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CAPACITANCE REQUIRED ANALYSIS FOR SELF-EXCITED INDUCTION GENERATEUR

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ABSTRACT

The main drawback of induction generator in wind energy conversion systems applications is its need for leading reactive power to build up the terminal voltage and to generate electric power. Using terminal capacitor across generator terminals can generate this leading reactive power. The capacitance value of the terminal capacitor is not constant but it is varying with many system parameters like shaft speed, load power and its power factor. If the proper value of capacitance is selected, the generator will operate in self-excited mode. This paper presents direct methods derived from loop and nodal analyses to obtain different criteria for maintaining self-excitation and performance characteristics of an isolated, three-phase, self-excited induction generator (SEIG). Results of a detailed investigation on a conventional 3kW induction motor operated as a SEIG are presented to illustrate the effectiveness of the proposed method.
Keywords: *Capacitance Requirements, Self-Excitation, Study State Analysis, Induction Generator*

1. INTRODUCTION

The self-excited induction generator (SEIG) has attracted considerable recent attention due to its applicability as a stand-alone generator using different conventional and non-conventional energy resources with its advantage over the conventional synchronous generator. The reason for the widespread popularity of induction generator is owing to its capability to generate the power from variable speed as well as constant speed prime movers, low unit cost, very simple, rugged, produces high power per unite mass of materials and requires very little maintenances.

In a standalone induction generator the major problem is that of guaranteeing self excitation. Self excitation of an induction machine and its sustenance depend on the appropriate combination of speed, load and terminal capacitance in relation to the magnetic non-linearity of the machine. These in turn cause certain limitations on the performance of the machine. In view of these, studies on the criteria for self excitation of an induction generator are considered to have practical significance. The excitation requirements, of an induction generator have been dealt with extensively in the literature [1].

For self excitation to occur, the following two conditions must be satisfied:

i. The rotor should have sufficient residual magnetism.

ii. The three capacitor bank should be of sufficient value.

If an appropriate capacitor bank is connected across the terminals of an externally driven induction machine and if the rotor has sufficient residual magnetism an EMF is induced in the machine windings due to the excitation provided by the capacitor. The EMF if sufficient would circulate leading currents in the capacitors. The flux produced due to these currents would assist the residual magnetism. This would increase the machine flux and larger EMF will be induced. This in turn increases the currents and the flux. The induced voltage and the current will continue to rise until the VAR supplied by the capacitor is balanced by the VAR demanded by the machine, a condition which is essentially decided by the saturation of the magnetic circuit. This process is thus cumulative and the induced voltage keeps on rising until saturation is reached. To start with transient analysis the dynamic modeling of induction motor has been used which further converted into induction generator [2]-[4]. Magnetizing inductance is the main factor for voltage buildup and stabilization of generated voltage for unloaded and loaded conditions. The dynamic Model of Self Excited Induction Generator is helpful to analyze

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all characteristic especially dynamic characteristics. For the past few years the researches has been developed positively in the steady state models of three phase self excited induction generator(SEIG) [5] and proposed the steady state equivalent circuit which represents the SEIG, the critical capacitance requirement and excitation balancing has been proposed [5]-[6]. Accordingly the better applicability of induction motor as a generator for isolated applications has been proposed [7]. The model was found suitable for steady state analysis but not transient analysis. Thus for analyzing the transient characteristics, dynamic model of SEIG has been developed [8] and analyzed the dynamic characteristics for various transient conditions and stability. As for the dynamic and transient operation, it was treated for no load and for different loads: resistive [9], inductive [10], induction motor [11], DC load.

In this context, this work presents generalized state-space dynamic model of a three phase SEIG developed using d-q variables in stationary reference frame for transient analysis and a method to finding the value of terminal capacitance required for self-excitation taking into account the rotor speed and load impedance using a computer program. The proposed model for induction generator, load and excitation using state space approach driving by wind turbine and supplying which is coupled to a centrifugal pump in order to optimize his performances.

This paper is organized as follows: section two gives the system modeling in static and a dynamic state. In this section, a simple method is also presented and analyzed to finding the minimum value of required capacitance for self-excitation. Simulation results are discussed in section three. Finally a conclusion resumes the developed work and its features.

2. SYSTEM MODELING AND ANALYSIS

2.1 Proposed system:

In the proposed system (Figure 1), a power generation system consisting of a wind turbine with SEIG .

The produced power is used to supply an induction motor coupled to a centrifugal pump. As the SEIG requires reactive power for its excitation, a three phase capacitor bank is connected across its stator terminals.

