Received: *27 September 2024* | *Revised:* *20 October 2024* | *Accepted:* *23 October 2024*
DOI: 10.37917/ijeee.22.1.49 *Vol. 22 | Issue 1 | June 2026*

Open Access

Iraqi Journal for Electrical and Electronic Engineering
Original Article

A Reliable Value Selection of Excitation Capacitance for a Self-Excited Induction Generator Operating Under Different Fault and Excitation Conditions

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Abstract
Recently, researchers have focused their efforts to generate electricity on renewable energy sources. Wind power systems are considered good alternative sources of clean energy. Induction generators are the best choice for generating this energy due to their simplicity, robustness, and low maintenance requirements. However, their main drawback is their need for leading reactive power to build the terminal voltage and generate electrical power. This drawback can be overcome using a terminal capacitor across the generator terminals to generate this leading reactive power. This research focuses on: 1-Provides a methodology for selecting an accurate and reliable value of the excitation capacitance required for self-excited induction generators (SEIG), which can be used in pumps operating as turbines (PATs + SEIG). When operating at different speeds and loads. For these systems, the choice of capacitance for the SEIG is of utmost importance. 2- A simplified and understandable method derived from nodal analysis is presented for calculating the exact excitation capacitance of a self-excited induction generator (SEIG) under various conditions. 3-A new analysis and model of (SEIG) is presented. The proposed model consists of an induction generator, a self-excited capacitor, and a RL load. It is used to study the performance of SEIG under different faults and excitation (sudden short circuit, unbalanced excitation, sudden load surge, sudden disconnection of excitation capacitance, and load disturbance). Simulations are created using MATLAB-SIMULINK to validate the proposed model.

Keywords
Induction Generator, Accurate Capacitance Value. Wind Turbine.

I. INTRODUCTION

The main reason for choosing self-excited induction generators over other generators to generate electricity from wind energy, especially in desert areas and areas where it is difficult to supply electricity, is because they do not need an external power source. However, one of their drawbacks is that they require reactive power to operate. By connecting three capacitors connected to the terminals of the generator's stator, the induction generator can be supplied with the required reactive power [1]. Kesari et al. presented a simplified, applicable technique that does not require complex derivations compared to other methods and takes into account the resistance losses to evaluate the steady-state performance of a self-excited induction generator [2].A simulation model of a small water-source wind turbine as an input source for SEIG is presented to study the effect of reactive power, rotor speed, and load on the self-excitation process of an induction generator and to test the generator at its maximum load capacity [3]. Due to the importance of the reactive power supplied to the stator of the generator, on which all voltage and frequency depend, and in order to avoid the problems of over- and under-excitation, various experiments were conducted on a three-phase induction generator to investigate the upper and lower permissible limits [4]. A new Formula and

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direct method, the nodal analysis method, is recommended to estimate the minimum excitation capacitance and achieve results comparable to previous studies [5]. Joao Francisco developed two models to improve the energy efficiency of water systems. The first model developed a comprehensive simulation model to analyze the SEIG operating behavior that will be applied later in the pumps operating as turbines (PATs) system (PAT+SEIG system). The second model developed an analytical model to understand the range of the required capacitor set and allows the calculation of the minimum excitation capacitances for a given load. Several facts were observed in the two models, the most important of which was that the voltage build-up was very fast with a balanced RC load and balanced excitation. Also, an increase in the voltage build-up and torque oscillation was observed for unbalanced excitation [6, 7]. Sarathbabu et al. presented an analytical study of the successful and economical operation, excitation requirements and load balance phenomenon of a self-excited induction generator (SEIG) is presented [8]. Wang and Lee presented a new method to predict both the minimum and maximum capacitance required for self-excited induction generator (based on eigenvalue sensitivity Estimably developed a new and direct method that does not require numerical repetition that can be used to determine the minimum capacity required for the SEIG [9]. Ghanim et al. presented a dq modeling approach for transient analysis of a self-excited induction generator driven by wind turbine . Calculating the required excitation capacitance and total impedance regulation are also included [10]. Hayder et al. presented the effect of iron losses on the selection the minimum excitation capacitance of SEIG with wind turbines, as there is an urgent need not to neglect these effects, mainly when wind energy is driving the IG. The analysis was carried out under different operating conditions [11]. Haque, M.H. et al. presented a simple method to determine the capacitance required based on combining the L-C resonance principle with the nonlinear magnetic property to build up the voltage at no load [12]. A complete dynamic model of the SEIG-WT system is presented to analyze and study induction generators [13]. A new mathematical method was presented by Farrag, et al. to calculate the excitation capacitance amplitude (minimum and maximum value). This model takes into account the effect of friction, wind and the effect of stray load resistance. [14] for a more accurate analysis of SEIG. The literature [15] used the nodal analysis model for steady-state analysis. Dynamic modeling and empirical formulas to calculate the minimum excitation capacitance for SEIG [16, 17, 18, 19].

II. Steady-State Equivalent Circuit and Mathematical Model

There are two models to determine the value of the required excitation capacity of SEIG:

- Steady-state model.
- The transient model.

In this study, the steady-state model will be presented for analysis. The main features of the proposed method for calculating the appropriate value of excitation capacitance.

