# A Generalized Dynamic and Steady State Analysis of Self Excited Induction Generator (SEIG) Based on MATLAB

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*Abstract* – **This paper presents a Matlab based generalized algorithm to predict the dynamic and steady state performance of Self Excited Induction Generators (SEIG) under any combination of speed, excitation capacitor and loading. The popularity of Self Excited Induction Generator and widespread use in stand-alone applications is centered on analysis, control and design suitable for the application. Three different methods, operational equivalent circuit, Newton–Raphson and equivalent impedance method are used for analyzing under any given situation. The excitation capacitors and load combined with the d-q model of the machine, together with the saturation is used to predict the dynamic behavior of the SEIG. The algorithms are implemented as MATLAB user friendly Tool boxes resulting in considerable simplification over earlier methods.**

*Keywords: Induction Generator, Stand alone applications, MATLAB toolbox, capacitor self excitation, Dynamic model.*

## 1. Introduction

In renewable energy applications of low and medium power, the induction motor operated as a generator offers considerable advantages due to its ruggedness, low cost, brush-less squirrel cage rotor, manufacturing simplicity, low maintenance and wide off-the-shelf range. While operation of the induction motor in the generating mode while connected to the grid is straightforward to analyze using the standard equivalent circuit due to the rigid frequency and voltage of the grid, its analysis and operation as a stand-alone power source is complicated since both the voltage and frequency are now variables and involves solving non linear equations of higher order. Under these conditions proper selection of equipment and the prediction of the system performance are essential for successful implementation of the scheme.

To study the design aspects, we require methods by which the generator performance is predicted by using the induction motor design data so that the effect of these basic parameters can be assessed. Having identified these it is essential to estimate correctly the magnetizing characteristics and related air-gap voltage under different flux conditions. Currently three methods are available to identify the steady state quiescent operating point under saturation for a given set of speed, load and excitation capacitor. These methods determine the saturated magnetizing reactance and per unit frequency. The operating air-gap flux can be then obtained by simulating zero rotor current conditions or a synchronous speed test. The predicted characteristics are validated by test results.

Maintaining terminal voltage is of prime importance in SEIGs driven by near constant speed prime movers such as oil engines and small hydro turbines, and this requires adjustable capacitive VAR sources. In varying speed applications like windmills the demand are higher since under all conditions the capacitance must be sufficient to prevent voltage collapse.

The task of simulating steady state behavior of SEIG requiring the solution of higher order non-linear equations is considerably simplified by using the inherent capabilities of MATLAB. The Simulink package is used to model the induction motor described by four electrical and one mechanical non linear simultaneous differential equations. However a model thus defined does not permit external connections of the load or excitation capacitances. Thus the case of induction generator requires a totally new treatment, where the differential equations describing the load and the excitation capacitors have to be part of the machine model. The only input to the model, then, is the shaft speed and torque. Furthermore the model should account for residual magnetization to correctly simulate voltage build up, and saturation which limit the generated voltage to a finite value.

Different loading conditions, both balanced and unbalanced cases, as well as various excitation capacitor topologies require the describing equations to be reformulated. This paper differs from the rest by modeling saturation using the instantaneous inductance-instantaneous current curve instead of rms values of voltage Vs magnetizing current. Parameter variation due to saturation is then accounted for at every step. This ensures that the dynamic performance prediction will be highly accurate. Steady state is then a particular case of this model. The models thus developed can be used for implementing various control schemes and assess the combined performance

The present work takes advantage of the MATLAB software package to make the numerical computations easier, by combining all the available methods into a user-friendly toolbox for MATLAB as it results in considerable ease of analysis. Results are presented for various combinations of inputs, thus enabling the designer to decide on the best setup.

## II. Implementation Method

The flow chart of Fig. 1 illustrates the implementation of the scheme. The user provides the machine system data, and enters desired outputs and the preferred solution methods. The program checks the consistency of the data with the desired procedures and outputs expected and interacts with the user for obtaining or correcting missing data. The algorithm implemented in MATLAB considerably simplifies the solution of higher order non-linear differential equations. The analytical techniques used in the program for evaluating the steady state and dynamic performance are described.

