Study the influence of excitation capacitance chooses and examines the use of external rotor capacitance techniques on the performance induction generator

دراسة تأثير اختيار متسعة الإثارةِ واختبارُ استعمال تقنيات متسعة الدوّارِ الخارجيةِ لتَحديد كيفه تأثيرها على أداء المولدات الحثية

حيدر حسين كاظم
جامعة بابل / كلية الهندسة / قسم الهندسة الكهربائية/قدرة ومكائن
E-Mail: hayderhussein2000@yahoo.com

Abstract

The generated voltage of the self – excited induction generator (SEIG) depending on the wind velocity fluctuations , load variations and is mainly depend on choosing the proper value of excitation capacitor .This value is very crucial for the self-excitation and voltage build-up as well as voltage regulation in an SCIG. This paper presents simple and accurate approach to compute the minimum value of capacitance required for initiating the voltage build-up and maximum value which the machine fails to self excitation in a three-phase slip ring induction generator and also attention is focused on the influence of external rotor capacitance along with the excitation capacitance which were used to achieve the reactive power requirements and observing their effect in building up the voltage. In this paper is the new method proposed based on the dq Model techniques is developed to find the capacitance requirement under R-L load and resistive load.

الخلاصة

الفولتية المتولدة في مولد الحث الذاتي تعتمد على سرعة الريح واختلاف الحمل وتعتمد بشكل رئيسي على اختيار القيمة الدقيقة لمتسعة الإثارة لان القيمة تكون حاسمة للإثارة ونمو الفولتية. يقدم هذا البحث دراسة بسيطة ودقيقة لحساب اقل قيمة متسعة يحتاجه المولد للإثارة وأعلى قيمة يخفق المولد عندها في نمو الفولتية وكذلك يركز البحث على تأثير متسعة الدوارِ الخارجية برفقة متسعة الإثارة لتحقيق المتطلبات الكهربائية التفاعلية المطلوبة وتحسين في نمو الفولتية.في هذا البحث الطريقةُ المقترحةُ مستندة على التقنيات النموذجية لإيجاد قيمة المتسعة في حالة الحمل مقاومة فقط والحمل محاثة ومقاومة

1- INTRODUCTION

The inherited poor characteristic of the generated voltage and frequency under varying loading conditions has limited the use of the self excited induction generator as a grid quality power feeder. The basic theory and working principles of self excitation in induction machines has been known for a long time[1] A wind power generation system generates electricity from wind energy and typically comprises an induction generator coupled to a wind turbine. In a wind power generation system, the mechanical energy of the wind turbine is converted into electrical energy by the induction generator. (SCIG) is highly suitable to be driven by wind turbine because of its small size and weight, robust construction and reduced maintenance cost [2-5]. In order to initiate voltage generation by the induction generator (self-excitation), a leading reactive power is provided to the stator windings of the generator by connecting a capacitor bank to the stator windings. The induced e.m.f. and current in the stator winding starts rising and attains its steady-state value with frequency dependent on rotor speed and machine parameters. The generated voltage is sustained at this operating point till reactive power balance is maintained [3]. The voltage so generated is unstable in the sense that its value changes drastically under various loading conditions. This, in turn, changes the generated torque and the rotor speed varies causing further changes in the generated voltage. This leads either to a collapse of the terminal voltage or building up to an excessively high value depending upon the values of the magnetizing inductance and the terminal (excitation) capacitance [2,4,5].. Hence, it is necessary to determine the range of capacitance value to keep the machine in excitation mode and regulate the generator terminal voltage within the limits. Tuning of capacitance is required with the variation of rotor speed and loading conditions. This is an impractical task due to the interdependence of the system variables, changing rotor speed and the system's non-linearity. It is essential that the capacitance value of the capacitor bank is such that at a given rotor speed, the generated voltage in the stator windings does not undergo large transients [4,6]. If the voltage generated in the stator windings is not sustained and smooth, there will be vibrations in the wind turbine leading to wear and tear of the wind turbine thereby reducing its life. In order to convert the wind energy into electrical energy efficiently, it is important that the induction generator operates smoothly i.e. voltage generated in the stator windings is sustained and is without transients. Therefore, calculation of the capacitance value of the capacitor bank is very critical for the desired operation of the induction generator. It is known that the induction generator operates in the saturated region during the self-excitation phase. It is also known that the maximum value of magnetizing inductance (Lmax) in the saturated region leads to sustained voltage generation in the stator windings. Therefore, in order to accurately calculate the capacitance value it is essential to know the maximum value of the magnetizing inductance in the saturated region. But this value is not known and unavailable. However, it is known that the magnetizing inductance value in the saturated region lies between zero and the Lmax value in the unsaturated region. For accurate calculation of the capacitance value it is necessary to take into consideration the magnetizing inductance value for the saturated region both in the steady state and dynamic state operating conditions of the induction generator[5-7].

Two models are reported in literature [2,3,6,8] for the analysis of self-excited induction machine. One is based on the per-phase equivalent approach and the other, the d-q axis model, is based on the generalized machine theory. Most of the work is based on per-phase equivalent circuit approach, which includes loop-impedance method [9] and the nodal admittance method [3,7,10]. In the per-phase equivalent circuit approach, highly non-linear simultaneous equations in per unit frequency or magnetizing reactance are solved using iterative methods to obtain minimum and maximum values of the excitation capacitance. Apart from being time consuming, this method uses the steady-state model and unsaturated magnetizing inductance value in the calculations. Hence, the minimum value of capacitance so obtained is an over estimation. This capacitance value is able to initiate self-excitation, but yields satisfactory results only under steady-state conditions. Higher value of capacitance is not technically viable as there may be a possibility that the current flowing in the capacitor might exceed the rated current of the stator, due to the fact that capacitive reactance reduces as the capacitance value increases [9,11]. This will cause higher transient currents during voltage build-up and hence more fluctuation in the mechanical load on the prime mover which may excite oscillatory mode of the prime mover. The d-q model based approach yields better results as it also captures transient phenomenon of the machine. But this is also an iterative approach and makes use of unsaturated value of magnetizing inductance. Therefore, this method also yields an over estimation of capacitance value. In view of the ongoing discussion, it is clear that there is a need to calculate the minimum value of capacitance taking the magnetizing inductance value in the range of saturated region which ensures self-excitation for a given induction generator.

The previous papers [3,10,12] 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. Wind speed can change from the minimum set point to the maximum set point randomly and the SEIG can be started at any point within the range of speed. It is essential to find the minimum and maximum speed required for self-excitation, when the generator is loaded. The previous papers [13-15] relay on numerical techniques and iterative procedures, which are used to solve the governing non-linear equations. Converging to the proper solution in numerical techniques depend on the values of the initial guesses. It uses an approximate model of induction generator and achieves the results comparable with the results of other techniques. A simple and direct method is recommended for estimation of the minimum capacitance It will provide good quality power with less harmonic distortion on load side with easy control of voltage and frequency. The unique feature can be added with this concept is that it has a variable additional rotor capacitance, which can be changed by an optically controlled converter, mounted on the rotor shaft[16-18]. The optical coupling provided at rotor terminals eliminates the need for costly slip rings that need brushes and maintenance. The rotor resistance can be changed and thus controls the slip. This way, the power output in the system is controlled [19,20].

In previous literature there is no discussion about the minimum and maximum capacitance at the same time influence of the external rotor capacitance self –excited induction generator and an improvement in the voltage build up. In this paper the new method proposed to compute the capacitance requirements of a self-excited induction generator. The proposed method differs from previously published methods in the following aspects

(a) The advantage of the d-q model techniques is that it is powerful for analyzing the transient and steady state conditions, giving the complete solution of any dynamics.

(b).The load and excitation capacitance branches in the equivalent circuit are decoupled to facilitate the solution of the self-excited frequency.

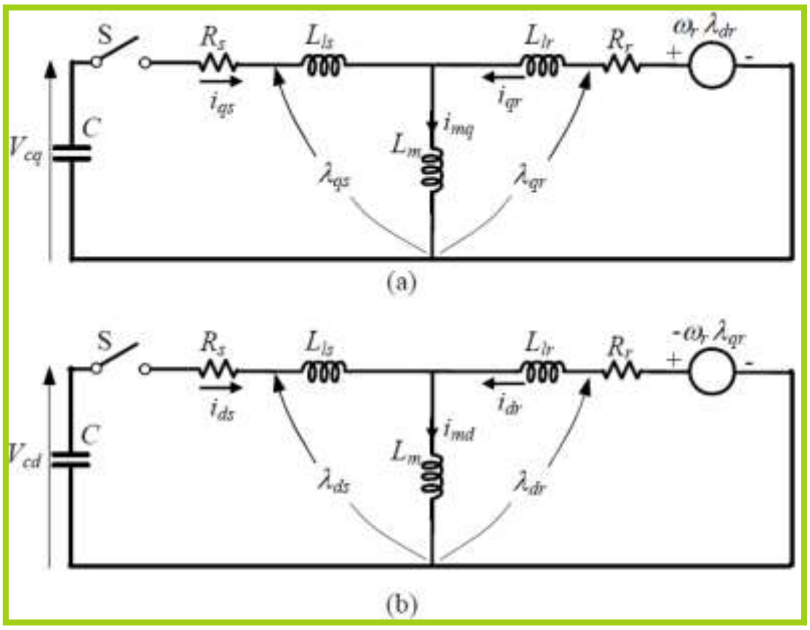
(c).No trial-and-error procedure is involved; hence it may be regarded as a direct method.

