Teaching the self-excited induction generator using Matlab

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Abstract This paper presents an attractive approach for teaching the self-excited induction generator. Three operating conditions of the generator are mathematically modeled and then simulated using conventional Matlab commands. Active windows with these models are created using Matlab's Graphical User Interface capability. An example is given to demonstrate the usefulness of the developed tool.

Keywords computer simulations; induction generators; teaching aids

List of symbols

R_S, R_R, R_M, R_L, R_C	p.u stator, rotor, magnetizing, load and exciting resistances, respectively
X_S, X_R, X_M, X_L, X_C	p.u stator, rotor leakage, magnetizing, load and exciting reactances at base frequency, respectively
Y_S, Y_R, Y_M, Y_L, Y_C	p.u stator, rotor, magnetizing, load and exciting admittances, respectively
f_S	synchronous frequency
F	p.u frequency
ν	p.u rotational speed
E_g, V_T	p.u air gap and terminal voltages, respectively
I_S, I_R, I_L	pu stator, rotor and load currents per phase, respectively
P_{out}	output electrical power
P_{in}	input mechanical power
Z_C	capacitor bank impedance

Three-phase squirrel cage induction generators are usually implemented in stand-alone power systems that employ renewable energy resources, like hydro-power and wind energy.[1–4] This is due to the advantages of these generators over conventional synchronous generators. The main advantages are: reduced unit cost, absence of a separate d.c. source for excitation, ruggedness, brushless rotor construction and ease of maintenance.

This paper presents an effective approach for teaching the self-excited induction generator (SEIG) using a Matlab environment. This approach enables a student to simulate different operating conditions of the generator easily using basic Matlab instructions. In addition, the student can learn Matlab's Graphical User Interface (GUI) capabilities to develop an attractive and user-friendly software package for teaching a SEIG.

The next section presents not only the requirements to operate an induction machine as a SEIG, but also the parameters affecting the performance of this generator. Mathematical modeling and simulations of a SEIG under three operating conditions (constant frequency operation, constant speed operation and variable frequency-variable speed operation) are then given. As a basis for developing an attractive and easy-to-use educational software tool, some of Matlab's GUI functions are implemented in creating an active link with these models. The next section demonstrates the effectiveness of the presented approach using an example of a SEIG under variable speed-variable frequency operating condition. Finally, conclusions of this work are given.

Self-excited induction generator

A three-phase induction machine can be operated as a SEIG if its rotor is externally driven at a suitable speed and a three-phase capacitor bank of a sufficient value is connected across its stator terminals. The block schematic diagram of a SEIG system is shown in Fig. 1. When the induction machine is driven at the required speed, the residual magnetic flux in the rotor will induce a small e.m.f. in the stator winding. The appropriate capacitor bank causes this induced voltage to continue to increase until an equilibrium state is attained due to magnetic saturation of the machine.

Fig. 2 shows both the magnetizing curve of an unloaded SEIG and the voltage–current characteristic of a capacitor bank plotted on the same set of axes. The intersection of the two curves is the point at which the capacitor bank exactly supplies the reactive power demanded by the generator. As shown in the figure the no-load terminal voltage of the generator may be determined from this point.

When a SEIG is loaded, both the magnitude and frequency of the induced e.m.f. are affected by: the prime mover speed, the capacitance of the capacitor bank and the load impedance. To simplify the discussion, we assume that all losses in the generator are ignored ($P_{in} = P_{out}$), the connected load is purely resistive and the rotor speed is kept constant. In this case, the decrease in the load resistance (increase in P_{out}) will result in a drop in the stator frequency to provide higher torque to match the increment in the power demand. This circumstance is illustrated in Figs 3 and 4.

In the above case, it is assumed that the SEIG was feeding a resistive load so that