## III. Analytical Techniques.

A Self-excited induction generator system shown in Fig. 2 consists of an induction machine driven by a prime mover. A three-phase capacitor bank provides for self-excitation and load VAR requirements. As the load varies randomly the capacitor has to be varied to obtain desired voltage regulation.

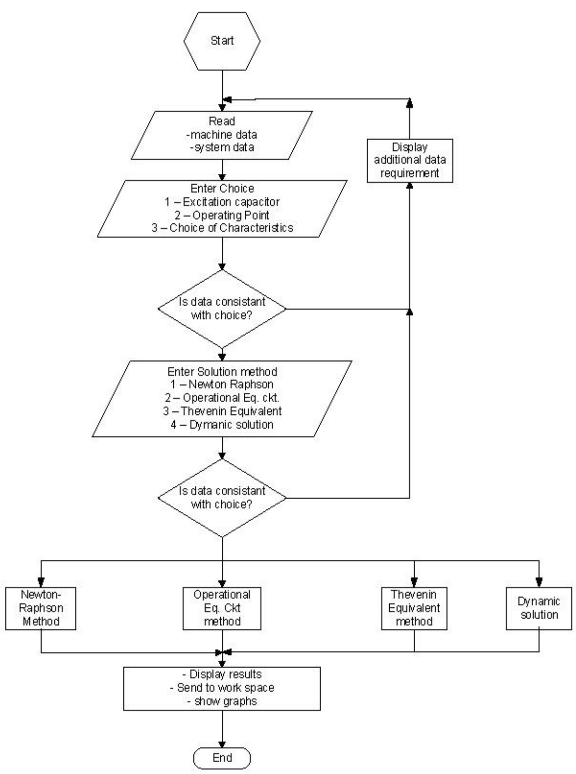


Fig. 1. Flow chart illustrating the implementation.

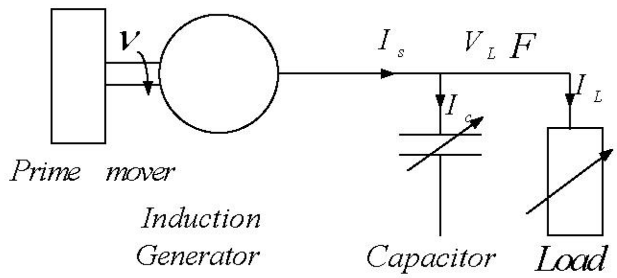


Fig. 2. Self Excited Induction Generator System.

### A. *Newton-Raphson Method* [1]

The steady state per phase equivalent circuit of such an arrangement is shown in Fig. 3 where

$R_s$, $R_r$ = per phase stator and rotor (referred to stator) resistance

$x_{ls}$,$x_{lr}$ = per phase stator and rotor(referred to stator) leakage reactance

$X_m$ = magnetizing reactance

$X_c$ = per phase capacitive reactance of the terminal capacitor C

$R_L$= load resistance per phase

(all reactances referred to above relate to base frequency f)

F,ν = p.u. frequency and speed, respectively

$I_s$, $I_r$, $I_L$ = stator, rotor *referred to stator) and load current per phase

$V_t$, $V_g$ = terminal and air gap voltage respectively.

Referring to Fig. 3 the loop equation for $I_s$ can be written as

$$I_s.Z = 0 \tag{1}$$

Since under steady state conditions Is cannot be zero,

$$Z=0 \tag{2}$$

Separating the real and imaginary parts this can be written as

$$f(x_m,F) = (C_1x_m + C_2)F^3 + (C_3x_m + C_4)F^2 + (C_5x_m + C_6)F + (C_7x_m + C_8) =0 \tag{3}$$

$$g(x_m,F) = (D_1x_m + D_2)F^2 + (D_3x_m + D_4)F + D_5 = 0 \tag{4}$$

where the constants $C_1$-$C_8$ and $D_1$-$D_5$ are functions of machine parameters.