(d.) Reduced computational effort as only a 4thdegree polynomial need to be solved to yield the value of capacitance. The main objectives of this study to investigate the influence of different capacitors and examines the use of external t rotor capacitance techniques to determine how it influences on the performance induction generator

2- Model of self – excited induction generator

2-1-Modeling at no-load

The d-q representation given in Fig. 1 can be redrawn in detail, in a stationary stator reference frame, with separate direct and quadrature circuits as shown in Fig. 1.



Fig(1) Detailed d-q model of SEIG in stationary reference frame at no-load (a) q-axis circuit (b) d-axis circuit

The no-load SEIG state space model could be expressed as state space equations. M is the mutual inductance between stator and rotor changing with the varying currents through the windings and relative position between stator and rotor. The derivation of the state space equation are given by:

$$\begin{bmatrix} V_{ds} \\ V_{qs} \\ V_{dr} \\ V_{qr} \end{bmatrix} = \begin{bmatrix} R_s + L_s p + \dfrac{1}{PC} & 0 & Mp & 0 \\ 0 & R_s + L_s p + \dfrac{1}{PC} & 0 & Mp \\ Mp & \omega_r M & R_r + L_r p + \dfrac{1}{PC_R} & \omega_r L_r \\ -M\omega_r & Mp & -L_r \omega_r & R_r + pL_r + \dfrac{1}{PC_R} \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix} \quad \text{------(1)}$$

where R_s - stator winding resistance, Ω

R_r - rotor winding resistance, Ω

L_m - magnetising inductance, H

L_s - stator leakage inductance (L_{ls}) + magnetising inductance (L_m), H

L_r - rotor leakage inductance (L_{lr}) + magnetising inductance (L_m), H

ω_r - electrical rotor angular speed in rad/sec and $p=d/dt$, the differential operator.

2-2- Modeling with load

The stationary reference frame representation of a loaded self-excited induction generator is shown in Fig. 2 and the equations used to analyze the loaded SEIG are modified from the equations representing the unloaded SEIG.

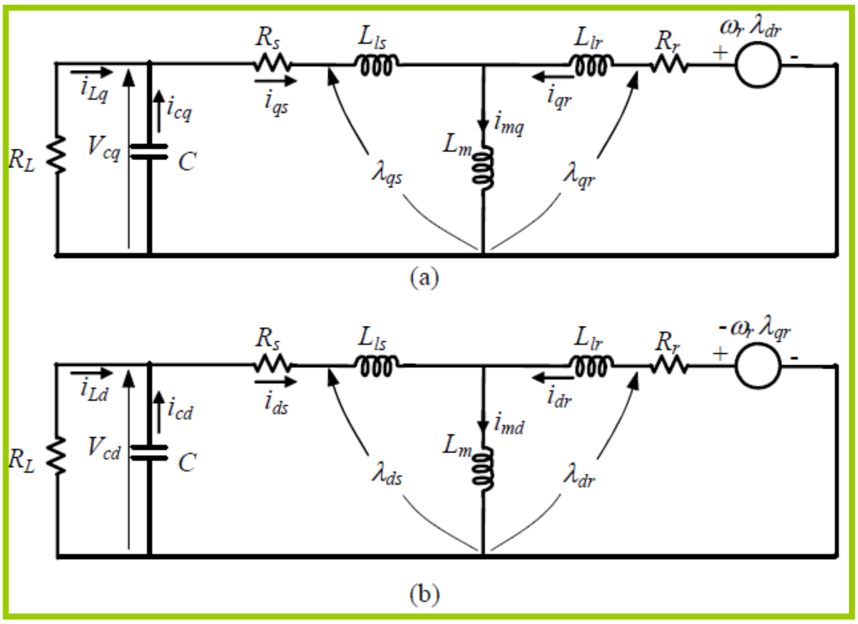


Fig. 2 d-q model of a loaded SEIG in a stationary reference frame (a) q-axis circuit (b) d-axis circuit

The load SEIG state space model could be expressed as state space equations (2)

$$\begin{bmatrix} V_{ds} \\ V_{qs} \\ V_{dr} \\ V_{qr} \end{bmatrix} = \begin{bmatrix} R_s + L_s p + \frac{Z}{(ZCp+1)} & 0 & Mp & 0 \\ 0 & R_s + L_s p + \frac{Z}{(ZCp+1)} & 0 & Mp \\ Mp & \omega_r M & R_r + L_r p + \frac{1}{PC_R} & \omega_r L_r \\ -M\omega_r & Mp & -L_r \omega_r & R_r + pL_r + \frac{1}{PC_R} \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix} \quad \text{.. ....(2)}$$

where Z can be one of the following cases:
(a) Z = R + pL (inductive load)
(b) Z = R (pure resistive load)
(d) Z = R + l 1+ pC (capacitive load)

3. Proposed method to find general solution for capacitance
(3-1) Excitation stator capacitor

The derivation of the state space equation (1) where the subscripts .s. and .r. are used to represent stator and rotor quantities and .d. and .q. represent direct and quadrature axis quantities espectively. For a stationary reference frame ($\omega = 0$) and before excitation all terminal voltages are considered to be zero. Using matrix partition equation (1) can be rewritten as

$$V(s) = A(s)I(s) \quad \text{................(3)}$$

$$V(s) = \begin{bmatrix} V_{qs}(s) \\ V_{ds}(s) \\ V_{qr}(s) \\ V_{dr}(s) \end{bmatrix}, \qquad I(s) = \begin{bmatrix} I_{qs}(s) \\ I_{ds}(s) \\ I_{qr}(s) \\ I_{dr}(s) \end{bmatrix} \quad \text{..................(4)}$$

$$\begin{bmatrix} Z_{ss} & Z_{sr} \\ Z_{rs} & Z_{rr} \end{bmatrix} \begin{bmatrix} I_s \\ I_r \end{bmatrix} = \begin{bmatrix} V_{os} \\ V_{or} \end{bmatrix} \quad \text{............(5)}$$

$$I_s = \begin{bmatrix} i_{qs} \\ i_{ds} \end{bmatrix}, \text{ and } \qquad I_r = \begin{bmatrix} i_{qr} \\ i_{dr} \end{bmatrix}, \quad \text{..........(6)}$$

$$Zss=\begin{bmatrix} R_S+PL_S+\dfrac{1}{PC_S} & 0 \\ 0 & R_S+PL_S+\dfrac{1}{PC_S} \end{bmatrix} \quad \text{..................(7)}$$

$$Zsr=\begin{bmatrix} PL_M & 0 \\ 0 & PL_M \end{bmatrix} \qquad Zrs=\begin{bmatrix} PL_M & -w_rL_M \\ w_rL_M & PL_M \end{bmatrix} \quad \text{......(8)}$$

$$Zrr=\begin{bmatrix} R_r+PL_r+\dfrac{1}{PC_R} & 0 \\ 0 & R_r+PL_r+\dfrac{1}{PC_R} \end{bmatrix} \quad \text{..........(9)}$$

$$A(s)=\begin{bmatrix} R_s+L_sp+\dfrac{1}{PC} & 0 & Mp & 0 \\ 0 & R_s+L_sp+\dfrac{1}{PC} & 0 & Mp \\ Mp & \omega_rM & R_r+L_rp+\dfrac{1}{PC_R} & \omega_rL_r \\ -M\omega_r & Mp & -L_r\omega_r & R_r+pL_r+\dfrac{1}{PC_R} \end{bmatrix} \quad \text{..............(10)}$$

$$\det A(F)=C^2X_1{}^2F^6+2C^2X_1X_2F^5+(C^2(X_2{}^2+X_1(2R_sR_r+\omega_r{}^2X_1))+2CL_2X_1)F^4+2(R_s(R_rX_2+L_2\omega_r{}^2X_1)C^2$$
$$+(L_2X_2+R_rX_1)C)F^3+(C^2R^2{}_sX_3+(2C(R_sR_rL_2+R_rX_2+\omega^2{}_rL_2X_1)+L^2{}_2))F^2+2(R_sCX_3+R_rL_2)F+X_3$$

....(11)

The 6th order polynomial obtained is as follows: where,

***L*₁ □□*L*ₛ □□*L*ₘ;**   ***L*₂ □□*L*ᵣ □□*L*ₘ;**   ***X*₁ □□*L*₁*L*₂ □□*L*ₘ;**
***X*₂ □□*R*ₛ *L*₂ □□*R*ᵣ *L*₁;**   ***X*₃ □□*R*ᵣ □□ᵣ *L*₂**

Equation (2), after a series of algebraic manipulation can be expressed as a **6th** degree polynomial in **f** as

$$A_6f^6+A_5f^5+A_4f^4+A_3f^3+A_2f^2+A_1f+A_0=0 \qquad \text{..................(12)}$$

A_6 ----- A_0 are constants whose numerical values are obtained by using MATLAB Software ackage where

$$A_6 = C^2 X_1{}^2 F^6$$
$$A_5 = 2C^2 X_1 X_2 F^5$$
$$A_4 (C^2 (X_2{}^2 + X_1 (2R_s R_r + \omega_r{}^2 X_1)) + 2CL_2 X_1) F^4$$
$$A_3 = 2(R_s (R_r X_2 + L_2 \omega_r{}^2 X_1) C^2 + (L_2 X_2 + R_r X_1) C) F^3$$
$$A_2 = (C^2 R^2{}_s X_3 + (2C(R_s R_r L_2 + R_r X_2 + \omega^2{}_r L_2 X_1) + L^2{}_2)) F^2$$
$$A_1 = (R_s C X_3 + R_r L_2) F$$
$$A_0 = X_3$$

where,

$$L_1 = L_s + L_m;$$
$$L_2 = L_r + L_m;$$
$$X_1 = L_1 L_2 - L_m;$$
$$X_2 = R_s L_2 + R_r L_1;$$
$$X_3 = R_r + \omega_r L_2$$