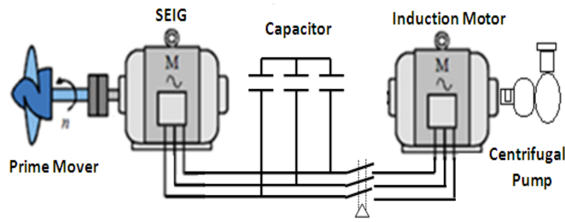

Fig.1 Wind Electric Pumping System

The Induction Motor cannot be supplied unless the SEIG stator voltage build up process occurs. For this reason an operating mode switcher selects first the no load condition until the voltage build up process is accomplished. Subsequently the switcher is turned on as to connect the Induction Motor to the SEIG.

In order to analyze the performances of self excited induction generator which supplies an induction motor driving pump, a system modeling is required. Following, a steady state and dynamic modeling are presented.

2.2 Steady state Analysis of SEIG:

Figure 2 shows the per-phase equivalent circuit commonly used for SEIG supplying an induction motor. 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. When the induction machine is driven at the required speed, the residual magnetic flux in the rotor will induce a small electromotive force 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.

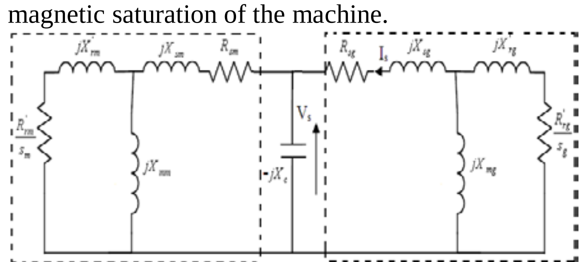
Fig.2 Per Phase Equivalent Circuit Of Self Excited Induction Generator Feeding An Induction Pump Motor

We note: Index **g** for Induction Generator
Index **m** for Induction Motor

All circuit's parameters except the magnetizing inductance L_{mg} are assumed to be constant and insensitive to saturation.

From Figure 2, the total current at node a may be given by:

$$Vs.(Yg + Yc + Ym) = 0 \tag{1}$$

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Where, Yg is a total admittance induction generator
Yc is admittance capacitive
Ym is a total admittance induction motor

If we denote: **a** P.U. frequency and **b** P.U. speed
So:
The expression of admittance capacitive is giving by:

$$Yc = j\frac{a}{Xc} \qquad (2)$$

The induction generator admittance is expressed as:

$$Yg = \frac{Yg_1(Yg_2 + Yg_3)}{Yg_1 + Yg_2 + Yg_3} \qquad (3)$$

With:

$$Yg_1 = \frac{1}{R_{sg} + jaX_{sg}}$$
$$Yg_2 = \frac{1}{jaX_{mg}} \qquad (4)$$
$$Yg_3 = \frac{1}{\frac{aR'_{rg}}{a-b} + jaX'_{rg}}$$

As a consequence of the symmetry of per phase equivalent circuit, the expression of total induction motor admittance Ym can be deduced from that of Yg by replacing the index **g** by **m**.

Therefore, under steady state self excitation, the total admittance must be zero, since:

$$Vs \neq 0 \quad \text{So} \quad (Yg + Yc + Ym) = 0 \qquad (5)$$

Equation 5 is divided into real and imaginary parts as:

$$\Re(Yg + Yc + Ym) = 0 \qquad (6)$$
$$\Im(Yg + Yc + Ym) = 0 \qquad (7)$$

Separating real and imaginary Parts of the Yg, we obtain:

$$Yg = \frac{1}{R_G + jX_G} = \frac{R_G}{R_G^2 + (X_G)^2} - j\frac{X_G}{R_G^2 + (X_G)^2} \qquad (8)$$

With:

$$R_G = R_{sg} + \frac{a(a-b)R'_{rg}X_{mg}^2}{(a-b)^2(X'_{rg} + X_{mg})^2 + R'^2_{rg}} \qquad (9)$$

$$X_G = aX_{sg} + \frac{aX_{mg}((a-b)^2X'_{rg}(X_{mg} + X'_{rg}) + R'^2_{rg})}{(a-b)^2(X'_{rg} + X_{mg})^2 + R'^2_{rg}} \qquad (10)$$

To simplify the equations and a nominal condition of the induction motor, we can write:

$$Ym = \frac{1}{R_M + jX_M} = \frac{R_M}{R_M^2 + (X_M)^2} - j\frac{X_M}{R_M^2 + (X_M)^2} \qquad (11)$$

R_M and X_M are expressed with the induction motor parameters.