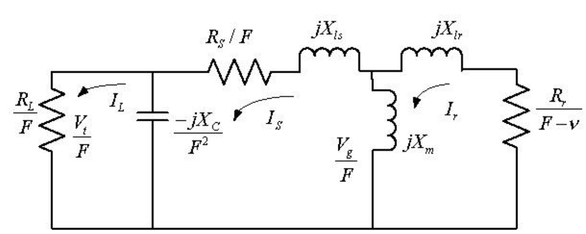


Fig. 3. Equivalent circuit of the induction generator with load.

Equations (3) and (4) are solved using Newton-Rapson method after forming the Jacobian matrix and using initial values for $x_m$ and F as $x_m$-unsaturated and ν respectively.

*B. Operational equivalent circuit method.*[2]

The positive sequence operational equivalent circuit of the system shown in Fig. 1 can be written as shown in Fig. 4, where p is the derivative operator (1.ω)(d/dt), ω being the base radian frequency and t the time.

The operational impedance for the loop current $i_s^+$ under self excitation is zero. This condition leads to the characteristic polynomial

$$K_1p^4 + K_2p^3 + K_3p^2 + K_2p + K_5 = 0 \qquad (5)$$

Where the constants $K_1$-$K_5$ are functions of machine parameters, capacitance, speed and load impedance.

Self excitation will occur if and only if at least one of the roots of the (5) has a positive real part. As the voltage builds up flux reaches saturation levels causing $x_m$ to drop. This in turn reduces the magnitude of the real part of the root damping the rate of rise of voltage. This process continues till $x_m$ reaches such a value that the real part becomes zero and consequently a entering into steady state. The imaginary part of the root under such conditions gives the p.u. frequency F.

*C. Equivalent impedance method.*[3]

The equivalent circuit shown in Fig. 2 can be redrawn as shown in Fig. 5a and further simplified the Thevenin equivalent as in Fig. 5b

The Thevenin equivalent impedance $Z_{eq}$ at the terminals Aand B of $x_m$ of Fig. 5b can be split into real and imaginary parts $R_{eq}$ abd $X_{eq}$ respectively, such that under steady state conditions

$$R_{eq} + jx_{eq} + jx_m = 0 \qquad (6)$$

i.e, $$R_{eq} = 0 \qquad (7a)$$

and $$x_{eq} = -x_m \qquad (7b)$$

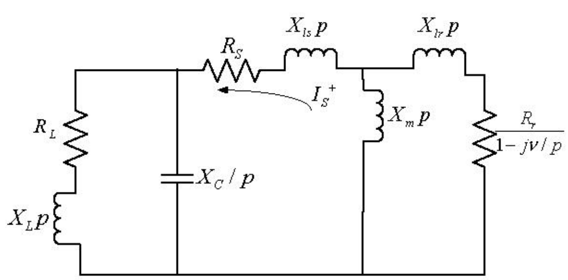


Fig. 4. Operational equivalent circuit.

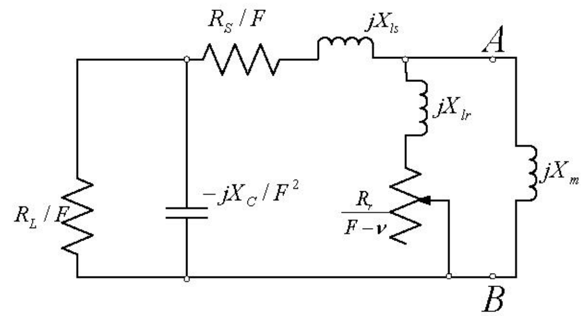


Fig. 5a. Modified equivalent circuit

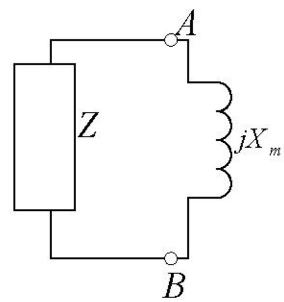


Fig. 5b. Thevenin equivalent.

these equations assume the form

$$R_{eq} = A_1F^7 + A_2F^6 + A_3F^5 + A_4F^4 + A_5F^3 + A_6F^2 + A_7F + A_8 = 0 \qquad (8)$$

$$X_m = -x_{eq} = B_1F^8 + B_2F^7 + B_3F^6 + B_4F^5 + B_5F^4 + B_6F^3 + B_7F^2 + B_8F + B_9 \qquad (9)$$

Where the constants are functions of the machine parameters, load and excitation capacitors.