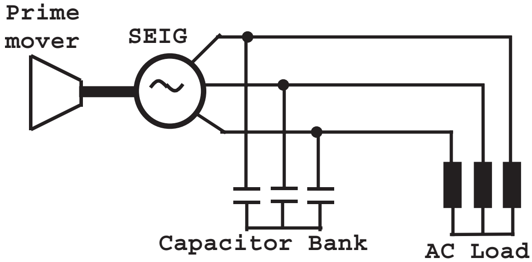

Fig. 1 *Self excited induction generator system.*

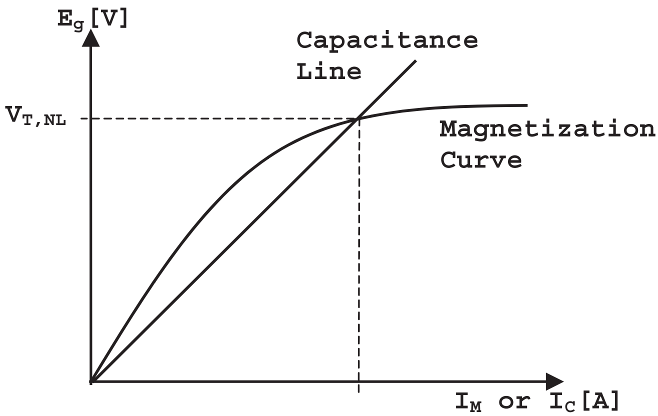

Fig. 2 *No-load magnetization characteristic and capacitive impedance line.*

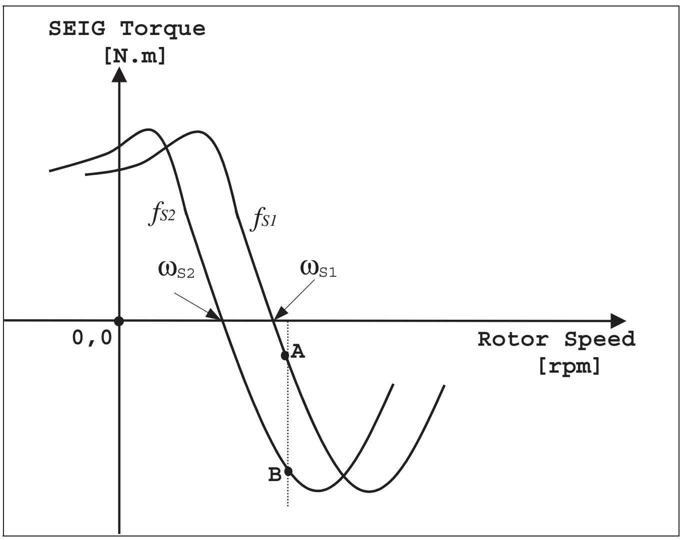

Fig. 3 *Torque speed characteristics of an induction machine,* $f_{S1} > f_{S2}$.

the steady-state operation point was A and the synchronous frequency was f_{S1}. When the power demand increases, the synchronous frequency reduces from f_{S1} to f_{S2} and the new steady-state operation point is changed to point B. The reduction in the synchronous frequency causes the induced e.m.f. to reduce in the same proportion, if emf/f_S ratio is kept constant. Moreover, the decrease in f_S changes the slope of the impedance line from Z_{C1} to Z_{C2}, as shown in Fig. 4, according to the following relationship:

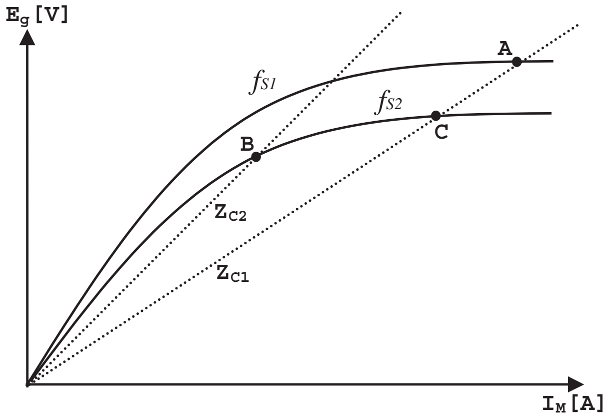

Fig. 4 *Magnetization characteristics and capacitive impedance lines of a loaded SEIG,* $f_{S1} > f_{S2}$.

$$Z_C = \frac{1}{2\pi f_S C}$$

The induced e.m.f. could be increased, by returning the slope of the Z_C line back to its previous value (increasing the capacitance value of the capacitor bank). Since the synchronous frequency remains f_{S2}, the steady-state operation point will now be at point C instead of point A.

