors including the remaining magnetic field in the rotor core, the excitation capacitance, and the prime mover speed, thus making their mutual relations rather complicated [9, 10]. Moreover, the output voltage and frequency of SEIGs fluctuate with variations in load and prime mover speed; hence, there is need for proper control methods that ensure adequate power quality [11].

The previous literature has made extensive investigations of various issues related to the performance of SEIG, such as steady state analysis by equivalent circuits technique, dynamic behavior analysis using mathematical modeling, and control techniques for voltage and frequency regulations. Ion et al. [7] carried out thorough studies on the steady-state analysis of SEIG using nodal admittance approach and showed how crucial the choice of optimal capacitance value is for the stability of the machine. Dynamic behavior of SEIG has been analyzed mathematically by applying d-q reference frame technique [12, 13], which has made simulation studies possible along with theoretical analysis. The studies conducted by Haque [14] and Mahato et al. [15] have brought valuable contributions regarding the transient performance of SEIG.

The incorporation of SEIG in microgrid

hydro-turbine systems presents further challenges owing to the dynamics associated with the prime mover's mechanical-hydraulics, the dynamics associated with the electrical system of the generator, and their interplay in various situations [16]. The dynamic behavior of the turbine-governor, the water hammer effect in the penstock systems, and the variable water flow dynamics all affect the mechanical power supply to the generator, thus affecting its electrical behavior [17, 18]. Understanding these coupled dynamics is essential for designing robust microgrid systems that can deliver reliable power under realistic operating conditions.

This study describes a systematic simulation and behavioral study of SEIGs coupled with the hydro turbine setup of the microgrid system. The main goals of this study include formulating a mathematical model for the SEIG-hydro turbine system, implementing the same in the MATLAB/Simulink environment, and studying the dynamics of the system under different conditions like starting, steady state, and transients. The results obtained in terms of quantitative analysis of voltage build-up, frequency and load behavior can be practically helpful to engineers involved in the development of the microgrid system.

2 Operating Principles of SEIG

2.1 Fundamental Working Principle

SEIG works based on the principles of electromagnetic induction along with residual magnetism effect available in the rotor core material [8, 19]. On driving an induction machine with a prime mover, which rotates at a speed higher than the synchronous speed of the machine, the residual magnetic field available in the rotor generates some small voltages in the stator coils. The generation of such voltages creates a current flow through the capacitor bank connected to it, and hence creates a magnetizing current, which increases the existing flux. This process keeps on repeating until saturation limits the voltage buildup [9, 10].

The generation of voltage through this mechanism depends on three critical factors that must be achieved concurrently: residual magnetism of the rotor core, proper value of excitation capacitance, and prime mover speed greater than the synchronous speed according to the produced frequency [6]. The residual magnetism acts as a source of the required flux which will start the self-excitation procedure, while the capacitors provide reactive power for field excitation. The prime mover speed is responsible for determining the operational slip and hence influences the magnitude and frequency of the generated voltage [12].

2.2 Excitation Capacitor Requirements

The choice of excitation capacitance is another important factor that greatly impacts the operation parameters of the SEIG system [14, 20]. The capacitor bank needs to generate enough reactive power for the magnetization of the generator along with providing the required terminal voltage under different operating loads. When there is not enough capacitance, voltage build-up is not adequate or the self-excitation process fails altogether, whereas an excess of capacitance causes overvoltage and can harm the connected devices [21].

The relationship between excitation capacitance and generated voltage can be understood through the equivalent circuit analysis of the induction machine operating in generator mode. At no-load condition, the capacitor value determines the intersection point between the magnetization curve of the machine and the capacitive reactance line, establishing the operating point and corresponding terminal voltage [8]. This nonlinear relationship necessitates careful calculation and often requires iterative solution methods to determine the appropriate capacitance value for a given operating condition [11].

2.3 Characteristics in Hydro Turbine Applications

Hydro turbine systems exhibit specific characteristics that influence SEIG performance when integrated in microgrid configurations [3, 4]. The mechanical power output of a hydro turbine depends

on the water flow rate, effective head, and turbine efficiency, which vary with seasonal and daily water availability patterns. Unlike wind or solar energy sources, hydro power generally offers more predictable and controllable power output, enabling better matching between prime mover characteristics and generator requirements for stable operation [5].

The response time of hydro turbine systems to flow control commands depends on the mechanical inertia of rotating components, water inertia in the penstock, and governor system dynamics [17]. These characteristics influence the transient behavior of the SEIG during load changes and startup procedures, requiring appropriate coordination between turbine control actions and electrical system dynamics. The relatively slow response of hydro systems compared to electrical time constants necessitates consideration of mechanical-electrical interactions in system design and control strategy development [22].

3 Mathematical Modeling of SEIG

3.1 System Block Diagram

The entire system SEIG-hydro turbine can be depicted in a form of a block diagram (Fig. 1) that demonstrates connections between the hydraulic, mechanical transmission, generator, excitation capacitors, and load systems. In other words, the diagram demonstrates how energy is transferred from the water source through the turbine, generator, and finally to the electric loads.