*D. Performance equations*

Having thus determined $x_m$ and F, the next step is to calculate the airgap voltage and terminal voltage this required the Vg/F verses $x_m$ characteristics shown in Fig. 5, and is obtained by conducting a synchronous speed test. The curve can be approximated in three a,b and c sections as

$$Vg/F = -3.09x_m + 370 \quad \text{(section A)} \qquad (10)$$
$$= -7.33\,x_m + 542 \quad \text{(section B)}$$
$$= -32.32\,x_m + 1765 \quad \text{(section C)}$$

as shown in Fig. 6

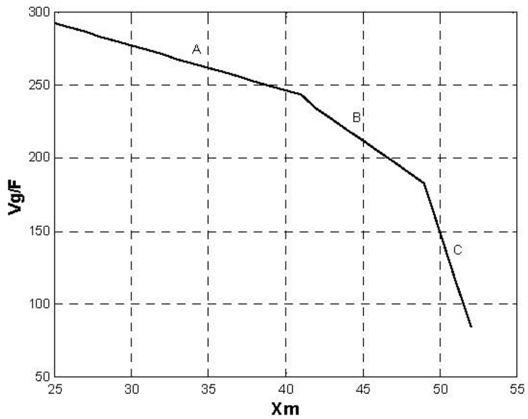


Fig. 6. Magnetization Characteristics.

The performance of the machine can then be calculated as Stator current

$$Is = \frac{V_g / F}{\frac{R_s}{F} + jx_{ls} - \frac{jx_c R_L}{F^2 R_L - jFx_c}} \tag{11}$$

Rotor current

$$I_r = \frac{-V_g/F}{\frac{R_r}{F-\nu} + jx_{lr}} \tag{12}$$

Load Current

$$I_L = \frac{-jx_c I_s}{R_L F - jx_c} \tag{13}$$

Terminal Voltage

$$V_t = I_L R_L \tag{14}$$

Input Power

$$P_{in} = \frac{-3|I_r^2| R_r \nu}{F - \nu} \tag{15}$$

Output Power

$$P_{out} = 3|I_L^2| R_L \tag{16}$$

Based on the analytical methods described above a general computer program has been developed which calculates the steady state performance of the induction machine operating as a self excited induction generator and displays the curves for various conditions.

*E. Dynamic Modeling*

Connection of excitation capacitors across the terminal can be represented in the d-q model of the machine as two additional equations with the capacitor voltages as state variables. The complete arrangement is shown in Fig. 7.

Referring to Fig. 7 it is seen that

$$i_q^s = i_{cq} + i_{rq} \tag{17a}$$

$$i_d^s = i_{cd} + i_{rd} \tag{17b}$$

i.e

$$i_q^s = Cpv_q^s + \frac{v_q^s}{R_l} \tag{18a}$$

$$i_d^s = Cpv_d^s + \frac{v_d^s}{R_l} \tag{18b}$$

combining the above two equations in the standard d-q model[4] of the induction machine we get the dynamic model of a self excited induction generator as