During the steps in the analysis of the above differential equation, the final 6th order differential equation can be divided, or reduced, by the term

$$L_r^2 p^2 + 2R_r L_r p + \omega_r^2 L_r^2 + R_r^2 = 0$$

Equation (12), after a series of algebraic manipulation can be expressed as a 4th degree polynomial in **f** as

$$a_4 f^4 + a_3 f^3 + a_2 f^2 + a_1 f + a_0 = 0 \qquad \text{.....................(13)}$$

The derivation of these constants (coefficients) a_4 to a_0 is given as.

a4=cg-aj ; a3=dg+hc+-al-bj; a2=eg+hd+ic-ma-bl; a1=he+id-pa-bm a0=ie-bp;

the mathematics for finding the roots in the 4th order case is simpler than for the 6th order case. and this results in an expression with a 4th order differential equation. Whether it is an 4th order or a 6th order differential equation the points of self-excitation remains the same, because the two roots that can be obtained by factorizing

$$L_r^2 p^2 + 2R_r L_r p + \omega_r^2 L_r^2 + R_r^2 = 0$$

are

$$p + (R_r - j\omega_r L_r)/L_r = 0 \text{ and}$$
$$p + (R_r + j\omega_r L_r)/L_r = 0$$

Equation (12) is a 4th order characteristic equation and it has four distinct roots which are first order complex roots in the form of

$$(p - \sigma_1 + j\omega_1)(p - \sigma_1 - j\omega_1)(p - \sigma_2 + j\omega_2)(p - \sigma_2 - j\omega_2)$$

If any of the roots has a positive real part, then at that given specific operating point there will be self-excitation. The current and voltage will grow until the magnetizing inductance saturates and makes the real part of the roots zero, which shows that there is a continuous oscillation (Alternating Current and Voltage) as long as the prime mover is driving the induction generator. The excitation capacitance required of the SEIG can be calculated from the equations

$$C_s = \frac{af + b}{cf^3 + df + e} \quad \text{.............(14)}$$

The constants are given as

$a=2\pi k(L_M r_1+L_1 r_1+L_2 r_1+L_M r_2+L r_2+r_L L_M+r_L L_2);$

$b=-2\ \pi N^* r_L(L_M+L_2)$

$c=-8\pi^3 k(LL_M r_1+LL_2 r_1+LL_M r_2-r_L L_1 L_M-r_L L_2 L_M)$

$d=-8\ \pi^3 N(r_L L_1 L_M+ r_L L_2 L_1+ r_L L_2 L_M+LL_2 L_M)$

$e=-2\pi k r_L r_1 r_2$

$g=-4\pi^2 k(L_1 L_M+L_1 L_2+L_2 L_M+LL_M+LL_2)$

$h=4\pi^2 N(L_1 L_M+L_1 L_2+L_2 L_M+LL_M+LL_2)$

$i=r_1 r_2+r_L r_2$

$j=-16\pi^4 k(LL_1 L_M+LL_2 L_M+LL_2 L_1)$

3-2 External rotor capacitance

Similarly the excitation rotor capacitance required and frequency of the SEIG can be solve the polynomial equation given by

$$C_R = \frac{E_3 f^3 + E_2 f^2 + E_1 f + E_0}{D_3 f^3 + D_2 f^2 + D_1 f + D_0} \quad \text{..................(15)}$$

When the SEIG is operating under no load condition, there will current through the rotor capacitor (C_R) and only shunt capacitor (C_S) will be effective in the circuit. Therefore, effect of C_R is reflected on the no load performance of the SEIG. But when loaded, both shunt and rotor capacitors will be effective. Hence, proper value of these elements can be chosen by first studying the variation of no load terminal voltage with Ce.Having chosen a suitable value for C_S, the influence of C_R can be studied by observing the effect of C_R on voltage regulation of the SEIG. Appropriate value of C_R can be selected from the range of values thus obtained depending upon the desired regulation and other operating constraints.With the real root of the frequencies from the above it is possible to calculate the values of the $C_R$and C_S.
Using this equation for a given frequency the value of the External Rotor Capacitance required for the required voltage can be calculated. The variables are as given in APPENDIX. For different values of capacitances the experiment were conducted and it was found that the value of the frequencies calculated from the polynomial and experimental verification are nearly equal. These

values can be used to predict the theoretically the minimum values of the terminal capacitance required for self-excitation. Of course, for stable operation of the machine C_R must be slightly greater than the minimum capacitance. Exact expressions for capacitor values under no-load, resistive loads and corresponding output frequencies are derived.

4- Conditions for self-excitation in induction generator occur

From equation (1), the self-excitation process will start when the polynomial presented in equation (13) has one root having a positive real part. Assuming a root is obtained in the form $\alpha_1 + j\beta_1$, as the capacitance C is increased, α_1 will change its sign from negative to positive passing through a zero value. The corresponding value of capacitance **C**, at $\alpha_1 = 0$, is the minimum value **(C min) required** to start the process of self excitation. As the capacitance **C** is increased further, the sign of $\alpha_1$changes from positive to negative passing through another zero value. At this new zero value of α_1 , the corresponding capacitance is the maximum capacitance**(C max)**.

5- Case study

5-1 Computer Algorithm

The induction machine used as the SEIG in this investigation is a three-phase induction motor with specification: 4 pole, 415V star connected, 7.8A, 3.6kW, 50Hz. A 3-Φ variable capacitor bank or a single capacitor was connected to the machine terminals to obtain self-excited induction generator action. The measured machine parameters were:
are $L_{ls} = L_{lr} = 11.4mH$, $L_m = 0.23H$, $R_s = 1.6\ \Omega$, $R_r = 2.75\ \Omega$.

Another way of finding the minimum rotor speed and corresponding minimum capacitance required for self-excitation is first to set the capacitance at a given value and then increase the rotor speed until one of the real parts of the complex roots becomes positive. This is a good way to find the minimum capacitance and its corresponding minimum rotor speed in the experimental setup. The detail of this procedure, theoretical determination of the minimum speed and minimum capacitance for a fixed speed by incrementing the capacitance, is given in the flow chart of Fig. (3)

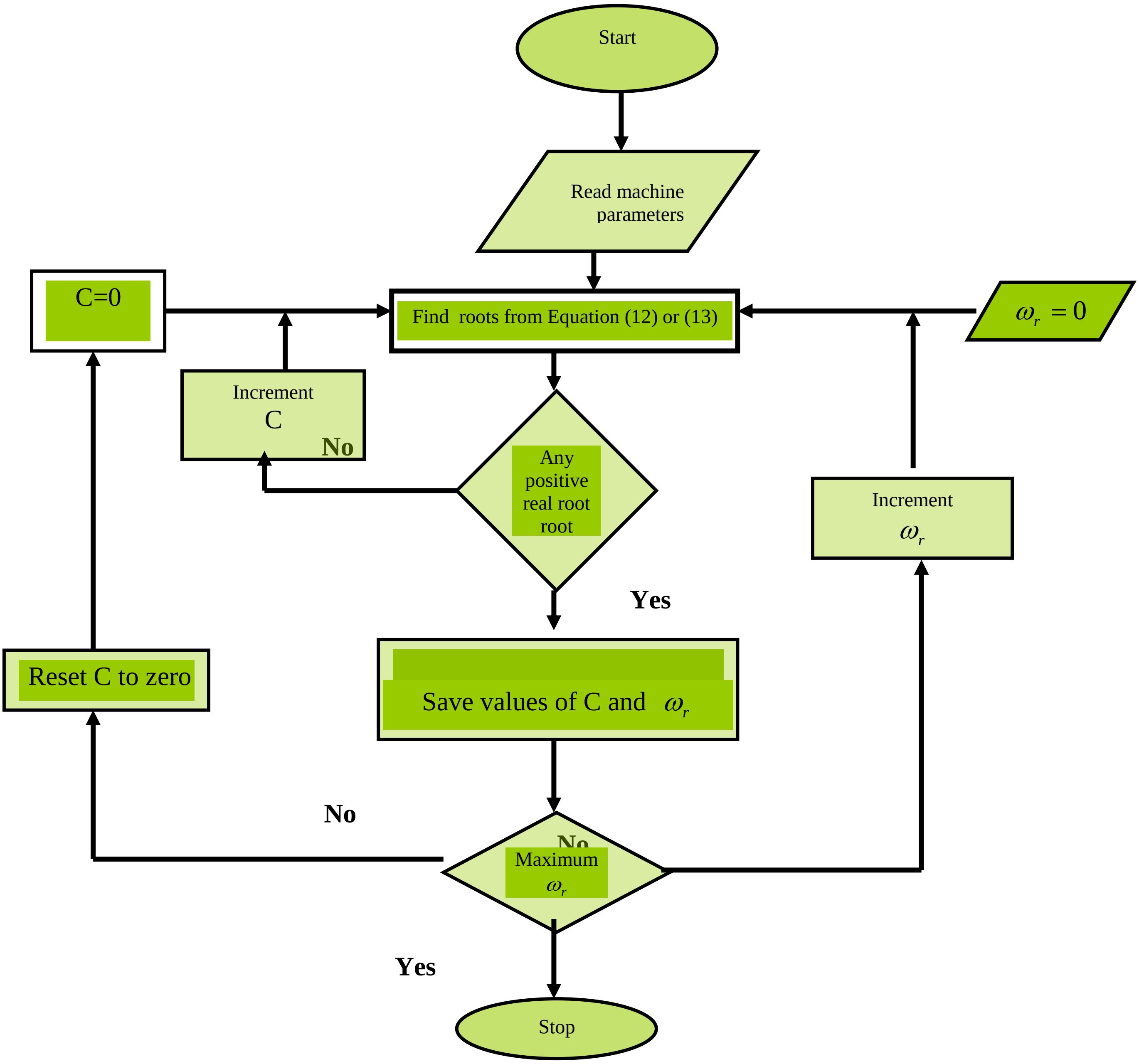


Fig. (3) Flow chart to determine the minimum speed and minimum capacitance In SEIG

5-2 Simulation of induction machine

The model of self excited induction generator is implemented with simulink. It is divided in blocks that consider the transformations: abc-qd0 of the stator voltages and qd0- abc of the stator currents equations. The SEIG model is as shown in Fig.4. The output voltage of SEIG depends upon the wind velocity, excitation capacitance value and wind fluctuations. Excitation capacitors are used to reduce the reactive power burden of self excited slip ring induction generators. The Figure shows the simulation model of the SEIG with grid. The d-q model of the self-excited induction generator is used to understand the all characteristics behavior of the generator system.