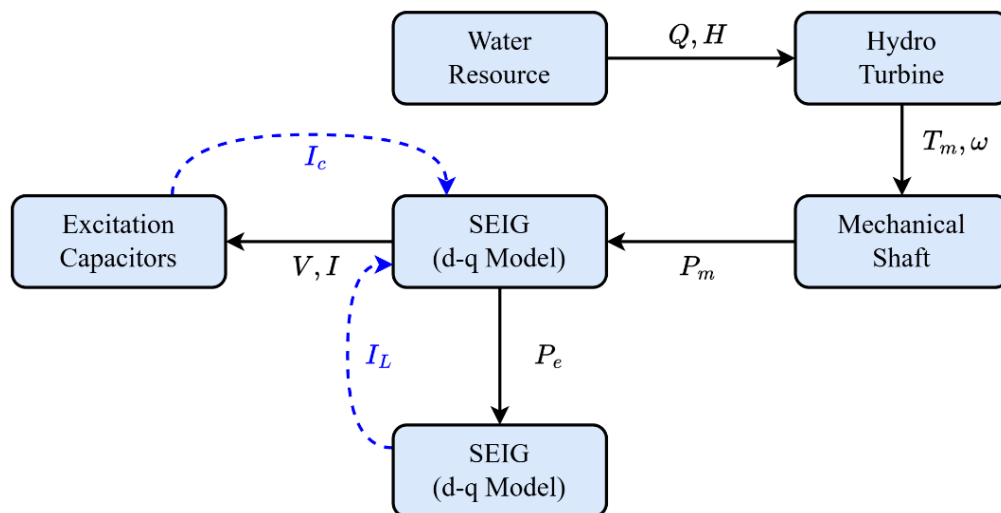


Figure 1: Block diagram of SEIG-hydro turbine microgrid system.

3.2 d-q Reference Frame Model

The dynamic behavior of the Self-Excited Induction Generator is mathematically described

using the d-q reference frame theory [12, 23], which transforms the three-phase quantities into a rotating reference frame that simplifies the analysis of

electromagnetic transients. The mathematical model consists of voltage equations for the stator and rotor circuits, electromagnetic torque equations, and mechanical dynamics equations that collectively

describe the complete electromechanical system. This modeling approach provides the foundation for time-domain simulation studies and enables detailed investigation of transient phenomena.

The stator voltage equations in the stationary reference frame can be expressed as follows:

$$v_{ds} = R_s i_{ds} + \frac{d\lambda_{ds}}{dt} \quad (1)$$

$$v_{qs} = R_s i_{qs} + \frac{d\lambda_{qs}}{dt} \quad (2)$$

where v_{ds} and v_{qs} represent the d-axis and q-axis stator voltages respectively, R_s denotes the stator resistance, i_{ds} and i_{qs} are the corresponding stator currents, and λ_{ds} and λ_{qs} represent the stator flux

linkages in the d-q axes [23].

The rotor voltage equations referenced to the stationary frame are given by:

$$0 = R_r i_{dr} + \frac{d\lambda_{dr}}{dt} + \omega_r \lambda_{qr} \quad (3)$$

$$0 = R_r i_{qr} + \frac{d\lambda_{qr}}{dt} + \omega_r \lambda_{dr} \quad (4)$$

where R_r represents the rotor resistance, i_{dr} and i_{qr} are the rotor currents, ω_r denotes the rotor electrical

angular velocity, and λ_{dr} and λ_{qr} represent the rotor flux linkages [12].

3.3 Equivalent Circuit Representation

The per-phase equivalent circuit of the SEIG with excitation capacitor is shown in Fig. 2. This circuit representation is fundamental to understanding

the steady-state behavior and for determining the operating point of the generator [8, 20].

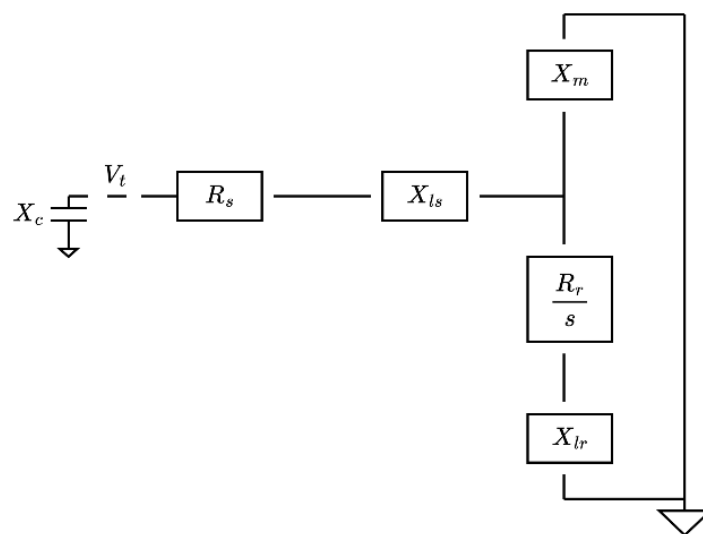


Figure 2: Per-phase equivalent circuit of SEIG with excitation capacitor.