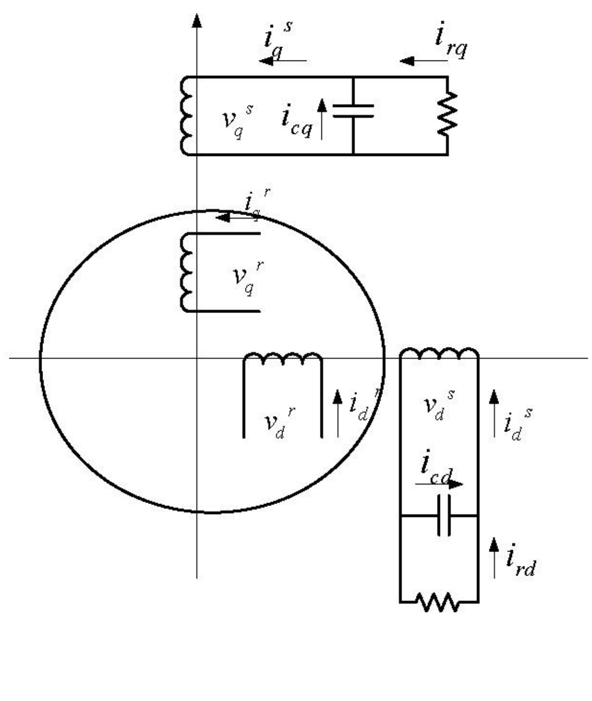


Fig. 7. d-q model of the induction machine with excitation capacitor and load.

$$\begin{bmatrix} v_d^{\ s} \\ v_q^{\ s} \\ v_d^{\ r} \\ v_q^{\ r} \\ i_q^{\ s} \\ i_d^{\ s} \end{bmatrix} = \begin{bmatrix} & & & & 0 & 0 \\ (R^s + L^s p) & 0 & M^{sr} p & 0 & 0 & 0 \\ 0 & (R^s + L^s P) & 0 & M^{sr} p & 0 & 0 \\ M^{sr} p & k\omega^r M^{sr} & (R^r + L^r p) & k\omega^r L^r & 0 & 0 \\ -k\omega^r M^{sr} & M^{sr} p & -k\omega^r L^r & (R^r + L^r p) & Cp + \frac{1}{R_l} & 0 \\ 0 & 0 & 0 & 0 & & \\ 0 & 0 & 0 & 0 & 0 & Cp + \frac{1}{R_l} \end{bmatrix} \begin{bmatrix} i_d^{\ s} \\ i_q^{\ s} \\ i_d^{\ r} \\ i_q^{\ r} \\ v_q^{\ s} \\ v_d^{\ s} \end{bmatrix} \quad \ldots\ldots.(19)$$

where.

$d^s$, $q^s - d^r$, $q^r$ stator and rotor direct and quadrature axes, respectively

$k$ number of pairs of poles

$L^s$,$L^r$ self inductance of stator and rotor coils, respectively

$M^{sr}$ mutual inductance between any pair of stator and rotor coils with their magnetic axes collinear

$p$ d/dt

$R_l$ load resistance in Ohms

$R^s$, $R^r$ resistance of the stator and rotor coils, respectively

$v_d^{\ s}$ $i_d^{\ s}$ stator voltage and current, respectively, associated with the d axis

$v_d^{\ r}$ $i_d^{\ r}$ rotor voltage and current, respectively, associated with the d axis

$v_q^{\ s}$ $i_q^{\ s}$ stator voltage and current, respectively, associated with the q axis.

$v_q^{\ r}$ $i_q^{\ r}$ rotor voltage and current, respectively, associated with the q axis

The simulated output for such a machine is shown in Fig. 8. It is seen that the output voltage increases exponentially without limit. This is due to saturation not being accounted for.

*F. Modeling of saturation*

Magnetic saturation of the machine is determined from synchronous speed test. The values of mutual inductance are adjusted at every instant depending on the load currents. The

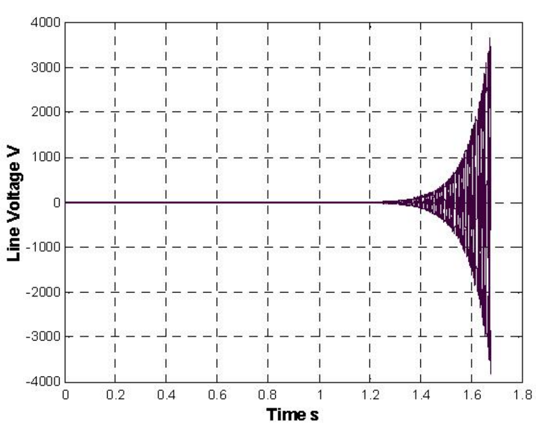


Fig. 8. Voltage build up of SEIG without saturation.