Modeling and simulation of SEIG

The steady-state per-phase equivalent circuit of a SEIG, supplying a balanced resistive load, is shown in Fig. 5. In this circuit, only the magnetizing reactance is assumed to be affected by magnetic saturation, and all other parameters are assumed to be constant. In addition, core losses and the effect of the harmonics are ignored. From Fig. 5, the total current at node a may be given by:[5,6]

$$E_1(Y_1 + Y_M + Y_R) = 0 \tag{1}$$

Therefore, under steady-state self-excitation, the total admittance must be zero, since $E_1 \neq 0$.

$$Y_1 + Y_M + Y_R = 0 \tag{2}$$

or

$$Real(Y_1 + Y_M + Y_R) = 0 \tag{3}$$

$$Imag(Y_1 + Y_M + Y_R) = 0 \tag{4}$$

Where

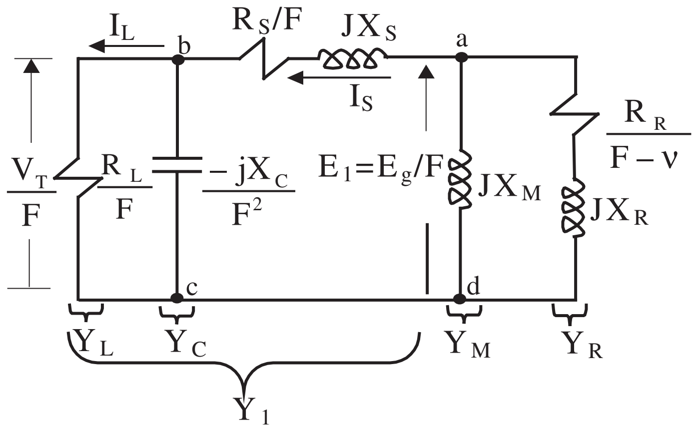

Fig. 5 *Per-phase equivalent circuit of a SEIG.*

$$Y_1 = \frac{(Y_C + Y_L)(Y_S)}{Y_C + Y_L + Y_S} \qquad Y_C = \frac{1}{-(jX_C/F^2)} \qquad Y_L = \frac{1}{(R_L/F)}$$

$$Y_S = \frac{1}{(R_S/F) + jX_S} \qquad Y_M = \frac{1}{jX_M} \qquad Y_R = \frac{1}{\frac{R_R}{F-\nu} + jX_R}$$

Equations 3 and 4 are nonlinear equations of four unknowns: F, X_M, X_C and ν. Two of these unknowns should be specified. The other two unknowns can be found by solving eqn. 3 for one unknown and the other unknown is calculated from eqn. 4. Having determined the two unknown parameters, the steady-state performance of the SEIG can be obtained by solving the circuit of Fig. 5 with the help of the generator's magnetization curve. The performance characteristics of the generator could be estimated using the following relationships:

$$I_S = \frac{E_g/F}{\frac{R_S}{F} + jX_S - \frac{jX_C R_L}{F^2 R_L - FX_C}} \qquad I_R = \frac{-E_g/F}{\frac{R_R}{F-\nu} + X_R} \qquad I_L = \frac{-jX_C I_S}{R_L F - jX_C}$$

$$V_T = I_L R_L \qquad P_{in} = \frac{-3R_R F|I_R|^2}{F-\nu} \qquad P_{out} = 3|I_L|^2 R_L$$

Three operating conditions of a SEIG are considered in the present work. These are constant speed operation, constant frequency operation and variable frequency-variable speed operation. To achieve constant speed operation, the generator should be driven by a fixed shaft speed turbine. To maintain the frequency of the output voltage constant, a controlled shaft speed turbine may be implemented to drive the generator. If an unregulated turbine drives the generator, the frequency and shaft speed are affected by the energy source. For example, these two parameters are affected by wind speed if the generator's prime mover is an unregulated wind turbine.

Based on eqns 3 and 4, the above three operating conditions are mathematically modeled. If the generator is operated at constant shaft speed, F and X_M will vary with the load and hence they must be taken as the two unknowns. For this case, a fifth order polynomial, independent of X_M, is extracted from eqn. 3, and the X_M eqn. is obtained from eqn. 4 as follows:

$$A_5F^5 + A_4F^4 + A_3F^3 + A_2F^2 + A_1F + A_0 = 0 \tag{5}$$

$$X_M = -1 \Big/ \left\{ \frac{X_R}{\left[R_R/(F-\nu)\right]^2 + X_R^2} + \frac{X_{ac}}{R_{ac}^2 + X_{ac}^2} \right\} \tag{6}$$