Equations (6) and (7) give:

$$\frac{R_G}{R_G^2 + (X_G)^2} + \frac{R_M}{R_M^2 + (X_M)^2} = 0 \qquad (12)$$
$$\frac{a}{Xc} - \frac{X_G}{R_G^2 + (X_G)^2} - \frac{X_M}{R_M^2 + (X_M)^2} = 0 \qquad (13)$$

It is noted that (12) is independent of Xc and the only variable is the per unit frequency **a**.
Once the value of **a** has been determined then Xc can be determined using (13).
For no load operation $R_M = \infty$ and $X_M = 0$
Substituting $R_M = \infty$ and $X_M = 0$ in (12):

$$R_{sg} + \frac{a(a-b)R'_{rg}X_{mg}^2}{R'^2_{rg} + (a-b)^2(X'_{rg} + X_{mg})^2} = 0 \qquad (14)$$

On simplification, it yields the following:

$$a_{\max} = b - \frac{b}{2}\left[\frac{1 - \sqrt{1 - (\frac{b_c}{b})^2}}{1 + \frac{R_{sg}}{R'_{rg}}(1 + \frac{X'_{rg}}{X_{mg}})^2}\right] \qquad (15)$$

Where b_c is given by:

$$b_c = \frac{2R_{sg}}{X_{ms}}\sqrt{\frac{R'_{rg}}{R_{sg}} + (1 + \frac{X'_{rg}}{X_{mg}})^2} \qquad (16)$$

Substituting $R_M = \infty$ and $X_M = 0$ in (13):

$$Xc = a_{\max}^2[X_{sg} + \frac{aX_{mg}((a-b)^2X'_{rg}(X_{mg} + X'_{rg}) + R'^2_{rg})}{(a-b)^2(X'_{rg} + X_{mg})^2 + R'^2_{rg}}] \qquad (17)$$

Hence $C_{\min}$ is given by:

$$C_{\min} = \frac{1}{2\pi 50.a_{\max}^2(X_{sg} + \frac{aX_{mg}((a-b)^2X'_{rg}(X_{mg} + X'_{rg}) + R'^2_{rg})}{(a-b)^2(X'_{rg} + X_{mg})^2 + R'^2_{rg}})} \qquad (18)$$

Thus, $C_{\min}$ is inversely proportional to the square of the p.u. machine frequency. The value of Cmin determined from (18) is just sufficient to have self-excitation under steady state. If a terminal capacitor $C = C_{\min}$ is used and the generator is started from rest, the voltage build up will not take place.

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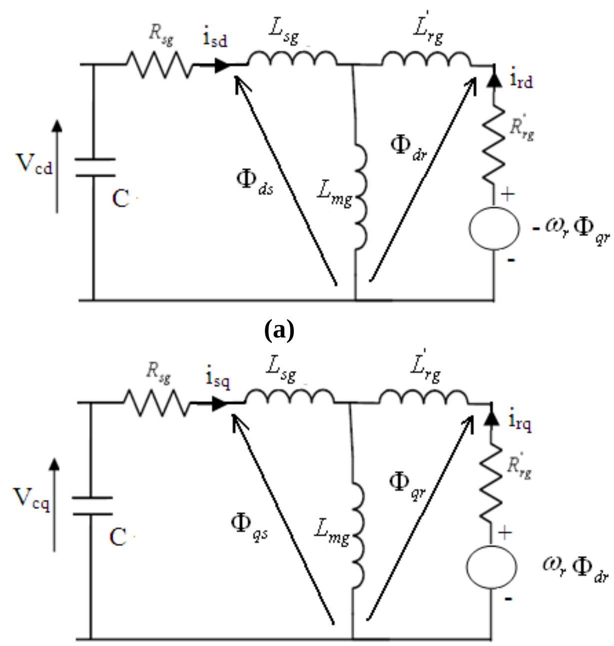
Thus in practice, terminal capacitor C having a value somewhat greater than C_{min} should be selected to ensure self-excitation.