I. The nodal admittance method is used to analyze and study the proposed method.
II. All the circuit parameters are assumed to be constant except magnetizing reactance
III. Find the frequency by solving a fourth-degree polynomial equation and substituting the frequency value to find the (Cexc).
IV. The proposed method does not require any trial and error

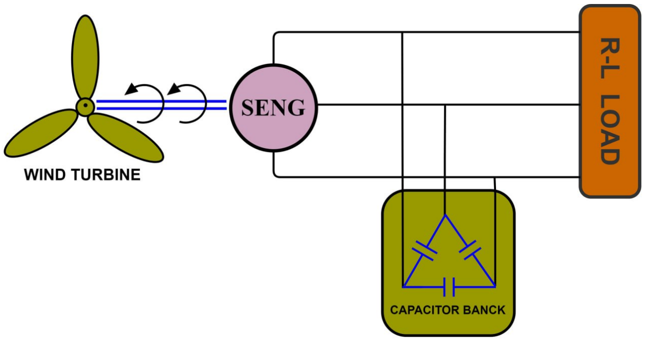


Fig. 1. Schematic diagram of the system under study

Fig 2. represents the equivalent circuit of the self-excited induction generator with the load and the excitation capacitance under study.

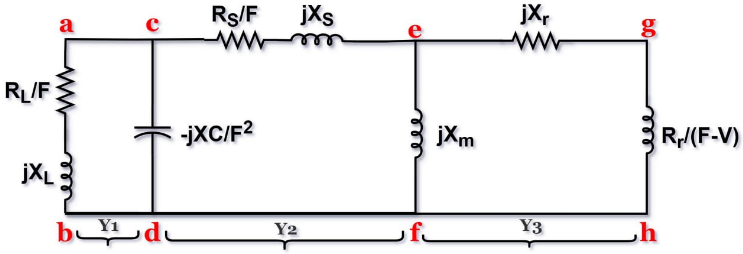


Fig. 2. Equivalent circuit of SEIG

$$Z_{ab} = \frac{R_L}{F} + jx_L \tag{1}$$

$$Z_{cd} = -j\frac{x_C}{F^2} \tag{2}$$

$$Z_{ce} = \frac{R_S}{F} + jx_S \tag{3}$$

$$Z_{T1} = [Z_{ab}//Z_{cd}] \tag{4}$$

$$Z_{T2} = \left(\frac{R_R}{(F-V)} + jX_R\right)//X_M \tag{5}$$

Where:

$$Y_1 = \frac{1}{Z_{T1}}, \quad Y_2 = \frac{1}{Z_{ce}}, \quad Y_3 = \frac{1}{Z_{ce}}$$

$$\mathbf{Y_{TOTAL}} = Y_1 + Y_2 + Y_3 \tag{6}$$

Apply the nodal admittance method in Fig. 2 yields equation 7.

$$Y_S V_S = \frac{V_1}{F}(Y_1 + Y_2 + Y_3) = 0 \tag{7}$$

Since $V_S \neq 0$, that equation 8 is obtained.

$$Y_{TOTAL} = 0 \quad \text{For } (Y_1 + Y_2 + Y_3) = 0 \tag{8}$$

From 8, separate the real terms and set them equal to zero, as shown as shown in 9:

$$\begin{aligned}\text{Real}(X_m, F) = (P_1 X_m + P_2)F^3 + {} \\ (P_3 X_m + P_4)F^2 (P_5 X_m + P_6)F (P_7 X_m + P_8)\end{aligned} \tag{9}$$

After rearranging Equation 9 against the reactance capacitance, the equation 10 will be obtained:

$$-\partial_1 F^3 + \partial_2 F^2 + (\partial_3 X_c + \partial_4)F - \partial_5 X_c = 0 \tag{10}$$

The reactance capacitance X_c can be obtained as shown in Equation 11:

$$X_c = \frac{\partial_1 F^3 - \partial_2 F^2 - \partial_4 F}{\partial_3 F - \partial_5} \tag{11}$$

$$\begin{aligned}Imag = (Q_1 X_m + Q_2)F^4 + (Q_3 X_m + Q_4)F^3 \\ + (Q_5 X_m + Q_6)F^2 + (Q_7 X_m + Q_8)F + Q_9\end{aligned} \tag{12}$$

The imaginary part of Equation 12 can be written versus X_C as follows:

$$\begin{aligned}&-\beta_1 F^4 + \beta_2 F^3 + (\beta_3 X_c + {} \\ &\beta_4)F^2 - (\beta_5 X_c + \beta_6)F - \beta_7 X_c = 0\end{aligned} \tag{13}$$

From Equation 12, the reactance capacitance X_c can be obtained as shown in yielding equation 13.

$$X_c = \frac{\beta_1 F^4 - \beta_2 F^3 - \beta_4 F^2 + \beta_6 F}{\beta_3 F^2 - \beta_5 F - \beta_7} \tag{14}$$

If Equation 11 is substituted into Equation 14, yields equation 15:

$$\begin{aligned}&\frac{\partial_1 F^3 - \partial_2 F^2 - \partial_4 F}{\partial_3 F - \partial_5} \\ &= \frac{\beta_1 F^4 - \beta_2 F^3 - \beta_4 F^2 + \beta_6 F}{\beta_3 F^2 - \beta_5 F - \beta_7}\end{aligned} \tag{15}$$

The equation 15 can be simplified to equation 16:

$$\begin{aligned}&(\partial_1\beta_3 - \partial_3\beta_1)F^4 - (\partial_2\beta_3 + \partial_1\beta_5 - \partial_3\beta_2 - \partial_3\beta_2)F^3 \\ &+ (\partial_2\beta_5 + \partial_3\beta_4 - \partial_4\beta_3 - \partial_1\beta_7 - \partial_5\beta_2)F^2 - (\partial_3\beta_6 \\ &+ \partial_5\beta_4 - \partial_4\beta_5 - \partial_2\beta_7)F + (\partial_5\beta_6 + \partial_4\beta_7) = 0\end{aligned} \tag{16}$$