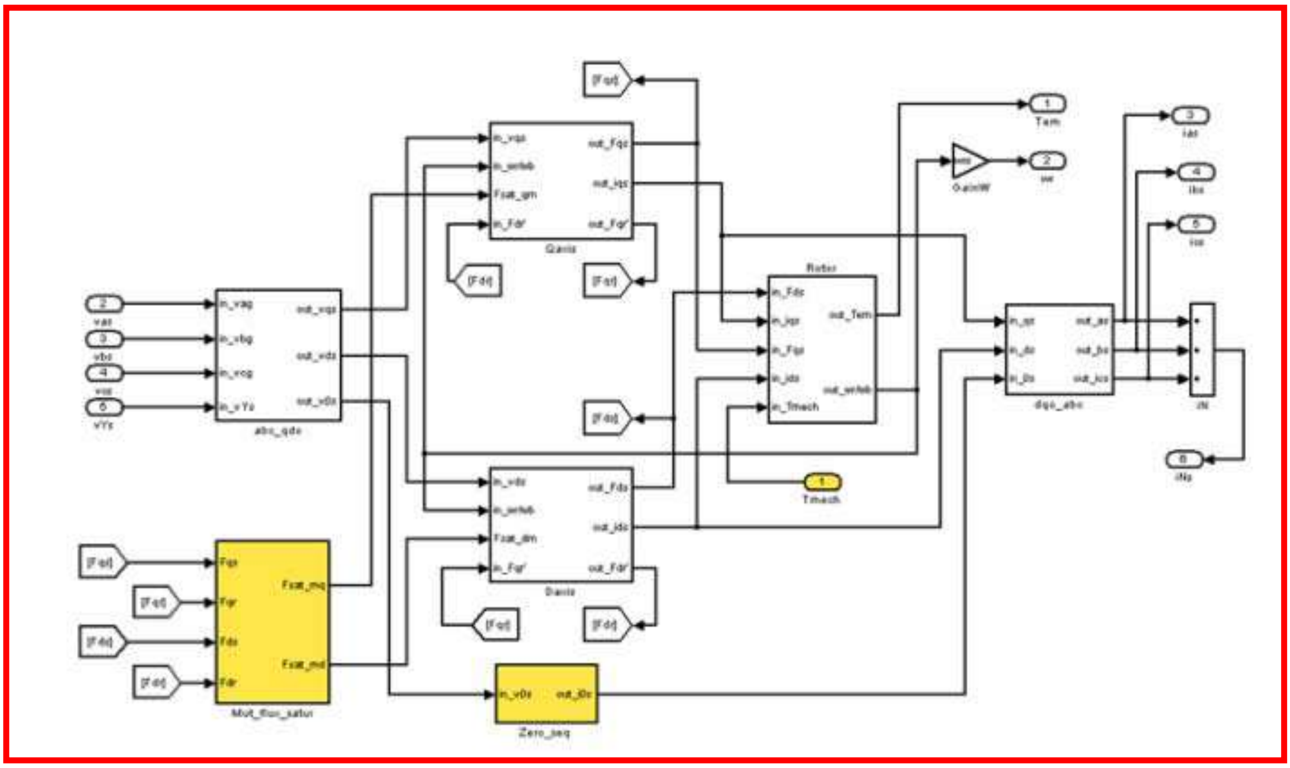


Fig.(4). Self excited Induction generator model implemented in Simulink

6-RESULTS AND DISCUSSIONS

Tthe d-q model of the self-excited induction generator is used to understand the all characteristics behavior of the generator system. **Table 1and 2** gives the values of minimum value of capacitance required for initiating the voltage build-up and maximum values which the machine fails to self excitation for variable speed operation under

R-L load and resistive load. The largest real root yields the maximum frequency that corresponds to the minimum capacitor. The smaller real root on the other hand yields the minimum frequency gives the value of excitation capacitance above which the machine fails to excite.the largest real root yields the maximum frequency that corresponds to the minimum frequency.

Table 1

R-L Load R=1 pu XL=2pu				
V(pu)	Imaginary roots	Real roots	Cmin(µF)	Cmax(µF)
0.9	r1=0.5905+0.1508j r2=0.5905-0.1508j r3=0.410+0.4769j r4=0.410-0.4769j	No real roots	No excitation ⟵⟶	
0.95	r1=0.0346+0.4615j r2=0.0346-0.4615j	r3=0.7511 r4=0.5892	230.88	469.8332
1	r1=0.0277+0.5290j r2=0.0277-0.5290j	r3=0.9796 r4=0.5290	45.69	657.7133
1.4	r1=-0.0142+0.4019j r2=-0.0142-0.4019j	r3=2.6352 r4=0.4829	31	1043.03
1.6	r1=-0.0269+0.3909j r2=-0.0269-0.3909j	r3=3.6148 r4=0.4844	16.01858	1095.673
1.8	r1=-0.0365+0.3829j r2=-0.0365-0.3829j	r3=4.715 r4=0.4876	9.31107	1121.7

Table 2

Resistive load R=2 pu				
V(pu)	Imaginary roots	Real roots	Cmin(μF)	Cmax(μF)
0.2	r1=-0.0213+1.6229j r2=-0.0213-1.6229j	r3=0.1831 r4=0.0995	611.7914	10770.38
0.4	r1=0.0032+1.639j r2=0.0032+1.639j	r3=0.3543 r4=0.1993	183.0825	3141.87
0.6	r1=0.0692+1.6382j r2=0.0692-1.6382j	r3=0.5132 r4=0.3085	105.8333	1306.051
0.8	r1=-0.163+1.599j r2=-0.163+1.599j	r3=0.64 r4=0.4239	95.32	745.593
1	r1=-0.2576+1.504j r2=-0.0269-0.3909j	r3=0.952 r4=0.5328	27.85076	570.4829

For different values of capacitances the experiment were conducted and it was found that the value of the frequencies calculated from the polynomial and experimental verification are nearly equal. Very good correlation between the computed and experimental results is observed as shown in **Table 3**. This verifies the accuracy of the proposed method for computing minimum value of the capacitance for SEIG.Hence, it is proved that the experimental frequency value must be greater than the computed frequency value. And it is also proved that the frequency is higher for SEIG with external rotor capacitance than with the SEIG without rotor capacitance. So, with the increase in the frequency the speed of the machine is increased, in turn increases the generated voltage, torque, active and reactive power

Table 3 (Comparison between Experimental and calculated frequency)

Without rotor capacitance		**With rotor capacitance**	
Experimental frequency	Calculated frequency	Experimental frequency	Calculated frequency
30.55	30.08	31.76	31.3
37.1	36.68	39.67	39.2
41.4	41.1	44.9	43.97
47.11	47.	49.55	48.64
50.088	49.9	51.4	50.66

Figure 5- shows Characteristics of a loaded generator(**Resistive load)** (green-blue) The capacitor characteristic appears as a surface (brown). The intersection between the capacitor and generator-load represents all possible steady-state operating points .When the generator is accelerated, with the capacitors(**95.32 μf**) connected, self excitation is not possible in the beginning. Then at about **38.4 Hz** the self excitation process starts and the voltage build-up.

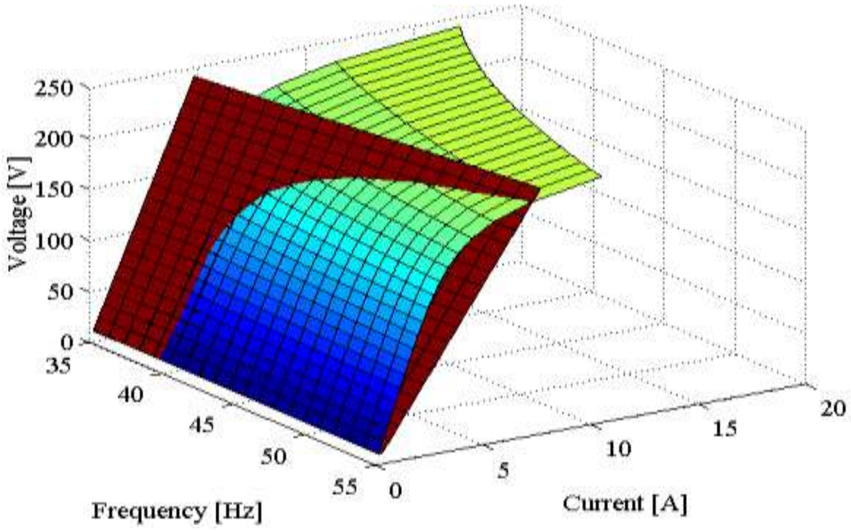


Figure 5 -Characteristics of a loaded generator

Fig. 6 -Simulated self-excitation induction generator .Shows the voltage build up in phase „a"with per phase excitation capacitance of 46μF at a rotor speed of 1600 rpm. It took about 2.15 seconds to settle to its steady state voltage of 300 volts. The phase voltage slowly starts building up and reaches a steady-state value.