where

$$A_0 = -\nu R_R\left(\frac{R_3}{R_L}\right)^2 \qquad A_1 = R_R\left(\frac{R_3}{R_L}\right)^2 + R_3\left(\frac{R_R}{R_L}\right)^2 + \nu^2 R_3\left(\frac{X_R}{R_L}\right)^2$$

$$A_2 = -2\nu R_3\left(\frac{X_R}{R_L}\right)^2 - \nu R_R\left\{\left(\frac{R_S}{X_C}\right)^2 + \left(\frac{X_S}{R_L}\right)^2 - 2\left(\frac{X_S}{X_C}\right)\right\}$$

$$A_3 = R_R\left[\left(\frac{X_S}{R_L}\right)^2 + \left(\frac{R_S}{X_C}\right)^2 - 2\left(\frac{X_S}{X_C}\right)\right] + R_3\left(\frac{X_R}{R_L}\right)^2 + R_S\left(\frac{R_R}{X_C}\right)^2 + \nu^2 R_S\left(\frac{X_R}{X_C}\right)^2$$

$$A_4 = -\nu\left[R_R\left(\frac{X_S}{X_C}\right)^2 + 2R_S\left(\frac{X_R}{X_C}\right)^2\right] \qquad A_5 = R_R\left(\frac{X_S}{X_C}\right)^2 + R_S\left(\frac{X_R}{X_C}\right)^2$$

$$R_{bc} = R_L X_C^2 \big/ \left[F\left(F^2R_L^2 + X_C^2\right)\right] \qquad X_{bc} = R_L^2 X_C \big/ \left(F^2R_L^2 + X_C^2\right)$$

$$R_{ac} = \frac{R_S}{F} + R_{bc} \qquad X_{ac} = X_S - X_{bc} \qquad R_3 = R_S + R_L$$

When a SEIG is operated at constant frequency, ν and X_M should be considered as unknowns. For this operating condition, eqn. 3 can be simplified to give eqn. 7, which is a quadratic equation of ν. For a given F, X_C and R_L, eqn. 7 can be used to obtain ν and then X_M may be calculated from eqn. 6.

$$B_2\nu^2 + B_1\nu + B_0 = 0 \tag{7}$$

where

$$B_0 = R_RF\left(R_{ac}^2 + X_{ac}^2\right) + R_{ac}\left(R_R^2 + F^2X_R^2\right) \qquad B_1 = -\left[R_R\left(R_{ac}^2 + X_{ac}^2\right) + 2FR_{ac}X_R^2\right]$$

$$B_2 = R_{ac}X_R^2$$

For the variable frequency-variable speed operating condition, F and X_M are affected by both R_L and ν. Therefore, F and X_M can be considered as the unknown parameters, but the effects of both R_L and ν on these unknowns should be considered. For a given ν, X_C and R_L, eqn. 5 can be solved to determine F, and X_M can be computed using eqn. 6.