After performing some algebraic operations, we simplify Equation 15. The fourth-order equation can be obtained as:

$$G_4 F^4 + G_3 F^3 + G_2 F^2 + G_1 F + G_0 = 0 \tag{17}$$

The Coefficients $G0$ to $G4$, $\partial 1$ to $\partial 5$, and $\beta 1$ to $\beta 7$ are given in Appendix A. The coefficients of equation 17 do not include the excitation reactance(XC). Solving this equation to obtain all the real or imaginary roots is possible. These roots represent the frequency in pu units. We take the largest positive real root. Note that there is no excitation if there is no real root in the equation mentioned, which means that the generator cannot produce voltage (This means that the generator fails to excite). Finally, the imaginary part of Equation (6) can be driven by a simple equation to find the minimum capacitance required $(C_(exc(min)))$ as shown in eq 18.

$$\begin{aligned}C_{\text{exc(min)}} = \frac{10^6}{2\pi f_b Z_b}\left[\frac{1}{F^2 x_m}\frac{x_L}{R_L^2 + F^2 x_L^2}\right] \\ \cdot \left[\frac{x_L + x_S}{\left[\left(R_S + \frac{FR_r}{F-v}\right)l\right]^2 + F^2\left(x_r + x_S\right)^2}\right]\end{aligned} \tag{18}$$

The results that can be obtained from Equation 18 when operating the machine at speed (1620 rpm) with a connected load impedance (RL=1pu and XL=2pu) are as shown in Equation (19).

$$8.4312F^4 - 11.8673F^3 + 5.8784F^2 - 2.5375 + 0.7173 = 0 \tag{19}$$

TABLE I.
THE RESULT OF THE PROPOSED METHOD

Speed (pu)	(Real and Imaginary)	C_{max} (μF)	$C_{exc}(min)$ (μF)
1	0.9796 0.5290 0.0277 + 0.4493i 0.0277 - 0.4493i	684.3798	684.3798
0.9	0.8783 0.4719 0.0287 + 0.4522i 0.0287 - 0.4522i	891.8233	56.4068
0.8	0.7770 0.4152 0.0295 + 0.4556i 0.0295 - 0.4556i	1139	69.9359
0.6	0.5749 0.3592 0.0296 + 0.4643i 0.0296 - 0.4643i	1502	116.0017
V=0.078, 140rpm	0.5749 0.3592 0.0066 + 0.4893i 0.0066 - 0.4893i 0.0544 + 0.0012i 0.0544 - 0.0012i	No excitation	No excitation

Solution equation 19 yielded two real roots (F1= 0.8783 pu) (F2= 0.4719 pu) and; two imaginary roots,
(F3= 0.0277 + 0.4493i pu)
(F4= 0.0287 - 0.4522i pu).
When substituting the first root in equation (18), Produces the minimum excitation capacitor required Cmin(exc)=. 56.4068 μF. Substituting the second root in the same equation, the value of the capacitor is equal = 684.3798 μF.

The results of the proposed method are shown in Table I. We note from this Table that there are no real roots at a speed of 140 rpm, so there is no self-excitation. We note from Table II the comparison between the results obtained using different methods and the proposed method. The machine parameters in the present analysis and tests are given in Table III in the Appendix.

TABLE II.
COMPARISON BETWEEN SEVERAL METHODS

[Ref]	Minimum and Maximum real roots	Minimum and maximum capacitance
[16]	0.9795 0.5292	C_{min}= 45.6983 μF C_{max}= 657 μF
[20]	0.9824 0.1630	C_{min}= 45.7993 μF C_{max}= 4300 μF
[5]	0.9937 0.5191	C_{min}= 42.95 μF C_{max}= 200 μF
[Proposed method]	0.9796 684.3798	C_{min}= 46.3847 μF C_{max}= 684.3798 μF

III. SIMULATION RESULTS AND DISCUSSION

Observed from Fig. 3 (a), the relationship between the required capacitance and the load resistance at a fixed load reactance of 0.5 pu and show from Fig. 3 (b) shows the relationship between the required capacitance and the load reactance at fixed load resistance 0.5pu. For different values of rotor speed, the values are $(0.5pu, 1pu, 1.5pu, and 2pu)$. It is noted in both figures that the capacitance value decreases when load resistance and load reactance increase.