2.3 Method of solution:

Equation (12), (13) and (18) represent the conditions that must be satisfied for the self-excitation of the induction machine corresponding to various generator and load configurations as discussed above. Each of these equations is complex and non-linear which can be expressed as two simultaneous real, nonlinear equations with two unknowns. Such equations can be solved using any suitable technique (Program computer). If the values of the machine parameters, its speed (or frequency), excitation capacitance as well as load impedances are given, the two equations can be solved for the magnetizing reactance and frequency (or speed). On the other hand, if the interest is to find the range of terminal capacitances to sustain self excitation, the two equations can be solved for the frequency (or speed) and these capacitances by specifying the machine parameters, its speed (or frequency), load impedances and the maximum magnetizing reactance Xmg.
Our Program Computer gives evolution of excitation capacitance required as function of speed and load impedance.

2.4 SEIG Modeling:

The model for the SEIG is similar to that of the induction motor. To model the SEIG effectively, the parameters should be measured accurately. The parameters used in the SEIG can be obtained by conducting tests on the induction generator when it is used as a motor. The traditional tests used to determine the parameters are the open circuit (no load) test and the short circuit (locked rotor) test.
In this paper the d-q model is used because it is easier to get the complete solution, transient and steady state, of the self excitation. The parameters given in the d-q equivalent circuit shown in Figure 3 are obtained by conducting parameter determination tests on the above mentioned induction machine. As it is a wound rotor induction machine there is no variation of rotor parameters with speed.
The parameters obtained from the test at rated values of voltage and frequency are $L_{sg}=L'_{rg}=229mH$, $L_{mg}=217mH$, $R_{sg}=2.2\Omega$, $R'_{rg}=2.68\Omega$. For motoring application these parameters can be used directly. However, for SEIG application the variation of L_{mg} with voltage should be taken into consideration.



(a)

(b)

Fig.3 D-Q Model Of SEIG At No Load
a) d-axis b) q-axis

$$\begin{bmatrix} R_{sg}+pL_{sg}+\frac{1}{pC} & 0 & pL_{mg} & 0 \\ 0 & R_{sg}+pL_{sg}+\frac{1}{pC} & 0 & pL_{mg} \\ pL_{mg} & -\omega_r L_{mg} & R'_{rg}+pL'_{rg} & -\omega_r L'_{rg} \\ \omega_r L_{mg} & pL_{mg} & \omega_r L'_{rg} & R'_{rg}+pL'_{rg} \end{bmatrix} \cdot \begin{bmatrix} i_{sq} \\ i_{sd} \\ i_{rq} \\ i_{rd} \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad (19)$$

The initial conditions for self-excitation, namely the remanent magnetic flux in the rotor and/or the initial charge in the capacitors are not considered because they will be cancelled when both sides are differentiated.
Derived from Equation (19) and including initial conditions, i.e. initial voltage in the capacitors and remanent magnetic flux in the core, one can obtain the following differential equation [5]:

$$pI = A.I + B \quad (20)$$

Where:

$$I = \begin{bmatrix} i_{sq} \\ i_{sd} \\ i_{rq} \\ i_{rd} \end{bmatrix} \qquad B = \frac{1}{L}\begin{bmatrix} L_{mg}K_q - L'_{rg}V_{cq} \\ L_{mg}K_d - L'_{rg}V_{cd} \\ L_{mg}V_{cq} - L_{sg}K_q \\ L_{mg}V_{cd} - L_{sg}K_d \end{bmatrix}$$

$$A = \frac{1}{L}\begin{bmatrix} -L'_{rg}R_{sg} & -L^2_{mg}\omega_r & L_{mg}R'_{rg} & -L_{mg}L'_{rg}\omega_r \\ L^2_{mg}\omega_r & -L_{sg}R_{sg} & L_{mg}L'_{rg}\omega_r & L_{mg}R'_{rg} \\ L_{mg}R_{sg} & L_{sg}L_{mg}\omega_r & -L_{sg}R'_{rg} & L_{sg}L'_{rg}\omega_r \\ -L_{sg}L_{mg}\omega_r & L_{mg}R_{sg} & -L_{sg}L'_{rg}\omega_r & -L_{sg}R'_{rg} \end{bmatrix}$$

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And $L = L_{sg} L'_{rg} - L_{mg}^2$

K_d and K_q are constants which represent the initial induced voltages along the d-axis and q-axis respectively due to remanent magnetic flux in the core.

3. RESULTS AND DISCUSSION

The induction machine used as the SEIG in this investigation is a three-phase squirrel cage induction generator with specification: 3Kw, 220/380V, 12.4/7.2A, 50Hz.
This later supplies an induction motor: 1.5Kw, 220/380V, 8/5.6A, 50Hz.
The fixed parameters of both induction machines used in this proposed system are:
R_{sg}=2.2Ω, R'_{rg}=2.68Ω, $L_{sg}=L'_{rg}$=229mH, $L_{mg}=f(I_m)$, p_g=2
R_{sm}=4.85Ω,R'_{rm}=3.80Ω,$L_{sm}=L'_{rm}$=274mH,L_{mm}=258mH, p_m=2.
The residual magnetism in the machine is taken into account in simulation process without which it is not possible for the generator to self excite. Initial voltage in the capacitor is considered.