The mathematical models representing the three operating conditions of a SEIG could be simulated in separated script files (M-files) using conventional Matlab language. The created Matlab code to simulate the variable frequency-variable speed operating condition is:

```
%The parameters of the per-phase equivalent circuit of
%the SEIG in PU
Rs=0.1; Xs=0.2; Rr=0.06; Xr=0.2; Xc=1.2; vv=0.7; FF=0.4;
%The speed and frequency
N=0.9;  Freq=0.9;
%The increment, and the last values for speed and RL
  %counters,
zz=10;  kk=4;  inc=0.1;

%Variable frequency-variable speed operating condition
if (m2==1)  default  zz=50;
else  user  end
for  ii=1:kk;
vv=vv+inc;
RLi=1.2;
  for  jj=1:zz;
    RLi=RLi+.6;
    RL(jj,ii)=RLi;

R3=Rs+RL(jj,ii);
  A5=Rr*(Xs/Xc)*(Xs/Xc)+Rs*(Xr/Xc)*(Xr/Xc);
A4=-vv*(Rr*(Xs/Xc)*(Xs/Xc)+2*Rs*(Xr/Xc)*(Xr/Xc));
A3_a=Rr*((Xs/RL(jj,ii))*(Xs/RL(jj,ii))+(Rs/Xc)*(Rs/Xc)
  -2*(Xs/Xc));
A3_b=R3*(Xr/RL(jj,ii))*(Xr/RL(jj,ii))
  +Rs*(Rr/Xc)*(Rr/Xc);
A3_c=vv*vv*Rs*(Xr/Xc)*(Xr/Xc);  A3=A3_a+A3_b+A3_c;
A2_a=-2*vv*R3*(Xr/RL(jj,ii))*(Xr/RL(jj,ii));
A2_b=-vv*Rr*((Rs/Xc)*(Rs/Xc)+
  (Xs/RL(jj,ii))*(Xs/RL(jj,ii))-2*(Xs/Xc));
A2=A2_a+A2_b;
A1=Rr*(R3/RL(jj,ii))*(R3/RL(jj,ii))
  +R3*(Rr/RL(jj,ii))*(Rr/RL(jj,ii))+vv*vv*R3*...
  (Xr/RL(jj,ii))*(Xr/RL(jj,ii));
A0=-vv*Rr*(R3/RL(jj,ii))*(R3/RL(jj,ii));
  coeff=[A5 A4 A3 A2 A1 A0];
R=[roots(coeff)];  R=R';
```

```
M(jj,1:5)=[R]; M1=M(jj,1); M2=M(jj,2); M3=M(jj,3);
  M4=M(jj,4); M5=M(jj,5);

%Check if the roots are real or complex.
C1=isreal(M1); C2=isreal(M2); C3=isreal(M3);
  C4=isreal(M4); C5=isreal(M5);

%check if a root is real & positive and only the
  %positive real root is taken
if C1==1 & M1>0 & M1<1;      F(jj,ii)=M1;
elseif C2==1 & M2>0 & M2<1;  F(jj,ii)=M2;
elseif C3==1 & M3>0 & M3<1;  F(jj,ii)=M3;
elseif C4==1 & M4>0 & M4<1;  F(jj,ii)=M4;
elseif C5==1 & M5>0 & M5<1   F(jj,ii)=M5;
else                         F(jj,ii)=1;
end

%Obtaining the value of the magnetizing reactance Xm
FV(jj,ii)=F(jj,ii)-vv;  Zp1(jj,ii)=RL(jj,ii)/F(jj,ii);
Zp2(jj,ii)=(-Xc*i)/(F(jj,ii)*F(jj,ii));
Zp(jj,ii)=(Zp1(jj,ii)*Zp2(jj,ii))/
  (Zp1(jj,ii)+Zp2(jj,ii));
Zs(jj,ii)=(Rs/F(jj,ii))+(Xs*i);
  Zps(jj,ii)=Zp(jj,ii)+Zs(jj,ii);
Yps(jj,ii)=1/Zps(jj,ii);
  Yr(jj,ii)=1/((Rr/FV(jj,ii))+(Xr*i));
Yps_R(jj,ii)=imag(Yps(jj,ii));
  Yr_R(jj,ii)=imag(Yr(jj,ii));
Ym(jj,ii)=-(Yr_R(jj,ii)+Yps_R(jj,ii));
  Xm(jj,ii)=-1/Ym(jj,ii);
```

The 'User' can access Matlab's GUI facilities to develop a powerful and attractive software package for teaching a SEIG. As an example of using Matlab's GUI capabilities, menu and plotting commands are implemented in a script file to provide interactive windows with the three simulated operating conditions. The main menu, which is displayed after running the file, is shown in Fig. 6.

Demonstration

The ease of using the presented tool for accurate analysis of a SEIG has been demonstrated by examining the variations of V_T with I_L at different prime mover speeds. The SEIG chosen for this study is a 3-phase, 4-pole, 60 Hz, 1 kW, 380 V, 2.27 A, Y-connected squirrel cage induction machine whose per phase equivalent circuit parameters in pu are:

$$R_s = 0.1 \qquad X_s = 0.2 \qquad R_r = 0.06 \qquad X_r = 0.2.$$

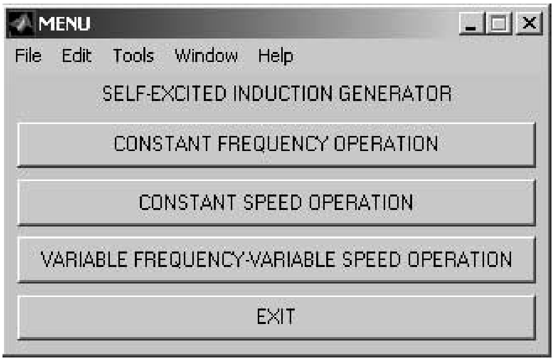

Fig. 6 *The main window of the developed software tool.*

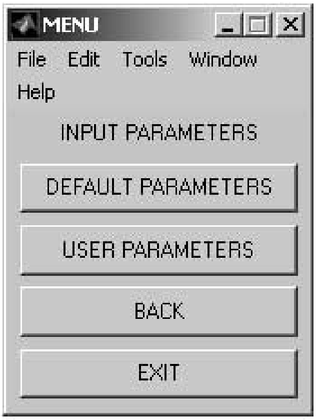

Fig. 7 *The window of inserting the inputs for the desired SEIG.*

The relationship between the magnetizing reactance X_m and the air-gap voltage E_g/F of the machine is:

$$\frac{E_g}{F} = 1.12 + 0.078X_M - 0.146X_M^2 \qquad 0 < X_M < 3$$

This study is carried out using the created GUI windows. Running the created GUI M-file, called *main_menu*, from Matlab workspace will display the main window shown in Fig. 6. The window shown in Fig. 7 will appear after clicking on the icon named 'VARIABLE FREQUENCY_VARIABLE SPEED OPERATION'. Selecting 'DEFAULT PARAMETERS' option will present the result menu shown in Fig. 8. The terminal voltage–load current characteristics can be displayed on the graph window by just clicking on 'VT-IL' icon. The V_T-I_L characteristics, shown in Fig. 9, are in full agreement with those obtained, by other authors.[1,6] It can be seen that the

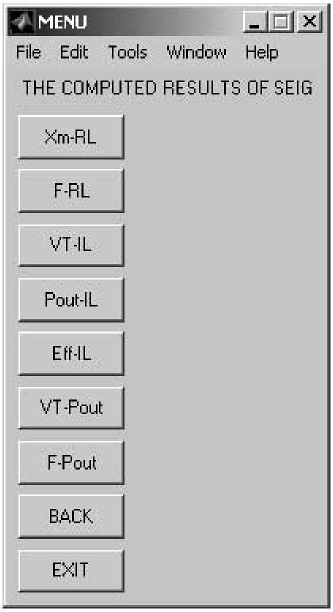

Fig. 8 *The window of the computed results for the desired SEIG.*

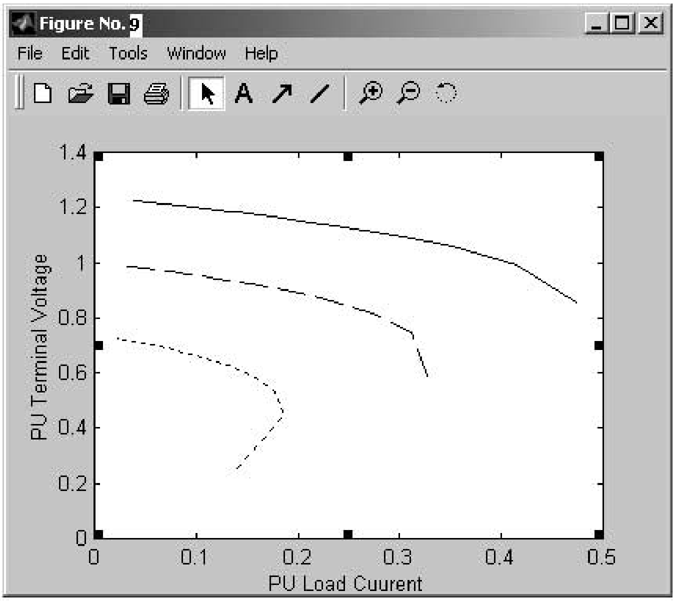

Fig. 9 V_T-I_L *characteristics under variable frequency-variable speed operating condition* ······ $\nu = 0.8\,pu$, – – – – $\nu = 0.9\,pu$, —— $\nu = 1\,pu$.

terminal voltage drops as the load current increases and it increases approximately linearly with prime mover speed.

Conclusion

An attractive and useful approach for teaching a SEIG has been presented in this article. Three operating conditions of the generator are mathematically modeled then simulated using basic Matlab instructions. The developed tool is made easy to use by providing an active link with the simulated models using some of Matlab's GUI functions. The given example demonstrates the usefulness of the developed tool for teaching self-excited induction generators.

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