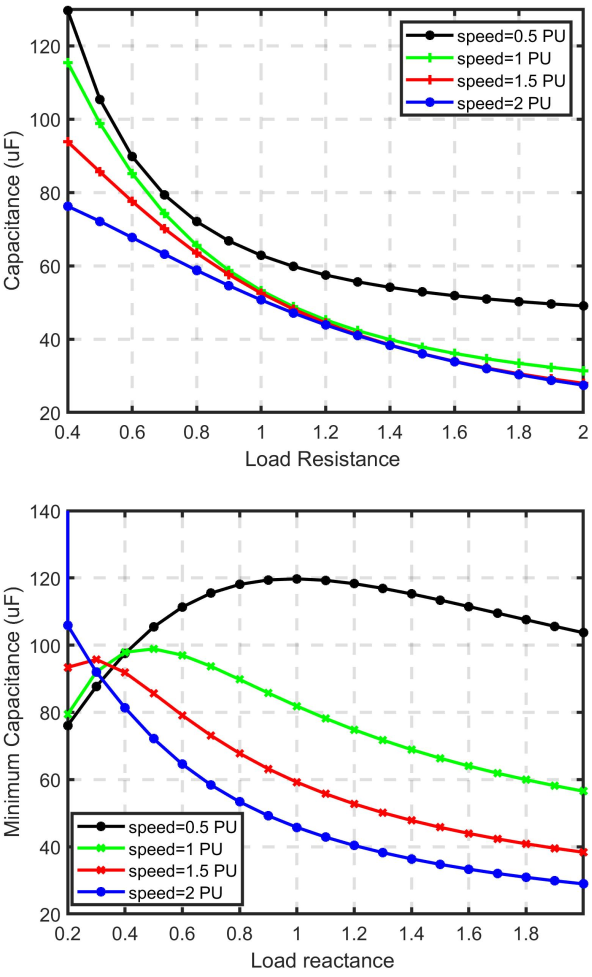
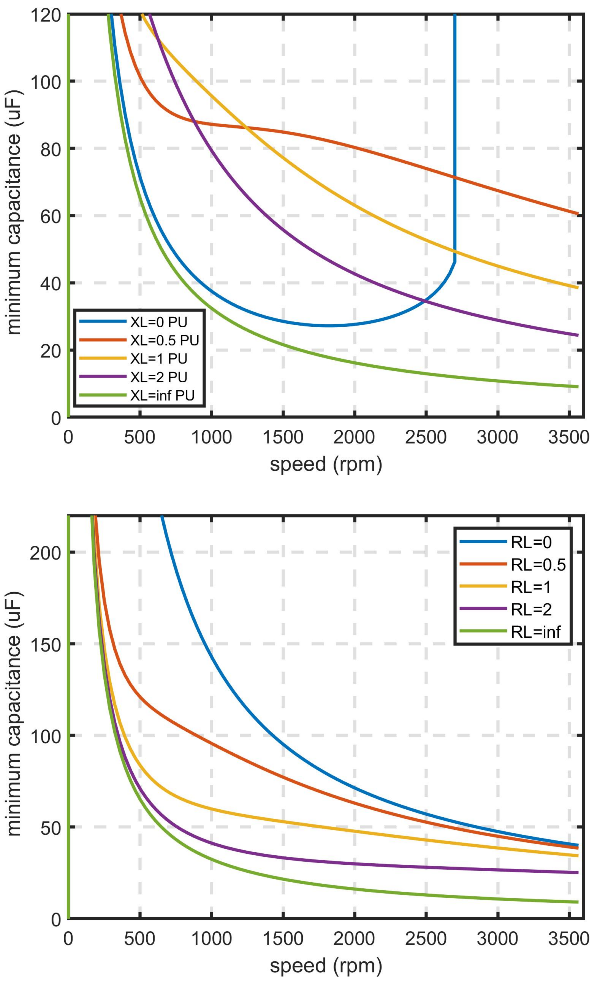


Fig. 3. Variation the capacitance with (a) Load resistance (b) Load reactance

Fig. 4 (a) explains the variation of the minimum capacitance Cexc(mim) with speed when load reactance varies from 0 to infinity. At fixed load reactance=0.5 pu. Fig. 4 (b) shows the variation of the minimum capacitance Cmin(exc) with rotor speed when load resistance varies from 0 to infinity. At fixed load reactance =0.5 pu. It is seen in both figures that the capacitance decreased rapidly with increased rotor speed. Also, it is seen that the induction generator fails to excite at load (RL=0.5 pu and XL=0) at speed 2700rpm.

The machine is simulated with two different resistive loads (50 ω and 190 ω) at the same capacitance of 65μf as shown in Fig. 5 (a) and (b) it is observed The effect of choosing the



(a)

Fig. 4. Minimum capacitance with speed(a) XL=0.5 (b) RL=0.5

accurate capacitance value and load on voltage build-up as well as on the magnitude of the generated voltage.

It is observed in Fig.**??** (a) and (b) how the voltage build-up and steady-state voltage are affected when the capacitance value increases from 35 μF to 65 μF under the same load, the steady state peak voltage increases from 544 volts to 686 volts. Also, the time for the machine to reach the steady state decreases from 1.25 S at the capacitance of 35 μF to 0.4S at the capacitance of 65 μF.

Fig. 7 (a) and Fig. 7 (b) show the voltage builds up and collapse of voltage when the capacitance decreased from 30 μF to 20 μF at the same load (RL=190 and L=6mH), the machine is run at 1900 rpm. Fig. 8 $(a) and$ (b) illustrate the

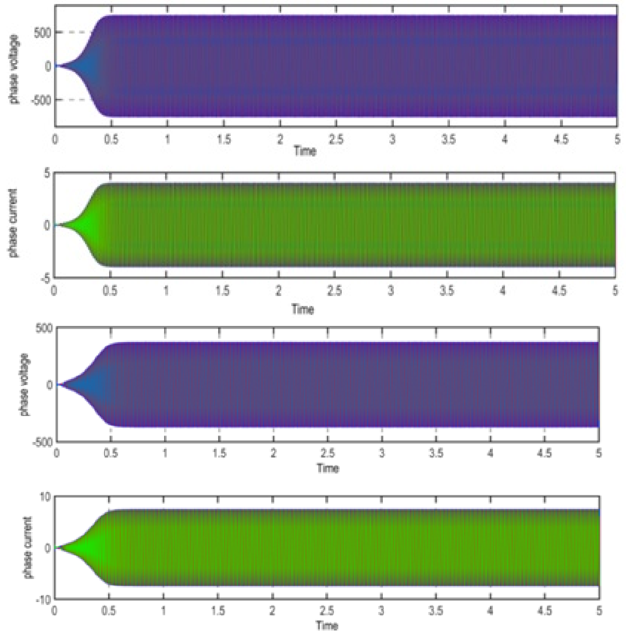
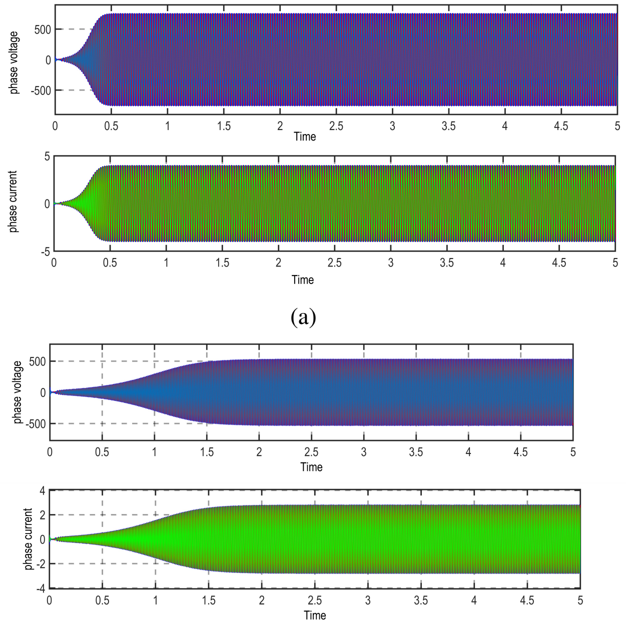


