

Analysis of Various Parameters of Self-excited Induction Generator Using MATLAB/GUI

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Abstract- In contrast to conventional generators, self-excited induction generators are found to be most suitable machines for energizing isolated locations using locally available renewable energy. This paper presents the analysis of a normal three-phase induction motor as a self-excited induction generator (SEIG) to feed single phase loads. Three Capacitor topology was considered for the star connected machine. In this paper the complete evaluation of steady-state behavior of SEIG under different operating conditions is done by user friendly software based solution. The mathematical modeling of the machine is carried out and then simulated in MATLAB's Graphical User Interface (GUI) environment and active windows are created with these models. Various parameters are stimulated through presented methodology and have shown close agreement with experimental results thus validating the performance of this software tool.

Keywords – Self Excited Induction Generator (SEIG), Graphical User Interface (GUI), Capacitor Estimation, MATLAB simulation, Single phase operation insert

I. INTRODUCTION

It is well known that when capacitors are connected across the stator terminals of an induction machine, driven by an external prime mover, voltage will be induced at its terminals [1]. The induced emf and current in the stator windings will continue to rise until steady state is attained, influenced by the magnetic saturation of the machine. At this operating point the voltage and current will continue to oscillate at a given peak value and frequency. In order for self-excitation to occur, for a particular capacitance value there is a corresponding minimum speed [2-4].

Self-excited induction generators are good candidates for wind powered electric generation application specially in remote areas, because they do not need external power supply to produce the magnetic field. Permanent magnet generators can also be used for wind energy applications but they suffer from uncontrollable magnetic field, which decays over a period due to weakening of the magnets, and the generated voltage tends to fall steeply with load. The SEIG has a self-protection mechanism because the voltage collapses when there is a short circuit at its terminals. Further, the SEIGs have more advantages such as cost, reduced maintenance, rugged and simple construction, brush-less rotor (squirrel cage), etc.

In several papers, it has been reported that the value of magnetizing reactance verses air-gap voltage is given as a constant for the unsaturated, low value of air-gap voltage, and then decreases when it saturates [5-8]. However, this representation does not reflect the actual variation of magnetizing inductance and as a result it does not show the actual phenomena during the initiation of self-excitation.

The magnetizing inductance should be represented in such a way that it depicts the actual value for each voltage. The characteristics of the magnetizing inductance as the air gap voltage increases from zero is that it starts at a given value, increases until it reaches its maximum value and then starts to decrease up to its rated value, which is a saturated value. The reason for this variation in magnetizing reactance and the effect on self-excitation is discussed in this paper. As the magnetizing reactance, X_m , is dependent on frequency, magnetizing inductance, L_m , is used in the analysis.

Wang et al [9] and others [10, 11] proposed an analysis to predict both minimum and maximum values of capacitance required for self-excitation of a three phase induction generator. Economically and technically it is not advisable to choose the maximum value of capacitance.

This is due to the fact that for the same voltage rating the higher capacitance value will cost more. In addition, if the higher capacitance value is chosen then there is a possibility that the current flowing in the capacitor might exceed the rated current of the stator, due to the fact that the capacitive reactance reduces as the capacitance value increases.

Our objective is to provide quality power at constant voltage and frequency to the consumer, appropriate system design has to be effected for different types of prime movers and loads at suitable power ratings.

This requires choosing suitable induction machine as a SEIG and finding the value of capacitor / capacitor variation so as to design a system comprising prime mover, machine, capacitor, VAR controller and load. Therefore, a system designer would require a very user friendly tool to be able to predict the performance under varying load conditions, easily design the system and fix the parameters of the components used e.g. the capacitors and VAR controllers.

In this paper the star connected machine with three capacitor excitation topology is considered to feed single phase loads. The paper demonstrates that the versatile facility available through MATLAB tool boxes can be effectively used to provide such a software and design package to interested users.

Only a limited effort is made in literature to this effect. This paper attempts to provide such a user friendly software package using MATLAB tool boxes with GUI facility for comprehensive analysis, design and capacitor estimation under different operating conditions. GUI facility is shown to be an effective tool for the design to visualize the results.