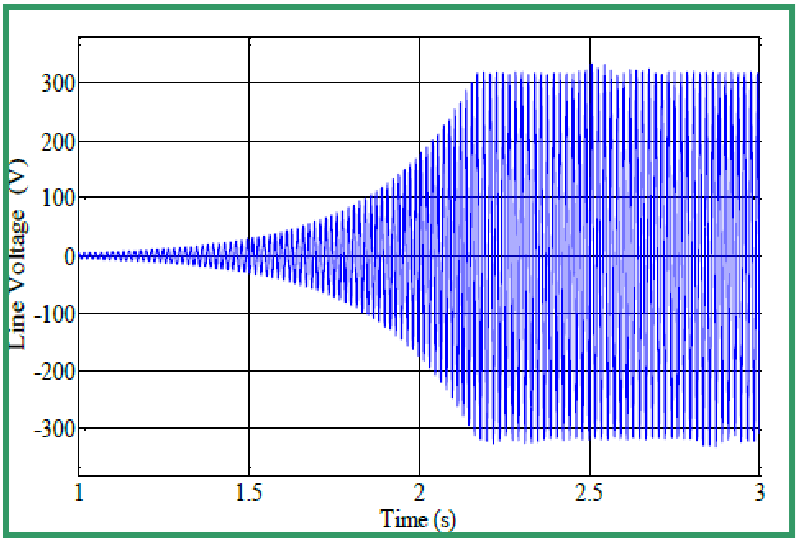
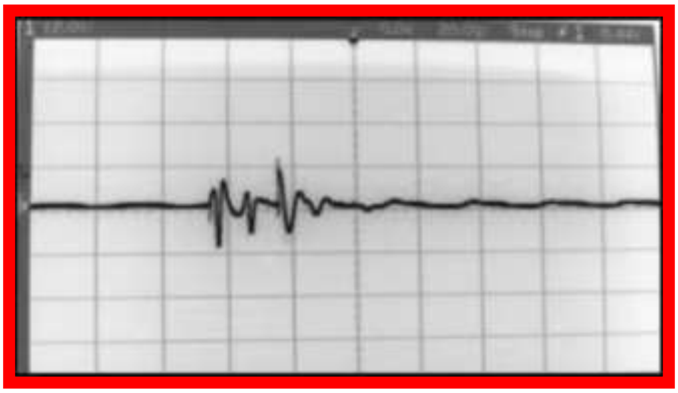


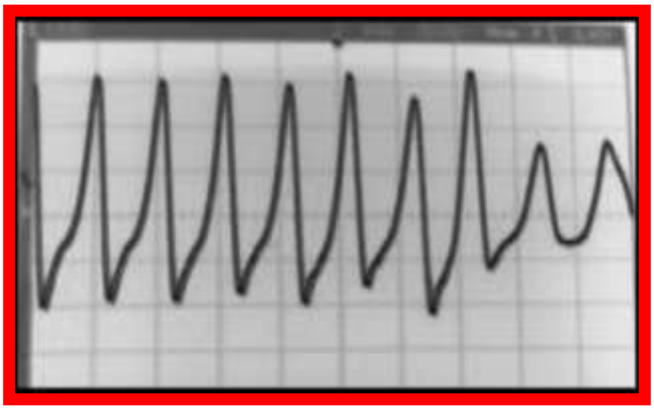
Fig. 6. Voltage build up in a self-excited induction generator(Simulated).

Fig.7. Shows experiment Voltage could not build up and collapses for a prime mover speed of 1180 rpm (for low values of speed the voltage collapses and fails to build up).

Fig 8-In this case prime mover speed is set at 1350 rpm. Stator voltage is taken through a 10:1 probe. Oscilloscope settings are 13.6 V/div and 20 ms/div. At this speed, SEIG is loaded using a lamp load of 200W/phase. The corresponding stator voltage waveform is shown in **Fig.9,** with same oscilloscope settings as in **Fig.8.** The stator voltage waveform during a build up process at 1440 rpm



Fig(7) Voltage could not build up and collapses

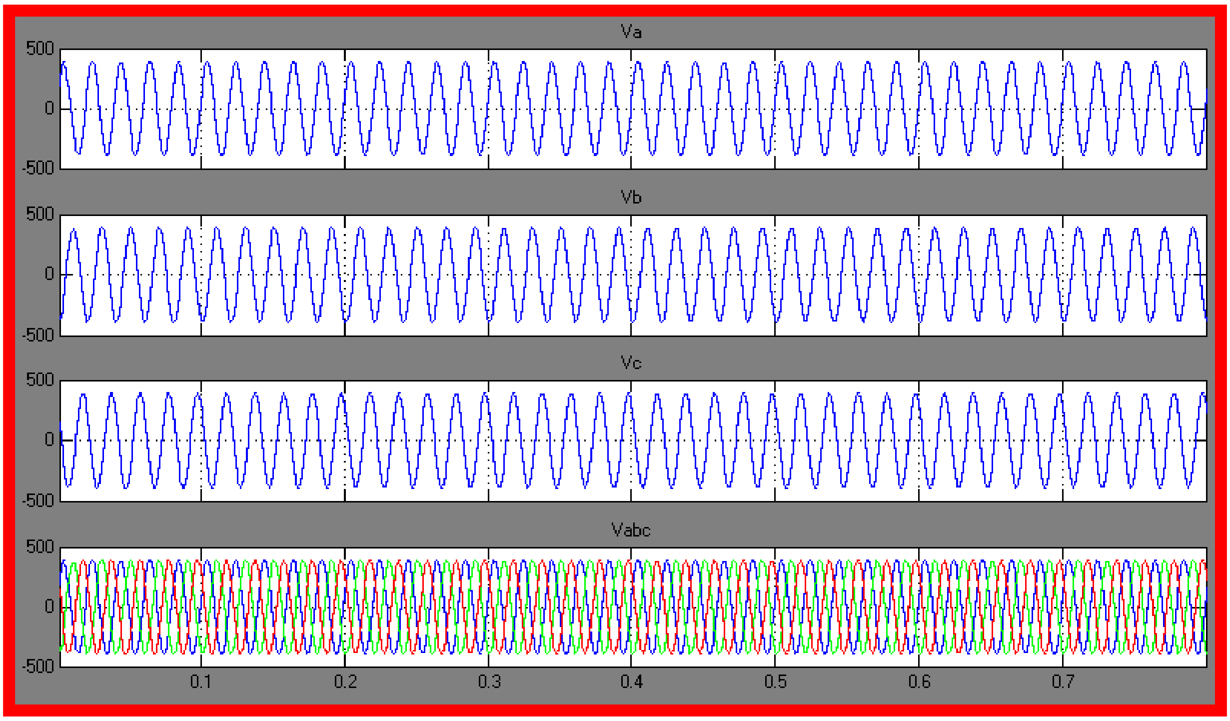


Fig(8)The voltage build up at a prime for   a prime mover speed of 1180 rpm
mover speed of 1115 rpm

Fig(9) The stator voltage waveform during a build up process at 1440 rpm

Fig(10)and **Fig(11)** From the simulink results it can be observed that the voltage Generated, increased with the use of the capacitance in the rotor. The voltage generated by the machine without the external rotor capacitance is 442 Volts.With the use of the external rotor capacitance the voltage generated is increased to525Volts.The rotor capacitance used is of 50µF with the excitation capacitance of 15μF.(When compared with the terminal voltage without rotor capacitance the voltage is increased by an amount of 18%). With this comparison we can conclude that for the improvement of the terminal voltage it is advised to use the external rotor capacitance in the circuit. But the proper capacitance value should be choosen, other wise the machine may collapse with the drastic increase in the voltage

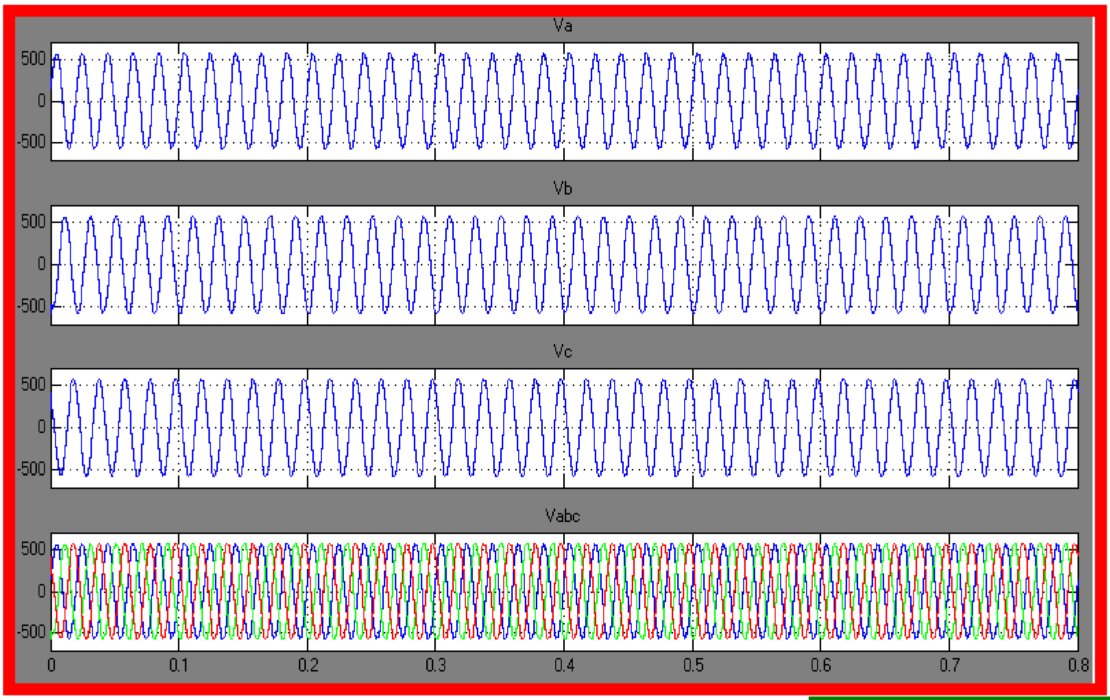
generated voltage(V)