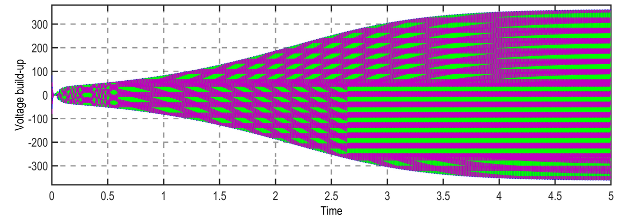
Fig. 5. Voltage build (a) C=65 μF and RL=190 ω (b) build (a) C=65 μF and RL=50 ω



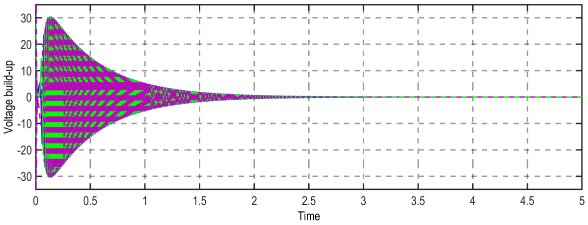
(a)

(b)

Fig. 6. Steady state voltage (a) C=65 μF (b)C=35 μF

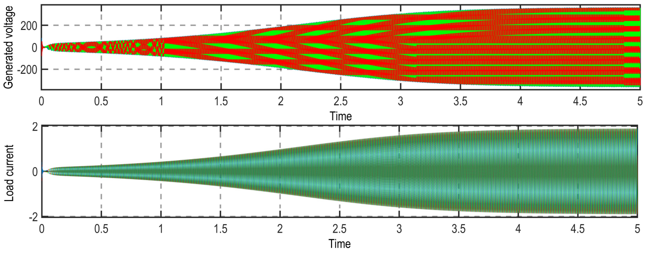


(a)

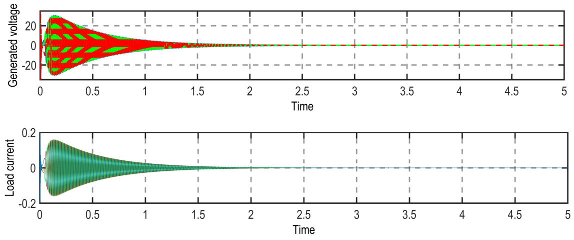


(b)

Fig. 7. The voltage builds up and collapse (a) C=30 μF (b) C=20 μF



(a)



(b)

Fig. 8. Voltage and load current at c=20 μF (a)generated (b) collapse

generated voltage and load current at capacitance =30 μF and show voltage collapse when the capacitance is decreased to 20 μF. The machine runs at 1800 rpm and the same load (RL=190 and L=6mH). Fig. 8 Voltage and load current at c=20 μF (a) generated (b) collapse.

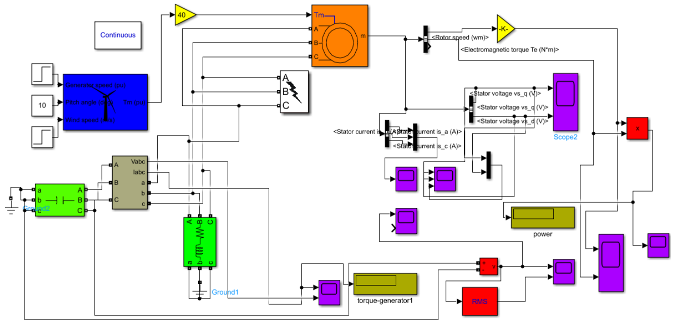


Fig. 9. SEIG model implemented by Matlab/Simulink

IV. SIMULINK TRANSIENT RESPONSES UNDER DIFFERENT FAULT

In this section, using MATLAB/SIMULINK will be described the transient responses under different faults (Sudden short circuit, Unbalanced excitation, Sudden increase of load, Sudden disconnection of excitation capacitance, and Load disturbance) and photos for best printing result. Fig. 9 and Fig. 7 (b) explains the MATLAB/Simulink diagram of the test system.