II. ANALYSIS AND MODELLING OF THREE PHASE SEIG FOR SINGLE PHASE LOAD

A. STAR CONNECTED MACHINE

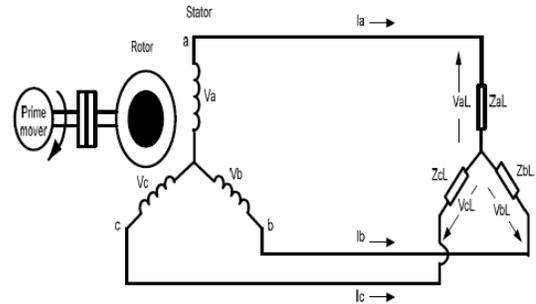


Fig. 2.1 Three-phase SEIG Feeding Three Phase Unbalanced/ Balanced Load

Assuming an unbalanced three-phase lagging power factor (PF) load, the net impedance across the three phases would be Z_{aL} , Z_{bL} and Z_{cL} . The impedance Z_{aL} across the a-phase may be written as

$$Z_{aL} = \frac{(R_{al} + jX_{al})(-jX_{ac})}{(R_{al} + jX_{al}) - jX_{ac}} \quad (1a)$$

Similarly,

$$Z_{bL} = \frac{(R_{bl} + jX_{bl})(-jX_{cb})}{(R_{bl} + jX_{bl}) - jX_{cb}} \quad (1b)$$

$$Z_{cL} = \frac{(R_{cl} + jX_{cl})(-jX_{cc})}{(R_{cl} + jX_{cl}) - jX_{cc}} \quad (1c)$$

Where, X_{ca} , X_{cb} , and X_{cc} are the reactances of excitation capacitance. From the fig. 2.1 we can write loop equation.

$$V_a - V_b = I_a Z_{aL} - I_b Z_{bL}$$

$$V_b - V_c = I_b Z_{bL} - I_c Z_{cL} \quad (2)$$

$$V_c - V_a = I_c Z_{cl} - I_a Z_{al}$$

Since $I_a + I_b + I_c = 0$, $I_0 = 0$ and $V_0 = 0$, i.e. zero sequence components are absent. The symmetrical components of phase currents and voltages are, there

$$\left. \begin{aligned} I_a &= I_1 + I_2 \\ I_b &= \alpha^2 I_1 + \alpha I_2 \\ I_c &= \alpha I_1 + \alpha^2 I_2 \end{aligned} \right\} (3)$$

And,

$$\left. \begin{aligned} V_a &= V_1 + V_2 \\ V_b &= \alpha^2 V_1 + \alpha V_2 \\ V_c &= \alpha V_1 + \alpha^2 V_2 \end{aligned} \right\} (4)$$

The load Voltages are,

$$\left. \begin{aligned} V_{al} &= I_a Z_{al} = (I_1 + I_2) Z_{al} \\ V_{bl} &= I_b Z_{bl} = (\alpha^2 I_1 + \alpha I_2) Z_{bl} \\ V_{cl} &= I_c Z_{cl} = (\alpha I_1 + \alpha^2 I_2) Z_{cl} \end{aligned} \right\} (5)$$

Solving above equations, we get

$$3Z_1 Z_2 + (Z_1 + Z_2)(Z_{al} + Z_{bl} + Z_{cl}) + (Z_{al} Z_{bl} + Z_{bl} Z_{cl} + Z_{cl} Z_{al}) = 0 \quad (6)$$

B. SINGLE PHASE LOAD

This can be considered as a particular case of general unbalance. To feed a single-phase load, three star connected excitation capacitors namely, one C_p and two C_s are connected across the terminals of the SEIG. The single-phase load is connected in parallel with C_p . This minimizes the winding current unbalance.