Table I: Variation Of Frequency With Speed Base Speed=1500rpm

SPEED (PU)	FREQUENCY (PU)	SPEED (PU)	FREQUENCY (PU)
1	0.9987	0.6	0.5978
0.9	0.8986	0.5	0.4974
0.8	0.7984	0.4	0.3967
0.7	0.6982	0.3	0.2955

The critical speed b_c Equation (16) is the speed below which the machine will not operate. For the given machine parameters R_{sg}, R'_{rg}, X_{sg}, X'_{rg}, speed b and magnetizing reactance X_{mg}, Equation (15) was solved to obtain the p.u. frequency a_{max} corresponding to self – excitation and the critical speed b_c was obtained from Equation (16), for each value of p.u speed, the frequency a_{max} was be calculated. Table I. shows the variation of a_{max} for different p.u speeds b with initial value of the reactance X_{mg}=68.138Ω.
We recall that R_M and X_M are the resistive and inductive terms of load impedance

Figures 4 a, b and c respectively show the variation of the capacitance required (µF) with rotor speed (rpm) for different values of R_M (i.e. 0.5, 1, 2) when X_M varies from 0 to infinity.
It is noted that the maximum capacitance value decreases when R_M increases particularly when X_M approaches zero. In steady state, different curves tend to almost the same values of capacitance.

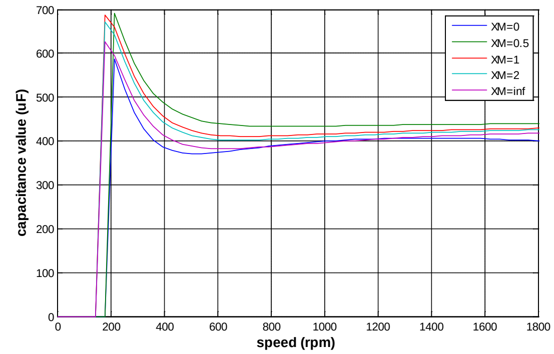

Fig.4 **a- R_M=0.5**

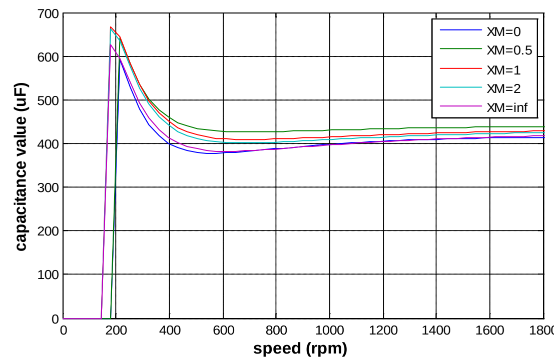

Fig.4 **b- R_M=1**

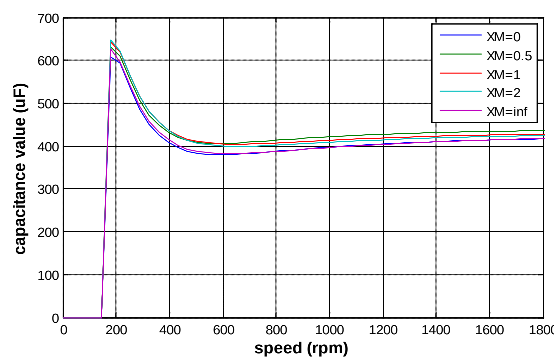

Fig.4 **c- R_M=2**

Fig.4 variation of capacitance required with rotational speed for several value of R_M and X_M:
a-(R_M=0.5) b-(R_M=1) c-(R_M=2)