Rotor capacitance (μF)

Fig(10) Generated voltage of SEIG without rotor capacitance

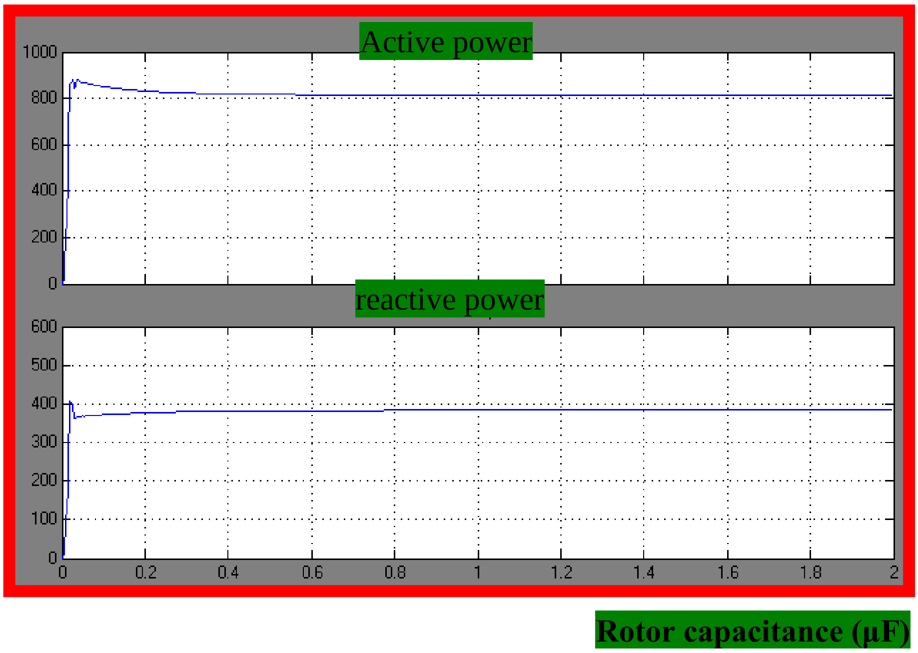
generated voltage(V)



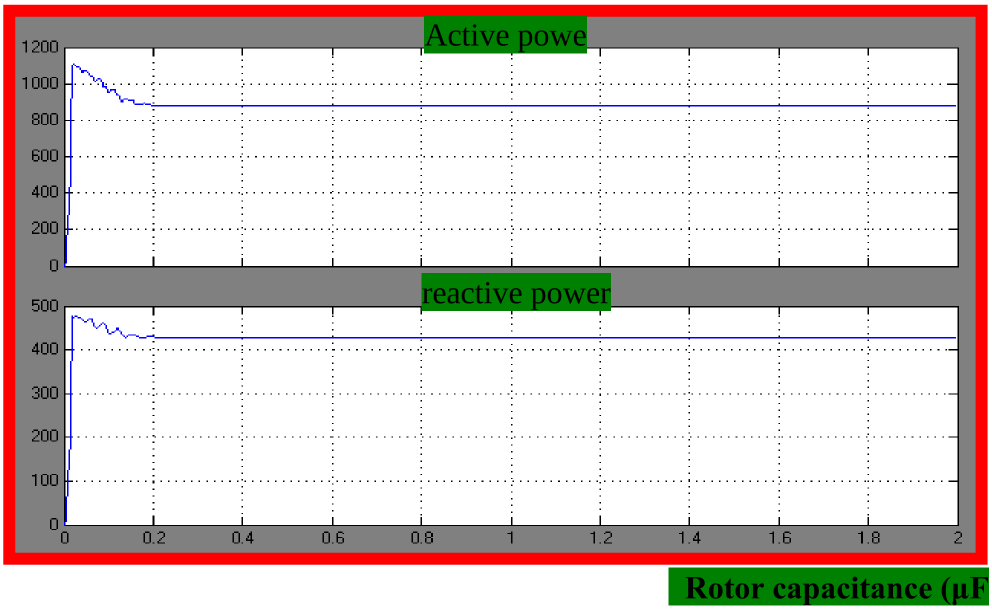
Rotor capacitance (μF)

Fig(11) Generated voltageof SEIG without rotor capacitance

Fig(12) and **Fig(13)** Generated active and reactive power of SEIG with rotor capacitance and without rotor capacitance. Observed that the active and reactive power generated by the machine is increased with the rotor capacitance. The comparison is made between the SEIG with rotor rotor capacitance. With this capacitance and without comparison we can conclude that for the improvement of the power we can use the external rotor capacitance in the circuit. But the proper capacitance value should be choosen, other wise the machine may collapse with the drastic increase in the voltage.