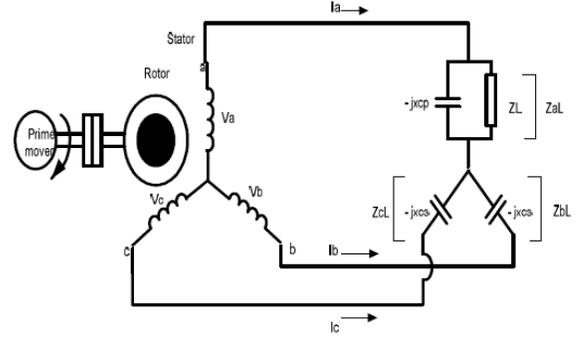


Fig. 2.2 Single Phase Load in Parallel with C_p

In this case, the impedances across the three phases namely, Z_{al} , Z_{bl} and Z_{cl} are-

$$Z_{al} = \frac{(R_{al} + jX_{al})(-jX_{cp})}{(R_{al} + jX_{al}) - jX_{cp}}$$

$$Z_{bl} = -jX_{cs}$$

$$Z_{cl} = -jX_{cs} \quad (7)$$

In this Case,

$$Z_{bl} = Z_{cl} \quad (8)$$

C. METHOD OF SOLUTION

Equation (6) is central to the analysis respectively for star connected system as it defines the status under self-excitation for the given external condition of capacitors, load, speed and machine equivalent circuit parameters under saturation conditions. By solving this equation one should be able to obtain the unknown parameters, namely the magnetizing reactance and per unit generated frequency. The positive sequence equivalent circuit of the induction machine is given in where reactances correspond to the base frequency (50Hz) and X_{m1} is the saturated value corresponding to the forward revolving air gap flux. The net response of the induction machine due to several revolving fields is often taken as the superimposed response of individual fields inspite of the inherent nonlinearity. Simplified equivalent circuits are given in,

Accordingly:

$$Z_1 = R_s + jvX_1 + \frac{jX_{m1} \left[\frac{vR_r}{F-v} + jX_1 \right]}{\left[\frac{vR_r}{F-v} + jX_1 + jX_{m1} \right]}$$

(9a)



$$Z_2 = R_s + \frac{R_r}{2} + j2vX_1 \quad (9b)$$

On substituting for Z_1 and Z_2 and rearranging (6), the following two equations with F and X_m as unknown quantities are obtained by equating real and imaginary parts to zero separately:

$$\begin{aligned} f(X_m, F) &= 0 \\ g(X_m, F) &= 0 \end{aligned} \quad (9c)$$

For Star Connected Machine,

$$\left. \begin{aligned} Z_1 + Z_2 &= A' + jB' \\ Z_1 Z_2 &= C' + jD' \end{aligned} \right\} \quad (10)$$

$$\left. \begin{aligned} Z_{a1} + Z_{b1} + Z_{c1} &= R_{s1} + jX_{s1} \\ Z_{a1} Z_{b1} + Z_{b1} Z_{c1} + Z_{c1} Z_{a1} &= R_{s2} + jX_{s2} \end{aligned} \right\} \quad (11)$$

$$f(X_m, F) = 3C' + VR_r R_{s2} + (A'R_{s1} - B'X_{s1}) - X_{s2}(X_1 + X_m)(F - V) \quad (12)$$

Here A' , B' , C' and D' are constants. Solving (12) by equating to zero, X_m and F are obtained.

III. PERFORMANCE EQUATIONS

After determining p.u. generated frequency F and saturated magnetizing reactance X_m the next step is to determine Normalized air-gap voltage V_g / F corresponding to this saturated X_m . As explained in [1], the relevant magnetizing Characteristics relating V_g / F with X_m can be obtained by a synchronous speed test. Performance equations can now be written using the

simplified equivalent circuit [5] modified to generating connection, in which the current direction of I_1 , I_2 and I_r reverses. Since F is known, now, the earlier assumption $F = V$ can be ignored.