A. *Sudden short circuit*

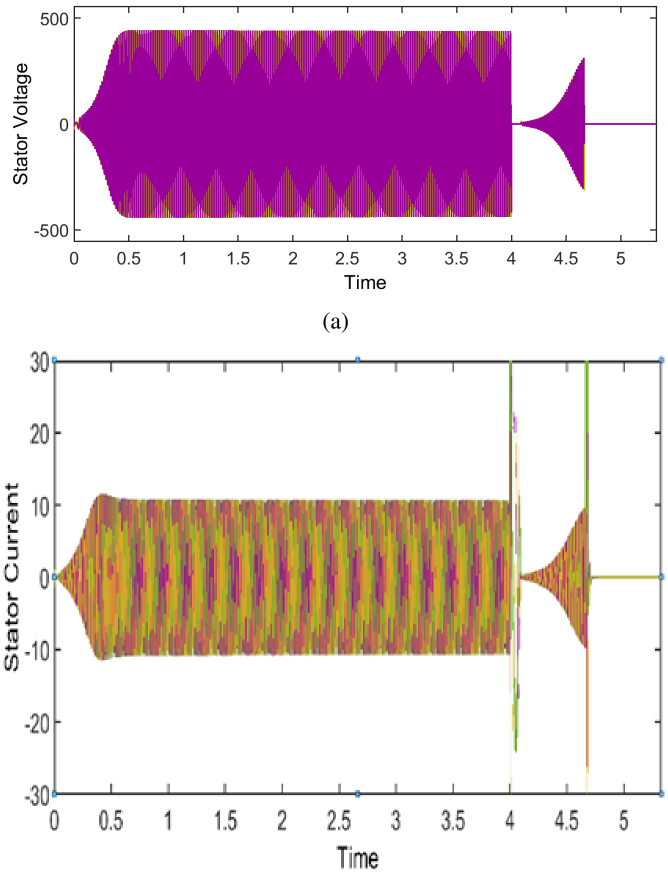
Fig. 10 (a) and (b) show the transient response of the stator voltage and current of the induction generator. When sudden short circuit. From these figures, we can find out the fast responses in case of sudden short circuits at machine terminals, voltage reaches zero value at about t = 4 s, and small oscillations are observed after that the machine will not be recovered till the end of the operation in the case of continuing the short circuit.

B. *Sudden Increase in Load*

The stator voltage and current, load voltage, and load current waveform when Sudden Increase of Load is shown in Fig. 11 (a), (b) and (c) both current and voltage are greatly affected (current increases to a very high value and voltage decreases to a very low). Still, no voltage collapse occurs when the fault is removed (a decrease in the reactive power of the machine causes a decrease in generator voltage). The overload is applied at t=2.5ec to 2.7seconds.

C. *Disconnection of excitation capacitance*

Fig. 12 (a), (b), (c) *and* (d) shows the transient responses of stator current, stator voltage, load current, load voltage, and active power. When the excitation capacitor is disconnected from the machine, the responses of this case quickly reach zero value at about t=3sec.



(a)

(b)

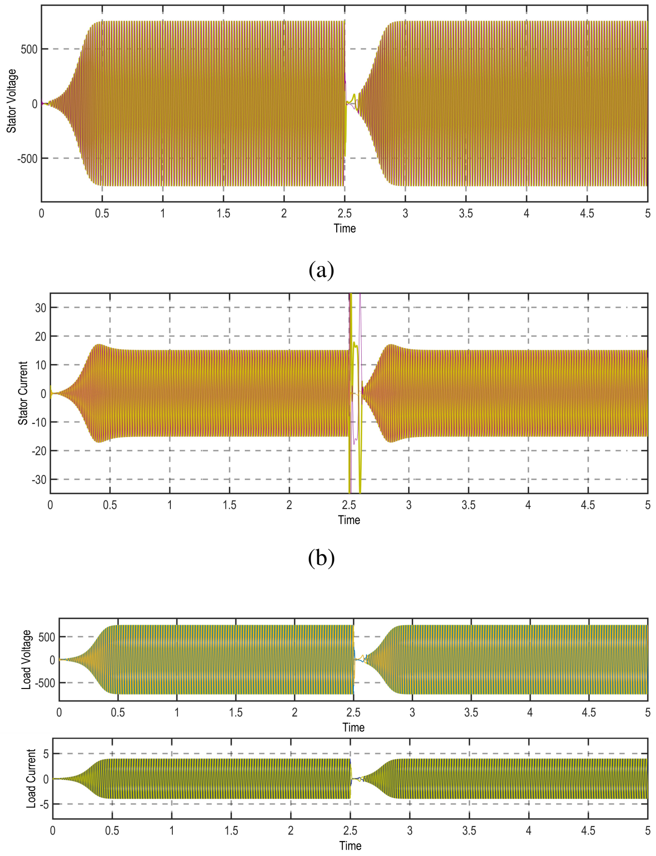
Fig. 10. Transient response (a) Stator voltage(b) Stator current

D. Load Disturbance

Fig. 13 (a), (b)*and* (c) represent the stator voltage and current, load voltage, and load current waveform when the sudden application and removal of load when the generator reaches the rated voltage. The stator current reached 28 A during fault at 2.5 seconds.

V. UNBALANCED EXCITATION

Fig. 14 (a), (b), (c) *and* (d) Shows the simulation result of transient responses with Load (R=190 Ω, L=6 mH) under unbalanced excitation, the stator voltage and stator current attain their steady-state value at 4 sec. The amount of active and reactive power required by the load is large, which leads to a voltage drop and possibly a collapse of the generator voltage.



(a)