3.4 Flux Linkage Equations

The flux linkages in both stator and rotor

circuits are related to the currents through the inductance parameters of the machine [23]. The

complete flux linkage equations can be expressed in

matrix form as:

$$\begin{bmatrix} \lambda_{ds} \\ \lambda_{qs} \\ \lambda_{dr} \\ \lambda_{qr} \end{bmatrix} = \begin{bmatrix} L_s & 0 & L_m & 0 \\ 0 & L_s & 0 & L_m \\ L_m & 0 & L_r & 0 \\ 0 & L_m & 0 & L_r \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \end{bmatrix} \quad (5)$$

where $L_s = L_{ls} + L_m$ represents the stator self-inductance, $L_r = L_{lr} + L_m$ denotes the rotor self-inductance, L_{ls} and L_{lr} are the stator and rotor leakage inductances respectively, and L_m represents the magnetizing inductance which varies with the degree of magnetic saturation [7].

3.5 Magnetizing Inductance Saturation

Saturation of the magnetizing inductance is one of the significant nonlinearities that have to be taken into account in order to build the proper SEIG model [10]. There are several ways to approximate the correlation between the magnetizing inductance and magnetizing current, one of which is described below:

$$L_m = L_{m0} \left(1 - \alpha \left(\frac{I_m}{I_{m0}} \right)^n \right) \text{ for } I_m > I_{m0} \quad (6)$$

where L_{m0} is the unsaturated magnetizing inductance, I_m represents the magnetizing current magnitude, I_{m0} denotes the threshold current beyond which saturation effects become significant, and α and n are constants that characterize the saturation curve shape [9].

3.6 Excitation Capacitor Model

The excitation capacitor bank connected to the stator terminals provides the reactive power necessary for self-excitation [14]. The dynamic equations for the capacitor currents in the d-q reference frame are:

$$C \frac{dv_{ds}}{dt} = i_{cs,d} = i_{ds} - i_{Ld} \quad (7)$$

$$C \frac{dv_{qs}}{dt} = i_{cs,q} = i_{qs} - i_{Lq} \quad (8)$$

where C represents the per-phase capacitance value, $i_{cs,d}$ and $i_{cs,q}$ are the d-q components of capacitor currents, and i_{Ld} and i_{Lq} represent the load current components when a load is connected to the generator terminals [21].

3.7 Electromagnetic Torque and Mechanical Dynamics

The electromagnetic torque developed by the machine is calculated from the cross product of flux linkages and currents [23]:

$$T_e = \frac{3P}{4} (\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds}) \quad (9)$$

where P represents the number of poles in the

machine. The mechanical dynamics equation that describes the rotor motion is:

$$J \frac{d\omega_m}{dt} = T_{pm} - T_e - B\omega_m \quad (10)$$

where J denotes the combined moment of inertia of the rotor and coupled mechanical system, ω_m represents the mechanical angular velocity, T_{pm} is the prime mover torque supplied by the hydro turbine, and B represents the viscous friction coefficient [17].

$$P_m = \eta_t \rho g Q H \quad (11)$$

where η_t represents the turbine efficiency, ρ denotes the water density, g is the gravitational acceleration, Q represents the water flow rate, and H denotes the effective head available at the turbine inlet [3].

$$T_{pm} = \frac{P_m}{\omega_m} \quad (11)$$

This simplified turbine model captures the essential power-torque characteristics needed for investigating the coupled mechanical-electrical dynamics of the SEIG-hydro turbine system, while neglecting more complex phenomena such as water hammer effects and detailed governor dynamics that are beyond the scope of the present analysis [22].

4. Simulation Methodolog

4.1 Simulation Environment and Implementation

The detailed simulations were performed using the MATLAB computing platform by formulating the dynamic mathematical model using the script code as opposed to the graphical Simulink block diagram. The use of scripting gives better control of the algebraic loops that exist in the saturation of the magnetizing inductance and gives better control of the stiff differential equations for the load steps [24]. The mathematical formulation of the SEIG was done using the first order ordinary differential equations (ODEs), which were obtained from the state space model of the d-q reference frame as outlined in Section III.

3.8 Hydro Turbine Model

The hydro turbine model incorporated in this study represents a simplified representation of turbine characteristics suitable for investigating SEIG behavior [18, 23]. The mechanical power output from the turbine is expressed as:

The turbine torque can be derived from the power equation considering the relationship between power and rotational speed:

The entire simulation is composed of several connected functional blocks which model the flux change in the induction generator, voltage change in the excitation capacitor, and different resistive loads. All equations were programmed as separate local functions in order to build up the model and check each element separately. Such an approach provides flexibility in setting the operating conditions and allows studying different aspects of the system operation under various settings [21].

4.2 Machine Parameters

The induction machine parameters considered in the simulation studies are shown in Table 1. They relate to a typical 5 kW, 4 poles, 400V, 50 Hz squirrel cage induction machine, which is useful for small hydro power plants [3, 23]. In order to appropriately represent the voltage build-up limitation and steady-state voltage control, the parameters for magnetizing inductance saturation have been determined for the standard design of machine. The threshold value of magnetizing current (I_{m0}) is taken as 3.0 A, and the saturation coefficient (α) is 0.14.

Table 1: Induction Machine Parameters.