Thus,

$$I_1 = \frac{V_g}{jFX_m} + \frac{V_g}{\frac{FR_r}{F-v} + jFX_1} \quad (13)$$

$$V_1 = V_g + (R_s + jFX_1) * I_1 \quad (14)$$

$$V_2 = KV_1 \quad (16)$$

Impedance is recalculated as we know F by now:

$$\left. \begin{aligned} Z_{a1} &= \frac{(R_{a1} + jX_{a1})(-jFX_{ca})}{(R_{a1} + jX_{a1}) - jFX_{ca}} \\ Z_{b1} &= \frac{(R_{b1} + jX_{b1})(-jFX_{cb})}{(R_{b1} + jX_{b1}) - jFX_{cb}} \\ Z_{c1} &= \frac{(R_{c1} + jX_{c1})(-jFX_{cc})}{(R_{c1} + jX_{c1}) - jFX_{cc}} \end{aligned} \right\} \quad (17)$$

$$\left. \begin{aligned} V_{a1} &= I_{a1} Z_{a1} \\ V_{b1} &= I_{b1} Z_{b1} \\ V_{c1} &= I_{c1} Z_{c1} \end{aligned} \right\} \quad (18)$$

$$P = \text{REAL}(V_{a1} * I_{a1} + V_{b1} * I_{b1} + V_{c1} * I_{c1}) \quad (19)$$

In this software package the aforementioned nonlinear equations are solved by a numerical based routine

'Fsolve' in the tool box of MATLAB to find the values of saturated magnetizing reactance X_m and the output p. u. frequency F for the given values of machine parameters. Based on the above analytical technique, a MATLAB's GUI program is developed which determine the load characteristics and complete steady state analysis by computing V_t , F , P_o , etc under different operating conditions. The above performance equations and the simulation techniques can be easily extended to reactive loads and variable speeds.

IV. RESULTS

In this section it is explained that how different parameters can be calculated of SEIG using GUI methodology.

- (i) Effect of Stator Resistance on terminal voltage
- (ii) Effect of Capacitance on terminal voltage
- (iii) Motor torque – speed curve
- (iv) Effect of rotor flux with time

A MATLAB based computer program is written for complete evaluation of the performance of the SEIG under different operating conditions. MATLAB's GUI capabilities, menu and plotting commands are implemented in a script file to provide interactive windows for the users. Running the created GUI M-file, called main-menu, from MATLAB workspace will display the interactive window.

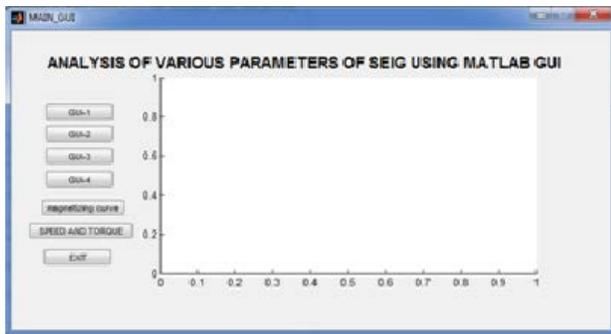
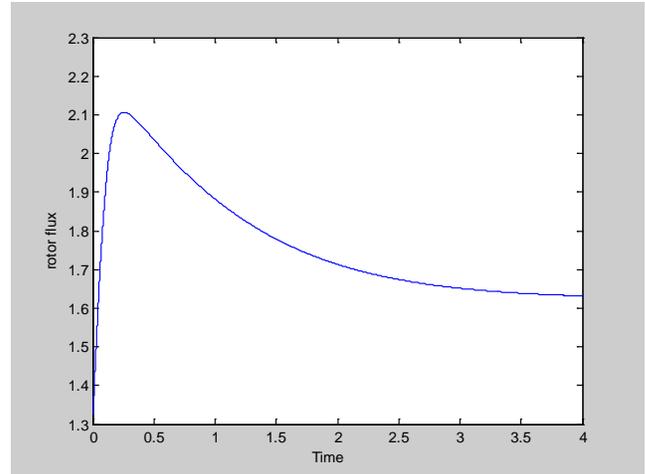


Fig. 4.1 The Main GUI Window



This GUI design software tool can facilitate the user for accurate and speedy analysis of SEIG. The mathematical models representing all the operating conditions of a SEIG have been programmed in script files (M-files) using conventional MATLAB language in GUI environment which makes it a very user friendly design tool. This will provide the interactive windows for all simulated operating conditions as shown below.