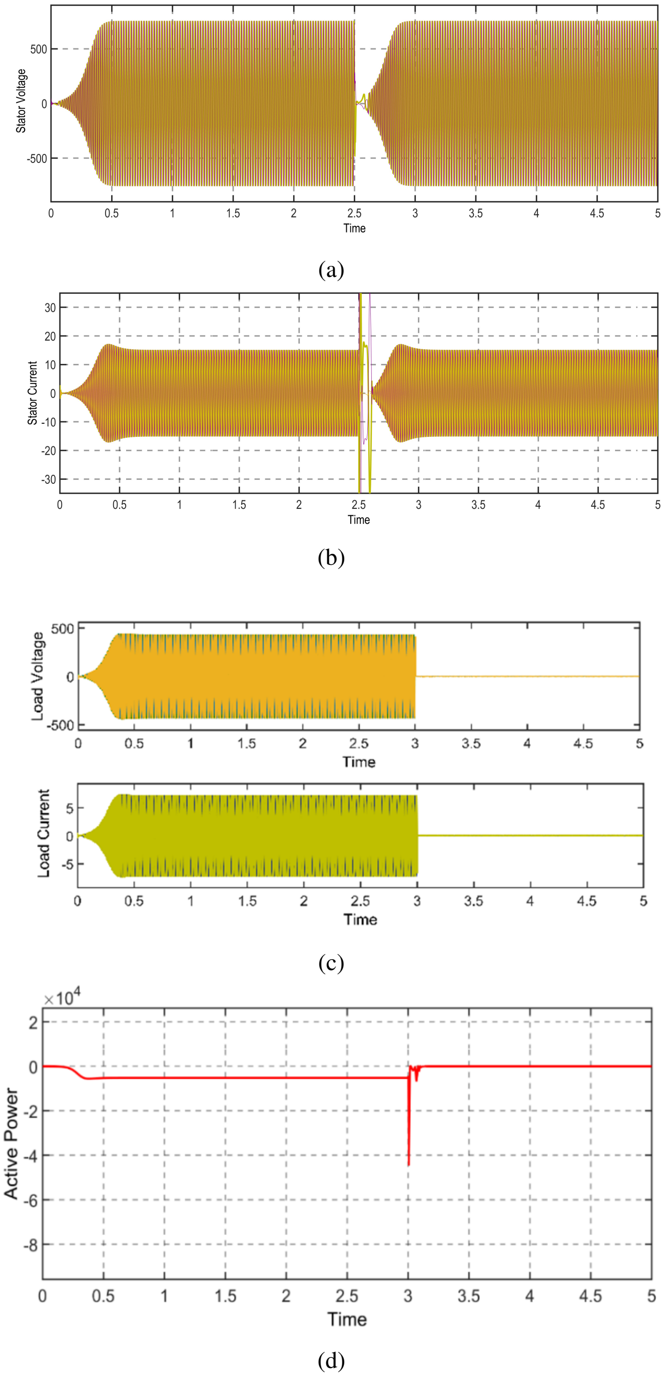
(b)

(c)

Fig. 11. Transient responses (a) stator voltage(b) stator current(c) load voltage and current. When a sudden increase in the Load

A. Conclusion and Scopes for the Future Work

Many important and interesting aspects of the self-excited induction generator are discussed in this research. The most important is presenting a simple and understandable proposed method for finding the capacitor. The study also included theoretical analysis, modeling, and simulation related to different types of faults (Sudden short circuits, excitation fluctuations, Sudden increase of load, Sudden disconnection of excitation capacitance, and Sudden disconnection of load). The specific conclusions of this paper are as follows: 1- When excitation is lost due to a short circuit across the generator terminals, the generator rebuilds its voltage after the fault is removed, and the voltage rebuilding process is faster if a temporary short circuit occurs in the load. 2-The voltage build-up in (SEIG) driven by wind turbines depends mainly on selecting the accurate value of excitation capacitors first and then on the wind speed fluctuations and load changes. 3- Simulations show that the voltage drops due to loading in a (SEIG) can be



(a)

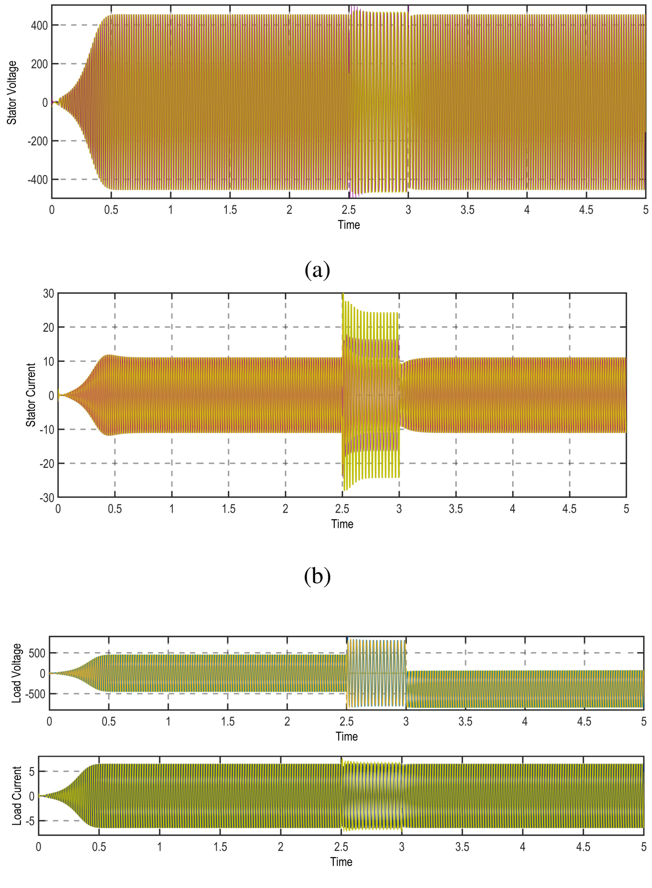
(b)

(c)

(d)

Fig. 12. Transient responses (a) stator voltage(b) stator current(c) load voltage and current. When a sudden increase in the Load

compensated by increasing the excitation capacitance value. 4- The excitation capacitance is very much affected by the type of load impedance. It is observed when the load resistance or load reactance increases, the value of the required capacitance decreases.



(a)

(b)

(c)

Fig. 13. transient responses (a) stator voltage(b) stator current(c) load voltage and current. When a sudden increase in the Load

CONFLICT OF INTEREST

The authors have no conflict of relevant interest to this article.