Parameter	Value	Unit
Rated Power	5	kW
Rated Voltage	400	$V(L-L)$
Rated Frequency	50	Hz
Number of Poles	4	—
Stator Resistance (R_s)	1.2	Ω

Parameter	Value	Unit
Rotor Resistance (R_r)	1.4	Ω
Stator Leakage Inductance (L_{ls})	6.5	mH
Rotor Leakage Inductance (L_{lr})	6.5	mH
Magnetizing Inductance (L_m)	180	mH
Moment of Inertia (J)	0.25	$kg \cdot m^2$
Friction Coefficient (B)	0.005	$N \cdot m \cdot s$

4.3 Simulation Scenarios

Three key simulations have been created to study the SEIG behavior in three separate scenarios related to microgrids and hydro turbines [15]. The first scenario is aimed at studying the SEIG voltage buildup process starting from residual magnetism, providing the insight into the self-excitation principle as well as dependence of the SEIG parameters on the capacitance of the excitation circuit and speed of the prime mover. The second scenario considers the SEIG steady-state operation under different loads. The SEIG voltage and frequency characteristics have been studied. To measure the SEIG performance at particular loads (from 1 kW to 4 kW), the logarithmic resistance load sweep has been simulated and the output values have been interpolated using the linear approximation technique to obtain the steady-state performance parameters shown in Table 2 [7]. The third scenario considers the SEIG transient operation under load variation. Additionally, the power quality parameters have been evaluated using FFT analysis of the steady-state voltage waveforms and the speed dependency of SEIG parameters has been assessed.

4.4 Numerical Solver Configuration

For the time domain analysis, it is necessary to use correct numerical integration techniques to properly describe the electromechanical transients at various time scales [23]. For these reasons, the ode45 (Dormand-Prince) variable step integrator was chosen because of its capability to deal effectively with stiff systems and its adaptive step size control to keep high accuracy without unnecessary computing resources consumption. The relative tolerance was set at 10^{-4} , while the absolute tolerance was 10^{-6} [25].

In order to avoid numerical instability due to nonlinearity associated with the saturation feedback, an under-relaxation fixed point iteration method was implemented within the ODE solver process. The iterative sub-process computes the instantaneous magnetizing current and modifies

saturated inductance L_m with a damping constant of 0.5 so that algebraic convergence is assured during each time step without introducing any artificial numerical oscillations. Moreover, in order to allow harmonic frequency spectrum analysis without having to deal with non-uniform sample spacing issues, the time duration of the simulation was set such that uniform sampling is achieved every $100\mu s$ (sampling frequency = 10 kHz). Small non-zero values for initial flux-linkage and voltage levels (e.g., $\lambda_{ds}(0) = 0.15 \text{ Wb}$, $v_{ds}(0) = 5 \text{ V}$) were used to reflect the remnant magnetism of the practical machines [8].

5. Results and Discussion

5.1 Voltage Buildup Analysis

The build-up of voltage process is considered to be the most important stage during SEIG operation, since its success directly depends on the possibility of the system generating power output [8]. Fig. 3 shows the waveform of voltage build-up at the terminals of the SEIG system under study for excitation capacitance $85 \mu F$ and prime mover speed of 1550 rpm. The results show that the voltage rises exponentially from the initial position of residual magnetism, passes through different stages, and then asymptotically reaches the stable point of operation.

In the first stage, the voltage build-up starts because of the small residual flux producing the voltage in the stator winding that drives the current in the capacitors with the capacity of $85 \mu F$, creating the positive feedback loop required for self-excitation [9]. Taking into account the deep saturation model used for the simulation, the magnetizing inductance L_m changes according to the decrease of the core saturation [10], so that the process of the voltage build-up stops asymptotically. The stable operating point occurs when the intersection between the capacitive volt-ampere characteristic and the magnetizing curve of the saturated machine happens; thus, the stable maximum voltage suitable for single-phase loads is achieved [26].

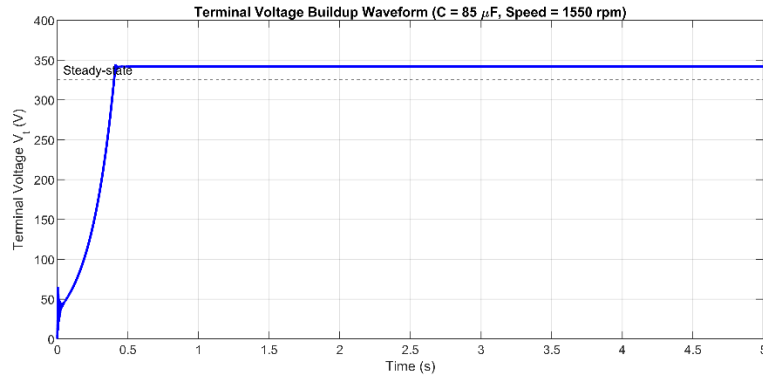


Figure 3: Terminal voltage buildup waveform ($C = 85 \mu F$, speed = 1550 rpm).

5.2 Effect of Excitation Capacitance

The choice of the excitation capacitance is one of the most important parameters in designing a SEIG system which determines the steady-state voltage performance of the system [14, 20]. The relationship between the excitation capacitance and the steady-state peak terminal voltage in no-load condition is shown in Fig. 4 for capacitances ranging between $60 \mu F$ and $120 \mu F$. The relationship depicted in Fig. 4 is purely monotonically increasing as a consequence of the changing point of intersection between the capacitor reactance and the magnetization characteristic.