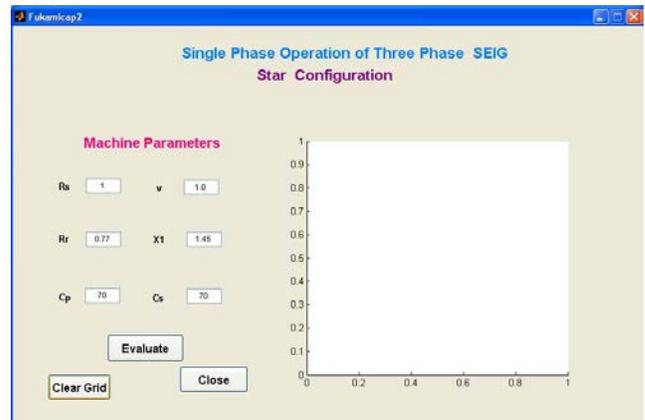


Fig. 4.3 The interactive window with clear grid and editable parameters

After running the program an interactive window as shown in Fig. 4.2 will appear with blank grid and all default parameters in edit box for predicting the performance.

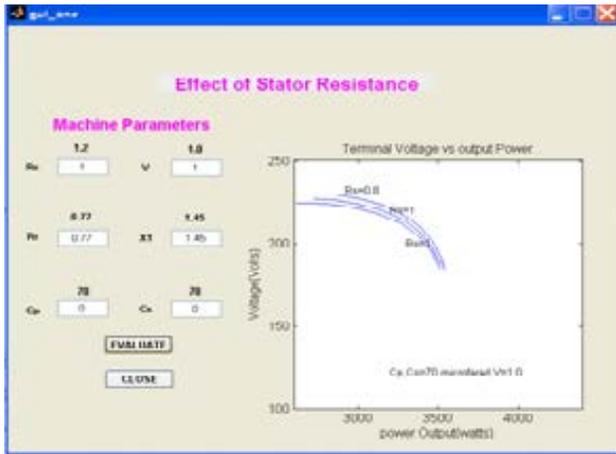


Fig. 4.4 The window of the computed result for effect of stator resistance on Terminal Voltage with fixed capacitance

In the window shown in Fig. 4.3, by changing the p.u. stator resistance in stator resistance edit box i.e 'Rs', the user can simulate the effect of stator resistance on terminal voltage as depicted in Fig 4.4. The clicking on evaluate button processes the values of parameters mentioned in respective edit boxes as described in above equations. Similarly, clicking on respective buttons in main menu the user can interact with this tool and will be able to compute the desired results by changing the parameters in edit boxes. Some simulation results are shown in Figs. 4.3, 4.4 and 4.5.

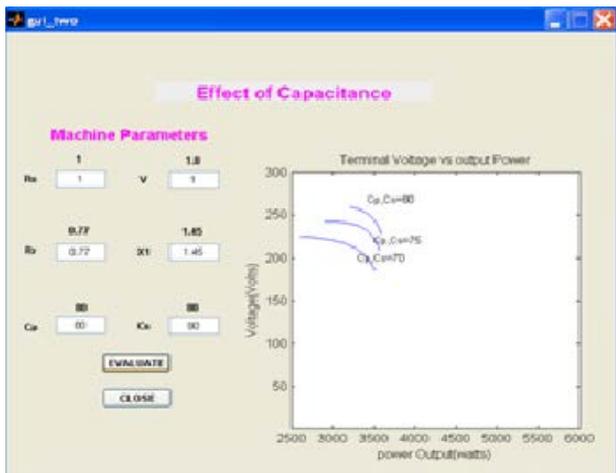


Fig. 4.5 The window of the simulated result for effect of capacitance on Terminal Voltage

The Terminal Voltage and Power output at constant speed with different values of capacitances are obtained from these experimental results which are incorporated in the GUI interactive window and compared with the simulated results as,