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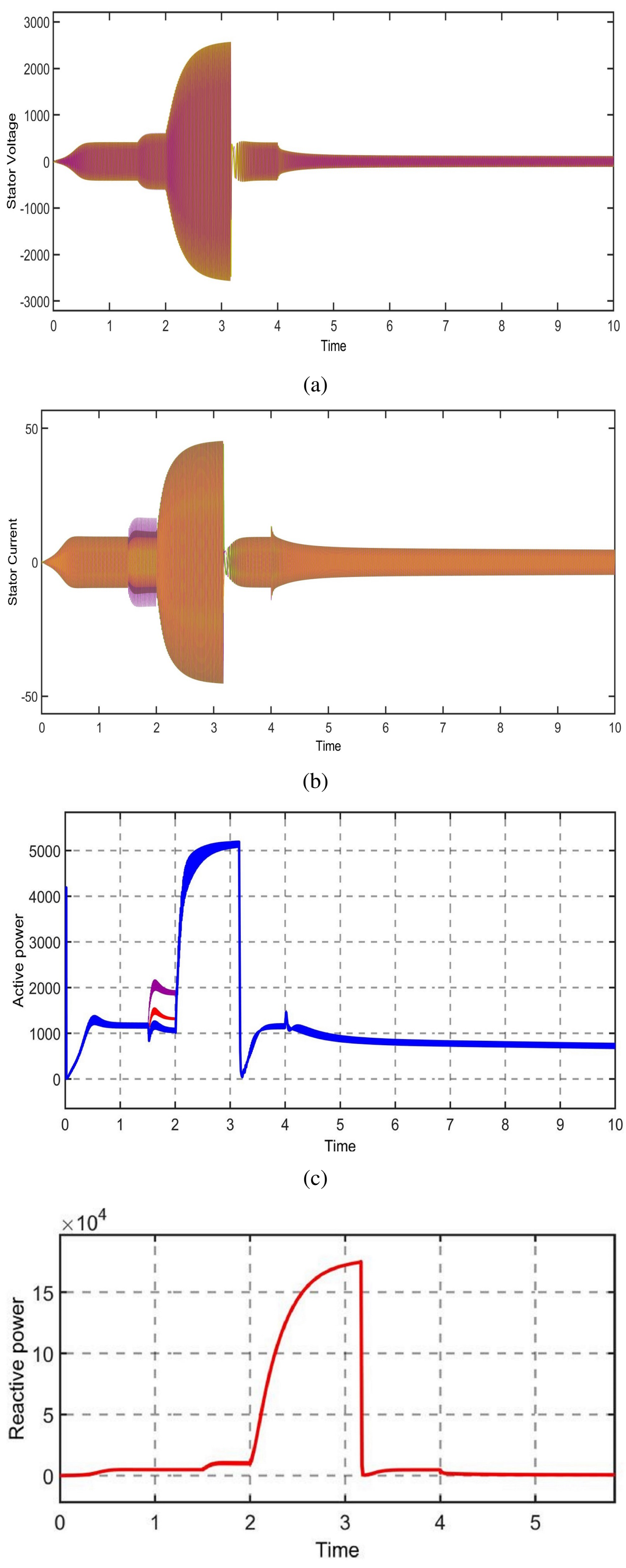

(a)

(b)

(c)

(d)

Fig. 14. Transient responses (a) stator voltage(b) stator current(c) Active power (d)Reactive power. When Unbalanced excitation

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APPENDIX-A

$$
\begin{aligned}
&\partial_1 = X_L\left[R_R(X_M+X_S)+R_S(X_M+X_R)\right]+R_L(M+X_R)\\
&\quad\left[X_S+\frac{X_M X_R}{X_M+X_R}\right]\\
&\partial_2 = V(X_R X_M)+\left[R_L\left(X_S+\frac{X_M X_R}{X_M+X_R}\right)+R_S X_L\right]\\
&\partial_3 = R_R(X_M+X_R+X_S)+R_L(X_M+X_R)+R_S(X_R+X_M)\\
&\partial_4 = R_S R_R R_L\\
&\partial_5 = VA_2(R_L+R_S)
\end{aligned}
$$

COEFFICIENTS FOR EQUATION (13)

$$
\begin{aligned}
&\beta_1 = X_L(X_R X_M+X_S X_M+X_R X_S)\\
&\beta_2 = -Vb_1\\
&\beta_3 = (X_R+X_M)(X_R+X_S)\left(X_S+\frac{X_M X_R}{X_M+X_R}\right)\\
&\beta_4 = R_L(R_R+R_S)A_2+R_R R_S X_L\\
&\beta_5 = Vb_3\\
&\beta_6 = VR_L R_S A_2\\
&\beta_7 = R_R(R_L+R_S)
\end{aligned}
$$

COEFFICIENTS FOR EQUATION (17)

$$
\begin{aligned}
&P = X_S+X_M\\
&Q = X_S+\frac{X_R X_M}{X_R+X_M}\\
&G_0 = R_L R_S(R_L+R_S)(V^2P^2+R_R^2)\\
&G_1 = -(2VR_L^2R_SP^2+2VR_LR_S^2P^2\\
&\quad +2VR_LR_SR_RP(P-Q)+VR_RR_L^2P(P-Q))\\
&G_2 = V^2R_SP^2X_L^2+V^2R_LP^2Q^2+R_LR_R^2P^2+R_SR_R^2X_L^2\\
&\quad +R_SR_L^2P^2+R_LR_S^2P^2+R_RR_L^2P(P-Q)+\\
&\quad 2R_RR_LR_SP(P-Q)\\
&G_3 = -(2VR_SP^2X_L^2)+(2VR_LP^2Q^2+VR_RX_L^2P(P-Q)\\
&G_4 = R_RX_L^2P(P-Q)+R_SX_L^2P^2+R_LP^2Q^2
\end{aligned}
$$

TABLE III. INDUCTION GENERATOR PARAMETERS

Parameters	**Unit**	**Value**
Rs	Pu	0.071
Rr	Pu	0.0881
Xs = Xr	Pu	0.1813
Xm	Pu	3.23
RL	Pu	1
XL	Pu	2
V	pu	1
Fb	Hz	60
Zb	Ω	43.3
N	rpm	1800