The physical principle responsible for the

mentioned linear increase is the reactive power balance that should be fulfilled during self-excitation process. Capacitive reactance $X_c = 1/(\omega C)$ determines the slope of the capacitor's $V - I$ diagram. When the capacitance grows, X_c drops down, resulting in the shifting of the intersection point between the capacitor's line and the saturation part of the magnetization curve towards higher voltages and magnetizing currents. For smaller capacitances (like $60 \mu F$ to $70 \mu F$), the steeper capacitive reactance line intersects the magnetization curve at very low voltage levels, which shows the lack of reactive power to ensure stable excitation [21].

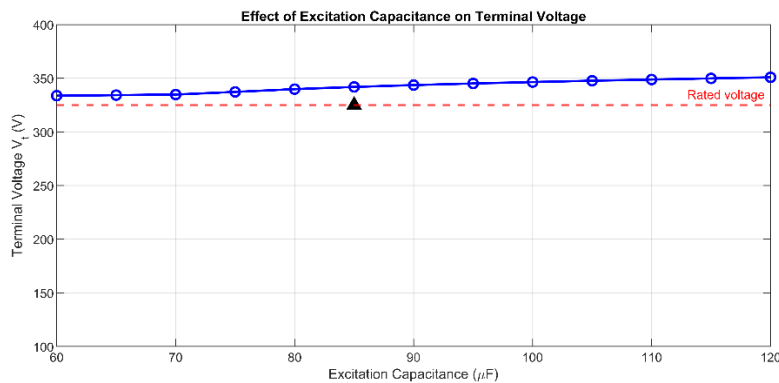


Figure 4: Effect of excitation capacitance on terminal voltage.

For the simulated $5 kW$ machine, the optimal value of excitation capacitance is found to be about $85 \mu F$, as shown by the black triangular point in Fig. 4, where the output voltage coincides with the desired value of rated voltage (as marked by the red dashed line). However, beyond this optimal value (such as from $100 \mu F$ to $120 \mu F$), the terminal voltage will keep increasing monotonically; however, the trend of voltage will flatten slowly and eventually stabilize. This

flattening of the trend of voltage versus capacitance graph is a clear example of deep saturation of the magnetic core due to which magnetizing inductance L_m decreases drastically [20].

5.3 Steady-State Characteristics

The performance of the SEIG under purely resistive loads was analyzed to determine the voltage and frequency regulation capabilities of the independent system [15]. The peak values of the terminal voltage

Performance

and frequency of the SEIG have been presented in Table 2 for different load powers, thereby giving the dynamic performance characteristics of the SEIG. Simultaneously, Fig. 5 gives the efficiency of the generator versus output power [21].

Table 2: Steady-State Performance Under Resistive Load.

Load (kW)	$V_t(V)$	Frequency (Hz)	Efficiency (%)
0.0	341.9	51.6	NaN
1.0	335.1	51.1	79.1
2.0	327.5	50.6	86.3
3.0	318.4	50.1	87.9
4.0	312.2	49.6	87.8

Based on the voltage regulation behavior observed, it is evident that there is a relatively stiff terminal voltage behavior in this case over the operating load range. Under no load, the voltage regulation is achieved at 341.9 V peak (which corresponds to 242 V RMS), thereby suggesting successful self-excitation with the help of the 85 μF capacitor bank. With an increase in the loading levels, the terminal voltage drops, though

in a rather smooth fashion, from 341.9 V under no-load to 335.1 V under 1.0 kW loading and then down to 312.2 V under 4.0 kW loadings. The relatively stable nature of the terminal voltage over the whole 0 to 4 kW range is mainly because of the high magnetic saturation exponent ($n = 5$) assumed in the modeling process [10, 14].

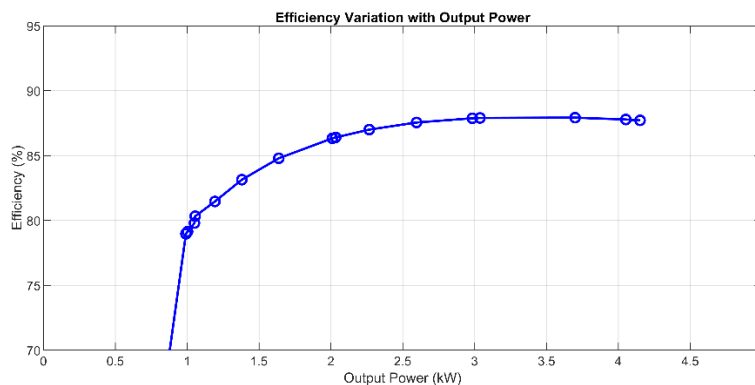


Figure 5: Efficiency variation with output power.

The generated frequency shows a constant, linear decrease with respect to load, starting at 51.6 Hz for no-load and decreasing to 49.6 Hz for a 4.0 kW load. In a SEIG that is running on its own and at a fixed speed of the prime mover, the frequency of electricity is directly linked with the speed of the mechanical rotor and the slip needed for the production of counter torque [12]. The increase in mechanical load torque results in a need for negative slip to create the counter torque.