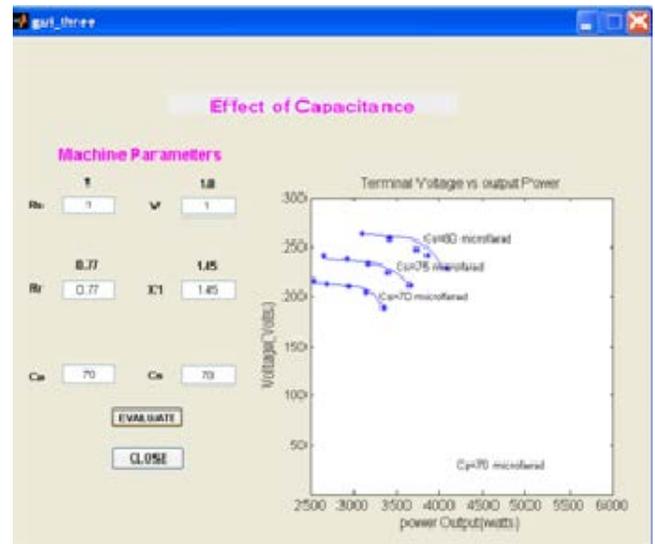


Fig. 4.6 The window of the simulated and experimental result for effect of Capacitance on Terminal Voltage

The simulated results are found very close to experimental values which demonstrate satisfactory performance of the proposed software package under different operating conditions.

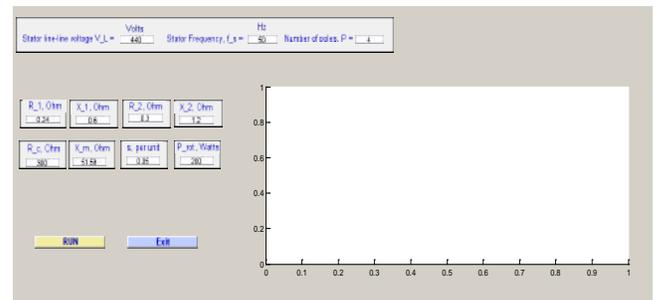
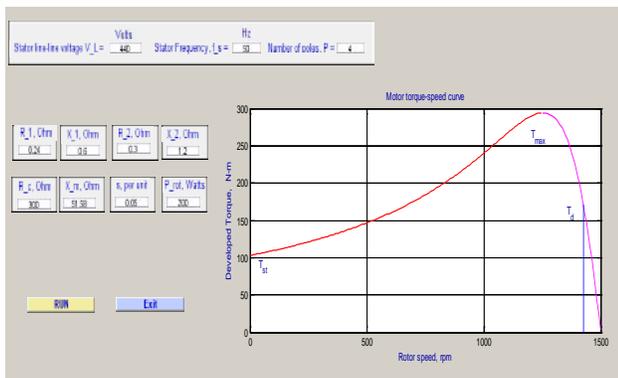


Fig. 4.7 Variable Induction Motor Parameter to Calculate the Torque Speed Curve

The parameters of the induction motor namely R, XS, P can be edited. The stator frequency can be varied as per

the stator line-line voltage in order to calculate corresponding torque, as per the number of poles.

The torque starts from 100 and builds upto the T_{max} and after reaching to maximum, the torque starts to decrease.



V. CONCLUSION

The versatile facility available through MATLAB tool boxes can be effectively used to provide such a software and user-friendly design package to interested users. The developed analytical design tool and software using MATLAB tool boxes such as “Fsolve” routine and GUI can be effectively used to predict the performance of SEIG with different types of prime movers. SEIG as the electrical generator is an ideal choice for isolated variable-wind power generation schemes, as it has several advantages over conventional synchronous machine. The variation in magnetizing inductance is the main variable that influences whether there will be steady state voltage generation or not in a SEIG. All the operating conditions of star connected machine with three capacitor excitation topology to feed single phase loads are mathematically modeled and then simulated using MATLAB instruction in GUI environment. Close agreement between simulated and experimental results demonstrates the usefulness for designing SEIG based stand alone systems using this software.

VI. REFERENCE

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