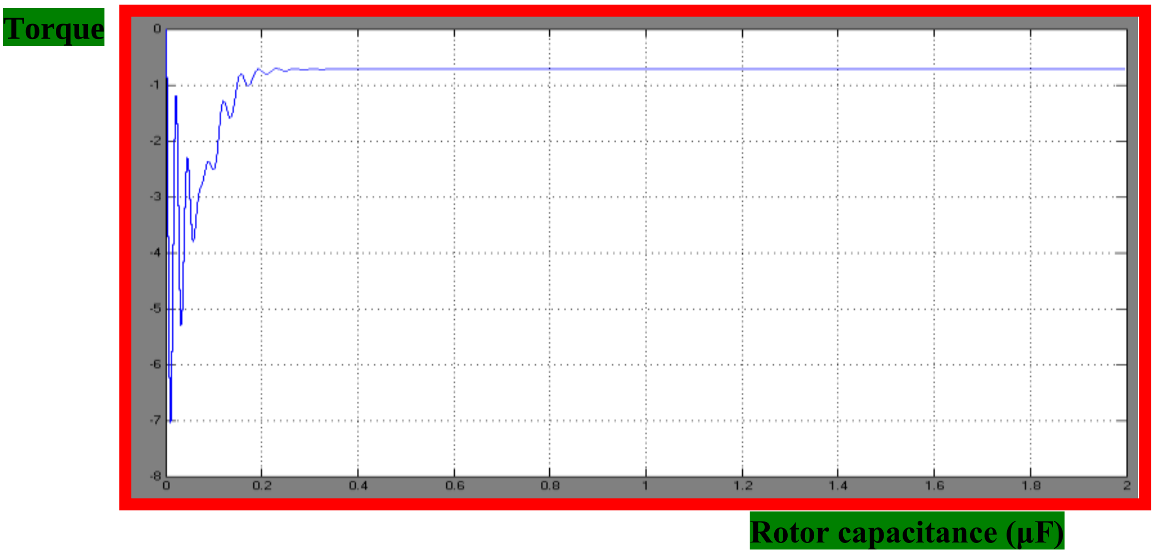


Fig(12)Generated active and reactive power without rotor capacitance

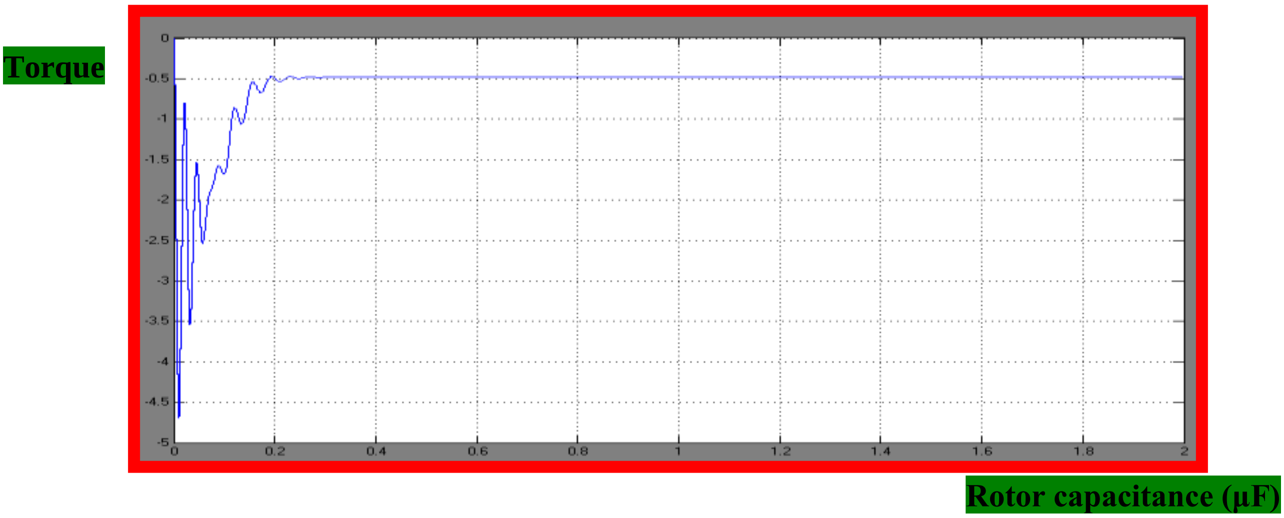


Fig(13)Generated active and reactive power with rotor capacitance

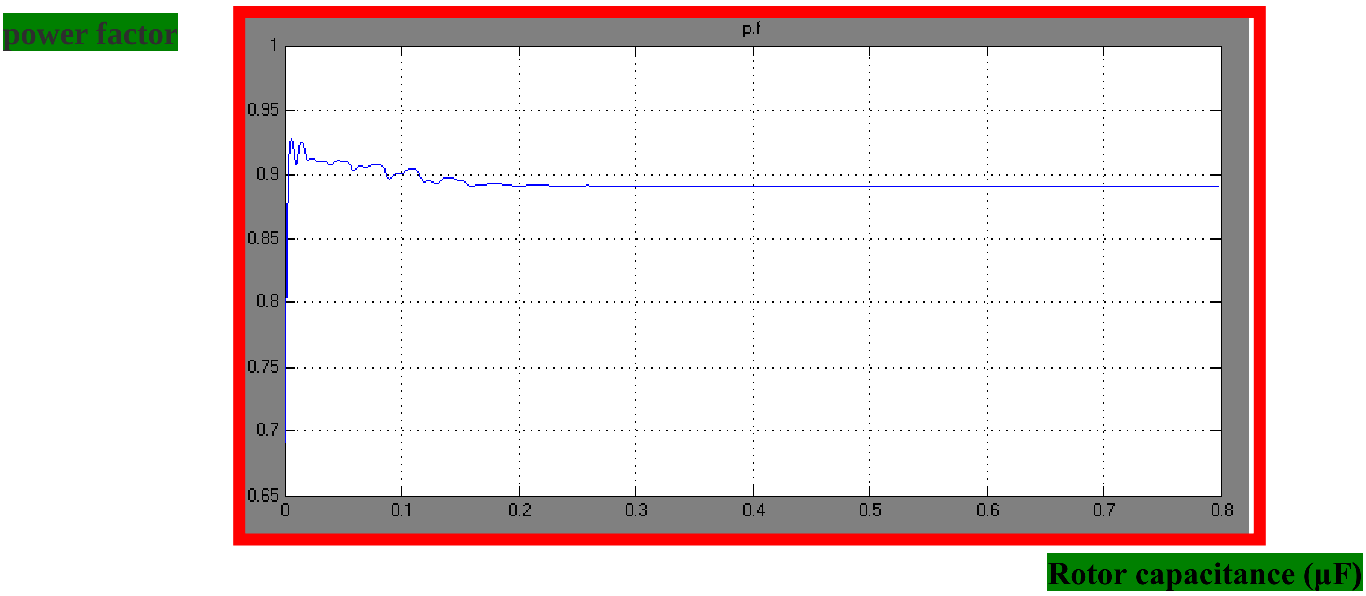
Fig(14,15,16.17,18,and 19) From the simulink results it can be observed that the active, reactive power generated by the machine to the grid is increased with the use of the capacitance in the rotor. And it is also observed that due to the increase in the active and reactive power, the power factor is decreased. And it is also observed with the external rotor capacitance the torque is increased about 5-10% then that of the SEIG without having the rotor capacitance. With the external rotor capacitance, there is increase in the speed of the generator when compared with the machine without rotor capacitance



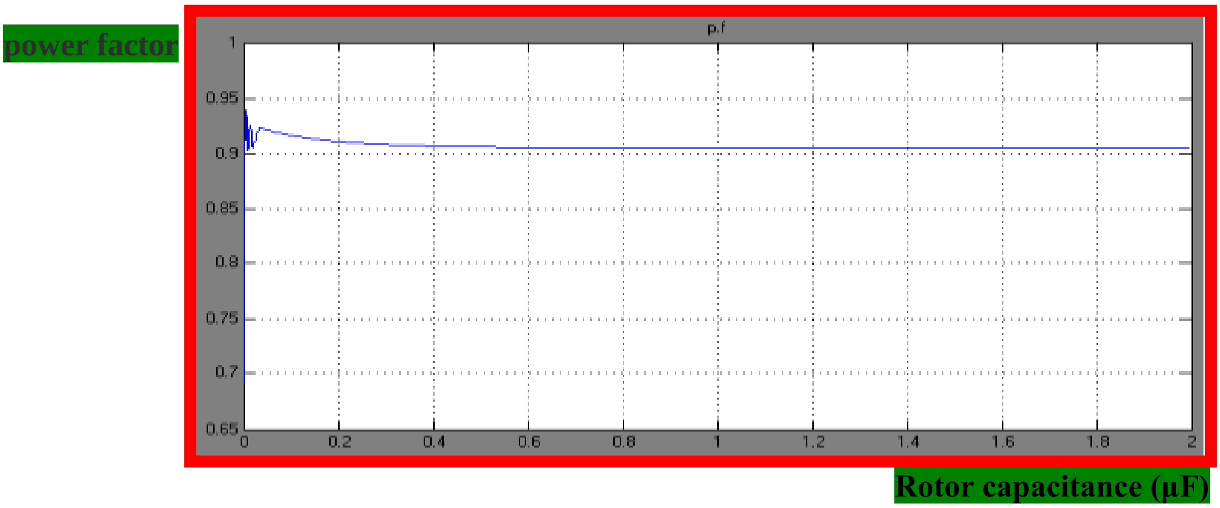
Fig(14) Response of p.u generated torque with rotor capacitance



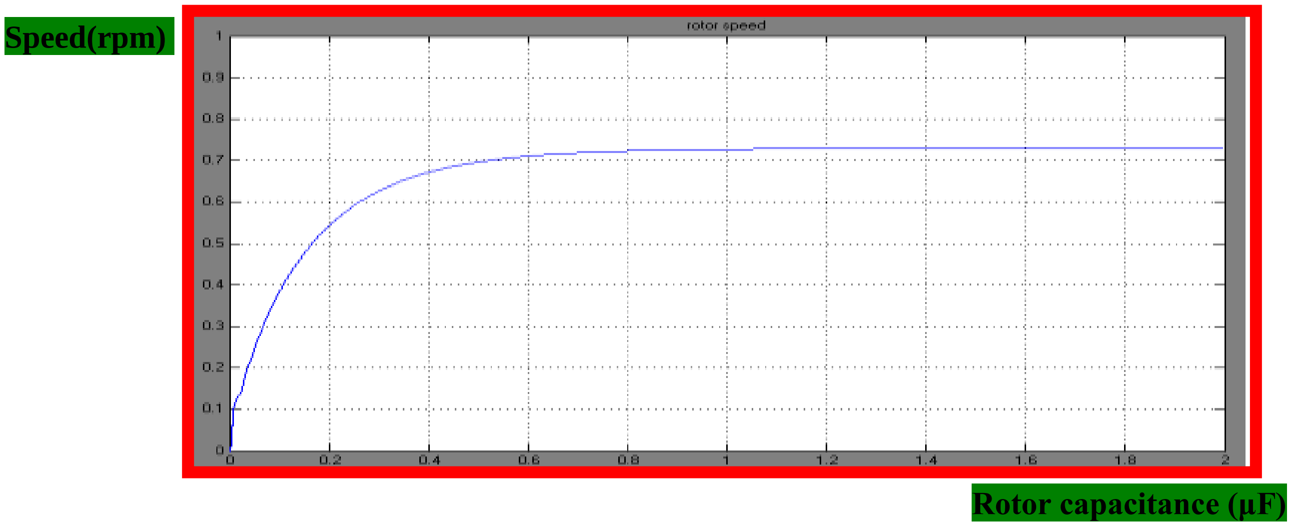
Fig(15) Response of p.u generated torque without rotor capacitance



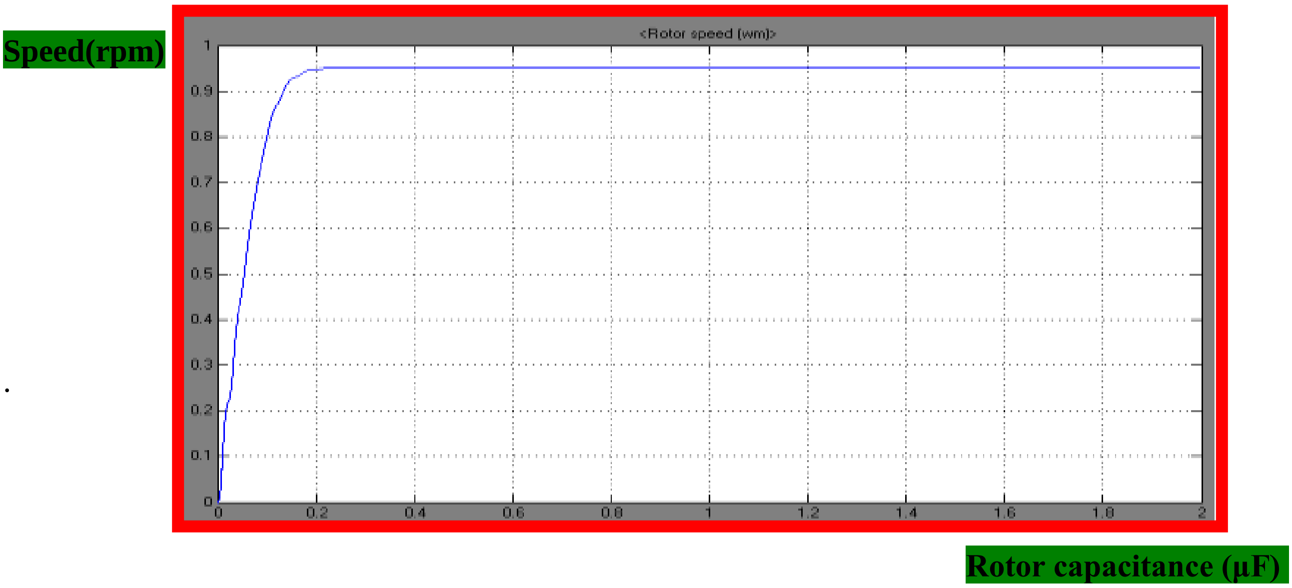
Fig(16) p.f at generator with rotor capacitance