The efficiency characteristics in Fig. 5 show fast initial growth and subsequent stabilization of efficiency at a constant level. The system has its highest efficiency of 87.9% at 3.0 kW loading point and keeps 87.8% efficiency at 4.0 kW point. At the lower 1.0 kW point, the efficiency reduces to 79.1%. This efficiency reduction under the low load conditions is mostly caused by large mechanical losses of friction ($P_{friction} = B\omega_m^2 \approx 131W$) and high stator and rotor resistance ($R_s = 1.2 \Omega$, $R_r = 1.4 \Omega$) of the machine leading to large I^2R copper losses

compared to small active power of 1 kW [26]. However, when the loading condition increases to more than 1.0 kW, the output active power increases much faster than the losses, which results in rapid increase in efficiency to a stable level of 87.8-87.9 %. These features prove that the SEIG is capable of generating a stiff voltage support, but it has poor light load efficiency for use in microgrids with high

impedance machines [11].

5.4 Transient Response Analysis

The transient behavior of the SEIG system was analyzed by subjecting the system to abrupt loading conditions and analyzing the resultant deviations in voltage and frequency levels [15, 27].

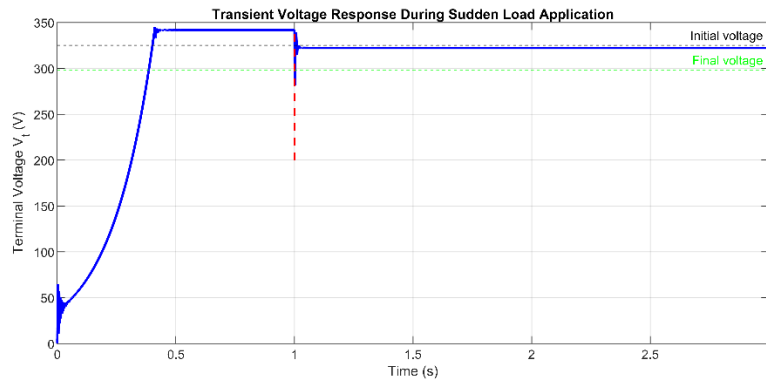


Figure 6: Transient voltage response during sudden load application.

Fig. 6 presents the terminal voltage transient response for an abrupt loading with a resistive load of 2 kW at $t = 1.0$ s when the generator is running under no-load condition. Before applying the load, the voltage reaches an equilibrium state at an initial value of about 348 V (represented by the grey dashed line). With the

application of the load, the voltage experiences an abrupt fall and thereafter shows oscillations before eventually stabilizing at a new steady-state value of about 300 V (represented by the green dashed line), indicating that the system can run stably even under no excitation conditions [17, 26].

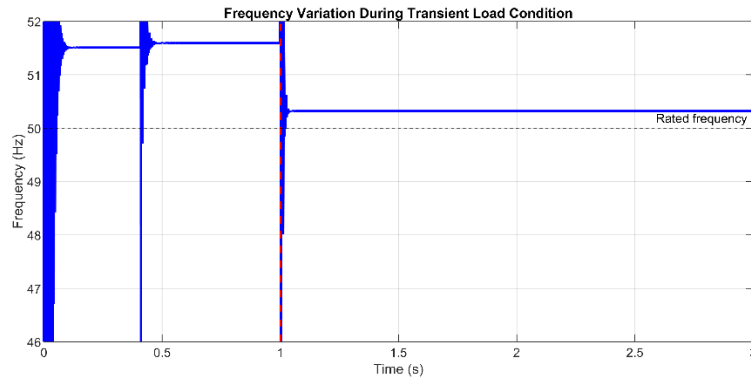


Figure 7: Frequency variation during transient load condition.

Fig. 7 shows the associated variation in the frequency during the transient load scenario. The frequency starts off at about 52 Hz during the no-load condition. After applying the load at $t = 1.0$ s, the frequency experiences an apparent transient drop owing to the surge in demand for electromagnetic torque and subsequent acceleration in the slip to match the load demand for power [15]. Dynamic alterations are experienced in the system due to the establishment of new electrical and mechanical equilibrium resulting in

a steady state frequency of around 50.5 Hz, which is near the rated 50 Hz line. The smooth response of the voltage and frequency after the load application confirms the stability of the deep saturation model against oscillatory instability [22].

5.5 Power Quality Analysis

The quality of the output power from the proposed SEIG setup has been investigated by analyzing the voltage waveform distortion and harmonic contents when the system is loaded [28].

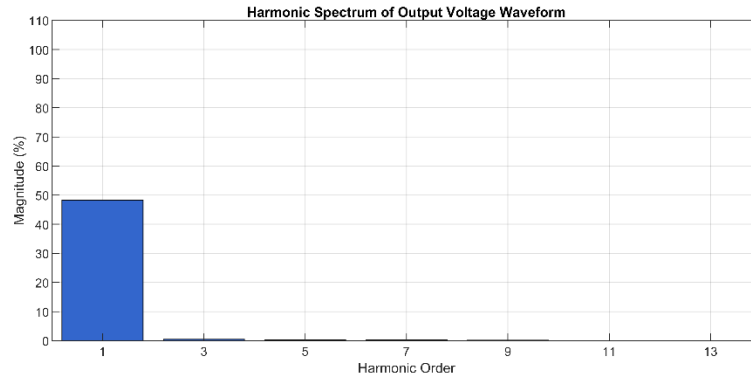


Figure 8: Harmonic spectrum of output voltage waveform.