Terminal voltage of the machine after accounting for saturation is shown in Fig. 9.

## IV. Methodology using Matlab

The task of simulating steady state behavior of Self Excited Induction Generator requiring the solution of higher order non linear differential equations is considerably simplified by using the inherent capabilities of MATLAB. The work presented is part of the project to develop dedicated toolbox for simulation of steady state behavior of SEIG. Different solution methods as shown in the flow chart are implemented.

## V. Experimental details

Relevant experiments were carried out on a three phase 415/240V 14.6/26.2A, 7.5kW, Y/Δ connected squirrel cage induction motor, driven by a thyristor fed DC motor of check the validity of the results obtained from simulation. To validate the mathematical modeling the performance of the induction machine as an SEIG is simulated at rated speed using the tool box developed and compared with corresponding experimental results.

Fig. 10 and Fig. 11 show variation in terminal voltage, and capacitance for near constant terminal voltage with output power for resistive load. There is good agreement between simulated and experimental results. Voltage and frequency remain nearly constant by varying the capacitor at constant speed. The capacitor requirement increases from 75.5μF at no load to 280 μF at 7.0 kW load

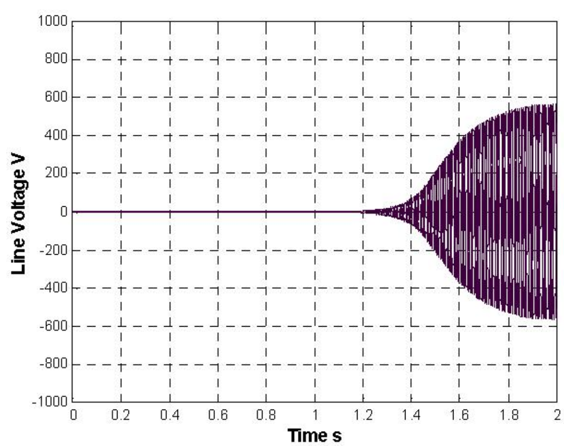


Fig. 9. Limitation of terminal voltage build up due to saturation of core.

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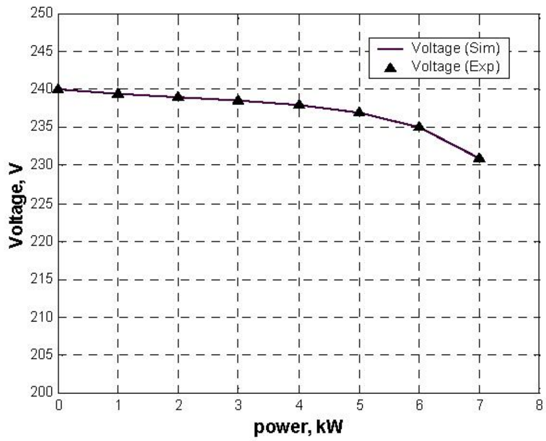


Fig. 10. Performance under balance load- voltage verses power

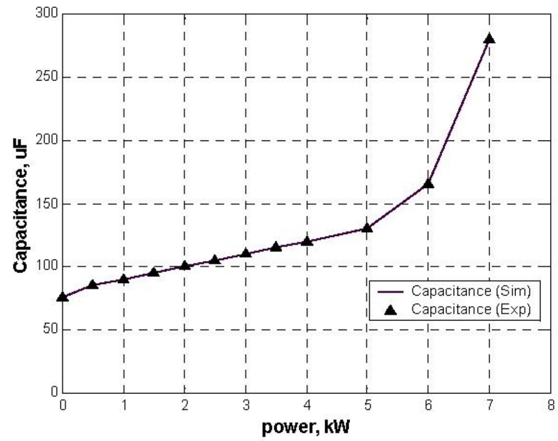


Fig. 11. Performance under balance load – capacitance (for constant voltage) verses Power.

## VI. Conclusion

A new comprehensive general analytic procedure implemented as MATLAB toolbox is presented. This facilitates prediction of performance of a chosen machine under given speed, capacitor and load condition, which helps in estimating system parameters and controller design.

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