Fig(17) p.f at generator without rotor capacitance



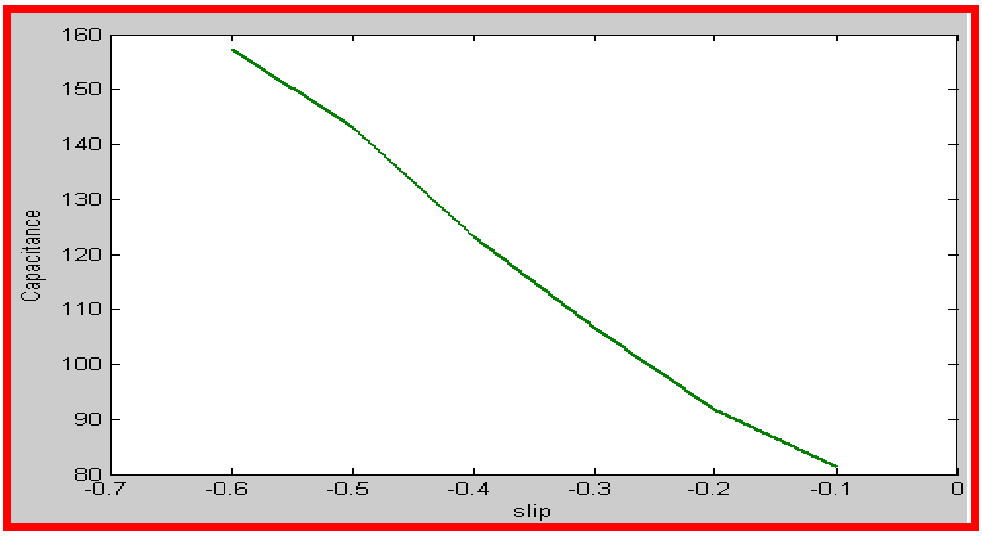
Fig(18) Response of p.u speed with rotor capacitance



Fig(19) Response of p.u speed without rotor capacitance

Fig.20. Shows the variation of the excitation capacitance with the slip,s . Capacitance is maximum at minimum value of slip and then increases as the slip moves in the negative direction. As the slip decreases the values of the frequency also decreases.

capacitance (µF



Slip

Fig20.Variation of slip with the capacitance

In order to reach the steady-state equilibrium point of the induction machine, the output voltage Vs is expressed as a function of the values of Rotor exaction capacitance (Equation below)

$$Vout = 1E-04C_R^{\ 6} - 0.0239C_R^{\ 5} + 2.3651C_R^{\ 4} - 124.61C_R^{\ 3} + 3679.7C_R^{\ 2} - 57732C_R + 376018$$

7- CONCLUSIONS

The roll of the external capacitor here is to minimize the steady state reaching time and stabilize the system within the minimum time. Due to the capacitance the output voltage of SEIG are increased but while choosing the value of the capacitance if the minimum value is selected the machine may not operate and if high value of the capacitance is selected the machine may collapse. Here in this paper the value of the capacitance is selected as per the equation derived for choosing the value of the external capacitance. It is observed that due to this capacitance the active and reactive powers are increased and p.f is decreased which is the requirement of the grid. It is also observed that the fluctuations in the shaft torque is also decreased.

A method for computing the minimum value of capacitance to initiate self-excitation in the SEIG has been described with the rotor capacitance. The method is based on the steady state equivalent circuit, but features the separate consideration of the load, rotor capacitance and excitation capacitance branches, which enables the frequency to be determined by solving a single 6th order polynomial .Computation studies on the experimental machine reveals that there exist critical values of load impedance and speed below which self-excitation is impossible irrespective of the capacitance used. Using the same analysis technique, an iterative procedure has also been developed for estimating the capacitance requirements for maintaining the terminal voltage constant when the SEIG is on load. The validity of the proposed methods are confirmed by experimental results obtained on a 3.6 kW laboratory induction machine.

8. REFERENCES

[1] Faiz and S. Hasanzadeh "Minimum capacitance requirement for starting a SEIG "International Symposium on Power Electronics Novi Sad, Republic of Serbia, November 7th - 9th, 2007

[2] R.C. Bansal, .Three-phase self-excited induction generators: An overview ., IEEE Trans. on EC, vol. 20, no. 2, pp. 292-299, 2005

[3] M. L. Elhafyani, S. Zouggar "Permanent and Dynamic Behaviours of Self-excited Induction Generator In balanced mode"M. J. CONDENSED MATER Volume7, number 1 1 January 2006

[4] Thakur R. K and Agarwal V., .Effect of excitation capacitance value on the transient behaviour of induction generator in wind energy conversion system., National Power Electronics Conference, Bangalore, India, Dec 2007.

[5]Harish Kumar, Neel Kamal " STEADY STATE ANALYSIS OF SELF-EXCITED INDUCTION GENERATOR International Journal of Soft Computing and Engineering (IJSCE) ISSN: 2231-2307, Volume-1, Issue-5, November 2011

[6] N. Ammasaigounden, M. Subbiah, and M. R. Krishnamurthy, "Wind-driven self-excited pole-changing induction generators", IEE proceedings, Vol. 133, Part B, No. 5, pp.315-321,September. 1987

[7] Li Wang,Ching-Huei Lee,.A novel analysis on the performance of an isolated self excited induction generator., IEEE transaction on Energy Conversion,vol. 12, no. 2, pp. 109-117, June 1997

[8] K.S.Sandhu,S.P.Jain, Steady state operation of self excited induction generator with varying wind speeds, International journal of circuits, systems and signal processing,Issue-1,volume2,2008

[9] K. Kalyan raj, E. Swati, Ch. Ravindra" Voltage Stability of Isolated Self Excited Induction Generator (SEIG) for Variable Speed Applications using Matlab/Simulink"International Journal of Engineering and Advanced Technology (IJEAT) ISSN: 2249 – 8958, Volume-1, Issue-3, February 2012

[10] Malik N.H., and Al-Bahrani A.H., .Influence of the terminal capacitor on the performance characteristics of a self excited induction generator., IEE Proc. C, vol. 137, no. 2, pp. 168-173, 1990

[11]Shakuntla BOORA" On-Set Theory of Self-Excitation in Induction Generator" International Journal of Recent Trends in Engineering, Vol 2, No. 5, November 2009.

[12] Chan T.F., .Capacitance requirements of self excited induction generators., IEEE transaction on Energy Conversion, vol. 8, no. 2, pp. 304-311, 1993

[13] Malik, N., and Haque, S., .Steady state analysis and performance of an isolated self excited induction generator., IEEE Transaction on Energy Conversion, vol. 1, no. 3, pp. 134-139, 1986

[14] C. H. Watanabe and A. N. Barreto, "Self-excited induct ion generator/force-commutated rectifier system operating as a dc power supply,"IEE Proc.,vol.134,pt.B,no.5,Sept.1987.

[15] Chan T.F., .Capacitance requirements of self excited induction generators., IEEE transaction on Energy Conversion, vol. 8, no. 2, pp. 304-311, 1993

[16] M. L. Elhafyani, S. Zouggar "Permanent and Dynamic Behaviours of Self-excited Induction Generator In balanced mode"M. J. CONDENSED MATER Volume7, number 1 1 January 2006

[17] S. Subramanian and R. Bhuvaneswari" Optimal Design of Self-excited Cage Induction Generator Using Particle Swarm Optimization"IRANIAN JOURNAL OF ELECTRICAL AND COMPUTER ENGINEERING, VOL. 6, NO. 1, WINTER-SPRING 2007

[18] R.Kannan, Dr.S.Subramanian, Dr.R.Bhuvaneswari" MULTIOBJECTIVE OPTIMAL DESIGN OF THREE-PHASE INDUCTION GENERATOR USING SIMULATED ANNEALING TECHNIQUE "International Journal of Engineering Science and Technology Vol. 2(5), 2010, 1359-1369

[19] N. Ammasaigounden, M. Subbiah, and M. R. Krishnamurthy, "Wind-driven self-excited pole-changing induction generators", IEE proceedings, Vol. 133, Part B, No. 5, pp.315-321,September. 1987

[20] T.F.Chan, "Capacitance requirements of self-excited induction generators", IEEE trans. on energy conversion, Vol. 8, No. 2, pp.304-310, June 1993

APPENDIX

B0=-mg; B1=lg+eh; B2=ki; B3=-mg-mk; B4=hi+gj+de; E3=hi+dj; E2=gf+im-bk; E1=mq+dh; E0=ab+ch-ml; D3=il-hj+mq; D2=hd+ie-bm; D1=ah+bm-lq; D0=pq+mh

a=2πk(LMr1+L1r1+L2r1+LMr2+Lr2+rLLM+rLL2);
b=-2 πN*rL(LM+L2)
c=-8π3k(LLMr1+LL2r1+LLMr2-rLL1LM-rLL2LM)
d=-8 π3N(rLL1LM+ rLL2L1+ rLL2LM+LL2LM)
e=-2πkrLr1r2
g=-4π2k(L1LM+L1L2+L2LM+LLM+LL2)
h=4π2N(L1LM+L1L2+L2LM+LLM+LL2)
i=r1r2+rLr2
j=-16π4k(LL1LM+LL2LM+LL2L1);
l=16π4N(LL1LM+LL1L2+LL2LM)
m=4π2k(Lr1r2+rLLMr1+rLL1r2+rLL1r2+rLL2r1+rLLmr2)
p=-4π2NrLLMr1;
q=c(L1LM+L1L2+L2LM+LLM+LL2)