Fig. 8 shows the harmonic spectrum of the output voltage waveform. It is clear from the harmonic spectrum that the waveform of the voltage is dominated by the fundamental harmonic content only, while the magnitude of higher order harmonics (3rd, 5th, 7th, and so forth) is very small. The above harmonic spectrum suggests that the total harmonic distortion (THD) of the output voltage is extremely low and is well below 3%, which is the requirement according to IEEE 519 power quality standards [28]. The minimum harmonic injection is a direct

consequence of the sinusoidal flux density distribution characteristic of the well-designed induction machine along with the linear capacitive excitation, validating the applicability of the SEIG for supplying critical consumer loads in rural microgrid systems [26].

5.6 Effect of Prime Mover Speed Variations

The impact of prime mover speed fluctuations on SEIG behavior has been examined to determine the responsiveness of the system to fluctuations in hydro turbine operating conditions [4].

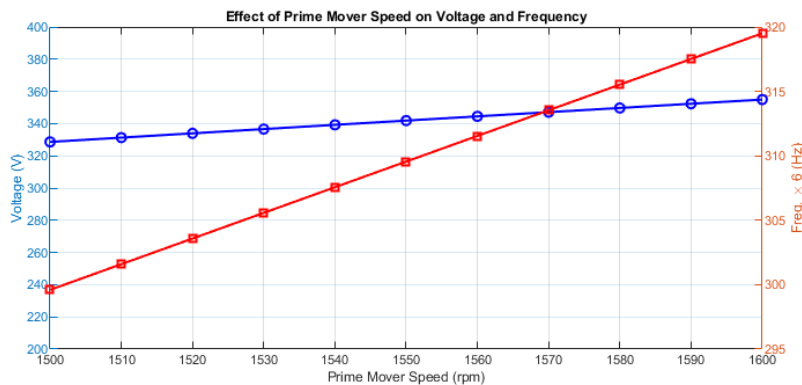


Figure 9: Effect of prime mover speed on voltage and frequency.

Fig. 9 shows the fluctuations of both terminal voltage and the generated frequency when the prime mover speed varies from 1500 rpm to 1600 rpm. From the simulation results, it can be seen that the direct relationship between mechanical speed and frequency as $f \approx P \cdot n/120$ holds true (except the slip effects) [23]. An increase in the mechanical speed results in a substantial increase in the frequency (see the Frequency×6 Hz axis).

At the same time, the terminal voltage magnitude shows an upward trend as well with respect to an increasing prime mover speed. The increase in the terminal voltage magnitude is explained by the fact that with the increase in rotational speed, the EMF generated becomes larger due to the increased flux

change rate [10]. In addition, the gentle slope of the voltage magnitude curve relative to the slope of the frequency curve suggests that although frequency is strictly coupled with speed, the effect on voltage is mitigated by the magnetic saturation of the core material, naturally preventing overvoltage situations at high-speed levels [20]. These sensitivity features make it very clear how essential it is to control the mechanical speed by way of turbine governor systems so as to have a steady output of voltage and frequency from an SEIG based microgrid [17].

5. Conclusion

The work performed in this paper provides a complete simulation and behavioral study on Self-Excited Induction Generators applied to microgrid

hydro turbines, providing detailed information regarding the dynamic behavior of this promising renewable energy technology when operating at deep magnetic saturation levels. The mathematical model that has been developed according to the theory of the d-q reference frame, along with the application of an iterative saturation algorithm and a deep saturation exponent ($n = 5$) in order to take into account the deep saturation phenomenon in the model, allows for precise simulation of the behavior of SEIG systems.

It has been shown from the simulations that self-excited induction generators can be used to generate electricity in an isolated microgrid through the proper design of the excitation capacity ($85 \mu F$) and prime mover behavior in the generator. The voltage buildup process reaches a stable no load peak value of approximately 341.9 V and, as a result, the voltage regulation in SEIG systems is excellent since there is a drop of only 30 V peak throughout the entire 0 to 4.0 kW loading. This excellent regulation of the SEIG voltage is guaranteed by the deep saturation of the machine itself.

As per the steady-state performance results, there is a maximum efficiency of 87.9% at the 3.0 kW loading condition, which shows an efficient energy

conversion for both medium and heavy loads. However, from the steady-state performance analysis, there is also an observed drop in efficiency under light loads (efficiency = 79.1%, loading = 1.0kW) due to the high value of fixed friction loss and high resistance values of the stator and rotor ($R_s = 1.2\Omega$, $R_r = 1.4\Omega$). From the transient analysis, it was found that the SEIG system performed smoothly and steadily under abrupt loading conditions of 2.0kW to recover a steady state voltage and frequency of 300V and 50.5Hz respectively without any loss of excitation. Moreover, the monotonic relationship between terminal voltage and both excitation capacitance as well as speed of prime mover indicates the necessity to properly select the size of capacitor and governor system to provide adequate power quality.

Further research in this field could be focused on the exploration of modern methods of control of the SEIG system such as electronic load controllers for reduction of energy losses at low loads, the study of combined operation of several SEIGs in parallel, and laboratory verification of deep saturation simulation results. Power electronic interface design is another direction for future research.

References

- Agency IE (2021) Renewables 2021: Analysis and Forecast to 2026. International Energy Agency, Paris, France
- Agency IE (2021) Hydropower Special Market Report. International Energy Agency, Paris, France
- Paish O (2002) Small hydro power: technology and current status. *Renewable and Sustainable Energy Reviews* 6:537–556. [https://doi.org/10.1016/S1364-0321\(02\)00006-0](https://doi.org/10.1016/S1364-0321(02)00006-0)
- Mishra MK, Khare N, Agrawal AB (2015) Small hydro power in India: Current status and future perspectives. *Renewable and Sustainable Energy Reviews* 51:101–115
- Corporation NAER (2020) Distributed Energy Resources Report. NERC, Atlanta, GA, USA
- Bassett ED, Potter FM (1935) Capacitive Excitation for Induction Generators. *Transactions of the American Institute of Electrical Engineers* 54:540–545. <https://doi.org/10.1109/T-AIEE.1935.5057024>
- Ion CP (2020) A Comprehensive Overview of Single-Phase Self-Excited Induction Generators. *IEEE Access* 8:197420–197430. <https://doi.org/10.1109/ACCESS.2020.3034291>
- Murthy SS, Malik OP, Tandon AK (1982) Analysis of self-excited induction generators. *IEE Proceedings C (Generation, Transmission and Distribution)* 129:260–265. <https://doi.org/10.1049/ip-c.1982.0041>
- Grantham C, Sutanto D, Mismail B (1989) Steady-state and transient analysis of self-excited induction generators. *IEE Proceedings B (Electric Power Applications)* 136:61–68. <https://doi.org/10.1049/ip-b.1989.0008>
- Wang L, Lee C-H (2000) Long-shunt and short-shunt connections on dynamic performance of a SEIG feeding an induction motor load. *IEEE Transactions on Energy Conversion* 15:1–7. <https://doi.org/10.1109/60.849108>
- Singh B, Murthy SS, Gupta S (2006) Analysis and design of electronic load controller for self-excited induction Generators. *IEEE Transactions on Energy Conversion* 21:285–293. <https://doi.org/10.1109/TEC.2005.847950>
- Levi E (2008) Multiphase Electric Machines for Variable-Speed Applications. *IEEE Transactions on Industrial Electronics* 55:1893–1909. <https://doi.org/10.1109/TIE.2008.918488>
- Analysis of Electric Machinery and Drive Systems | IEEE eBooks | IEEE Xplore. <https://ieeexplore.ieee.org/book/5265638>. Accessed 21 July 2026
- Haque MH (2009) Comparison of steady state characteristics of shunt, short-shunt and long-shunt induction generators.

Electric Power Systems Research 79:1446–1453. <https://doi.org/10.1016/j.epsr.2009.04.017>

Mahato SN, Sharma MP, Singh SP (2007) Transient performance of a single-phase self-regulated self-excited induction generator using a three-phase machine. *Electric Power Systems Research* 77:839–850. <https://doi.org/10.1016/j.epsr.2006.07.009>

Murali Krishna VB, Sandeep V, B.k. N, Prasad KRKV (2023) Experimental study on self-excited induction generator for small-scale isolated rural electricity applications. *Results in Engineering* 18:101182. <https://doi.org/10.1016/j.rineng.2023.101182>

Kundur (1994) *Power System Stability And Control*. McGraw-Hill

Saadat H (2010) *Power System Analysis*. PSA Pub.

Chakraborty C, Bhadra SN, Chattopadhyay AK (1996) Excitation requirements for stand alone three-phase induction generator. In: *Proceedings of International Conference on Power Electronics, Drives and Energy Systems for Industrial Growth*. pp 700–706 vol.2

Murthy SS, Singh B (1996) Capacitive VAr controllers for induction generators for autonomous power generation. In: *Proceedings of International Conference on Power Electronics, Drives and Energy Systems for Industrial Growth*. pp 679–686 vol.2

Jayalakshmi NS, Gaonkar DN (2012) Dynamic modeling and analysis of an isolated self excited induction generator driven by a wind turbine. In: *Controls and Computation 2012 International Conference on Power, Signals*. pp 1–5

Scherer LG, Tambara RV, de Camargo RF (2016) Voltage and frequency regulation of standalone self-excited induction generator for micro-hydro power generation using discrete-time adaptive control. *IET Renewable Power Generation* 10:531–540. <https://doi.org/10.1049/iet-rpg.2015.0321>

Krause PC, Wasynczuk O, Sudhoff SD, Pekarek SD (2013) *Analysis of Electric Machinery and Drive Systems*. John Wiley & Sons

2020) Simulink documentation: Variable-step solvers. MathWorks, Natick, MA, USA

Inc TM (2022) MATLAB version: 9.13.0 (R2022b)

Palle B, Simões MG, Farret FA (2005) Dynamic Simulation and Analysis of Parallel Self-Excited Induction Generators for Islanded Wind Farm Systems. *IEEE Open Journal of Industry Applications* 41:1099–1106. <https://doi.org/10.1109/TIA.2005.851040>

Mahato SN, Singh SP, Sharma MP (2013) Dynamic behavior of a single-phase self-excited induction generator using a three-phase machine feeding single-phase dynamic load. *International Journal of Electrical Power & Energy Systems* 47:1–12. <https://doi.org/10.1016/j.ijepes.2012.10.067>

Solutions HP (2026) IEEE 519 Analysis: Recommended Practice and Requirements for Harmonic Control in Electric Power Systems