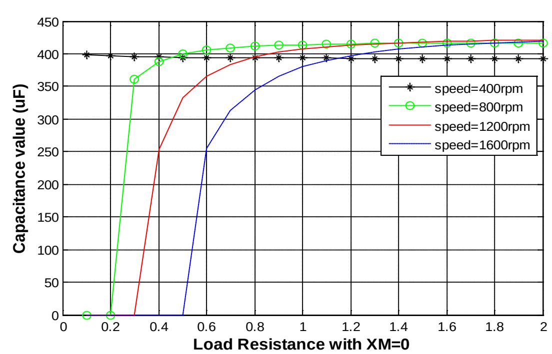

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Fig.5 **a- X_M=0**

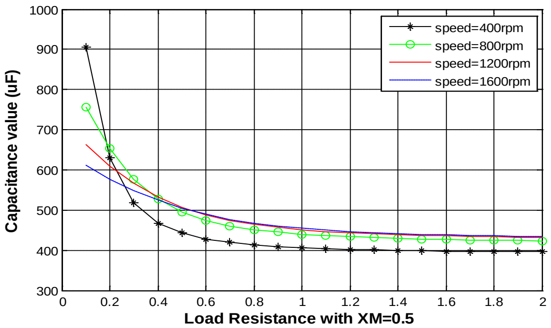

Fig.5 **b- X_M=0.6**

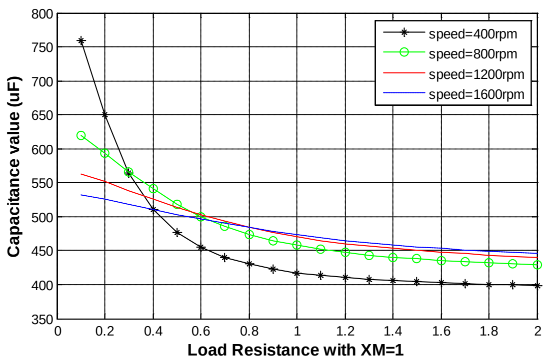

Fig.5 **c- X_M=1**

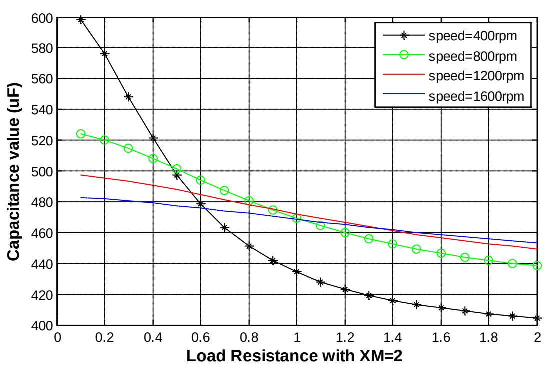

Fig.5 **d- X_M=2**

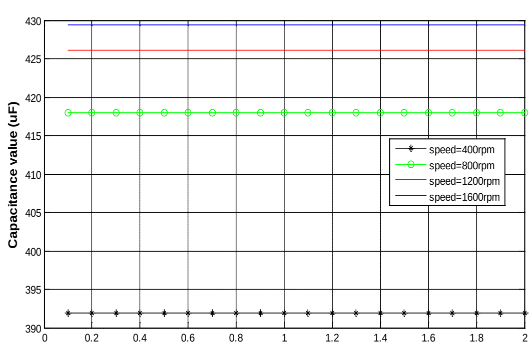

Fig.5 **e- X_M=inf**

Fig.5 Variation Of Capacitance Required With Load Resistance For Several Value Of Speed

Effect of X_M

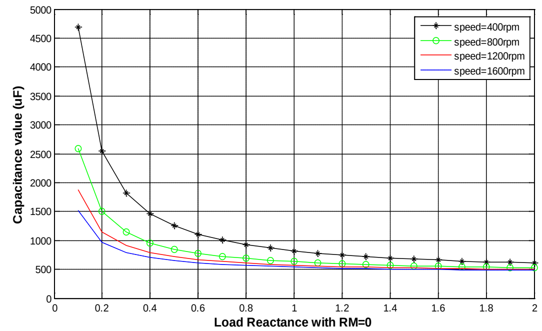

Fig.6 **a- R_M=0**

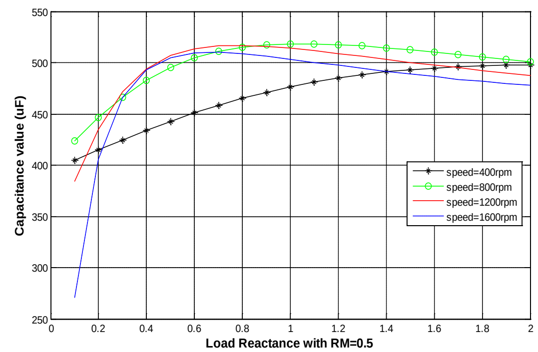

Fig.6 **b- R_M=0.5**

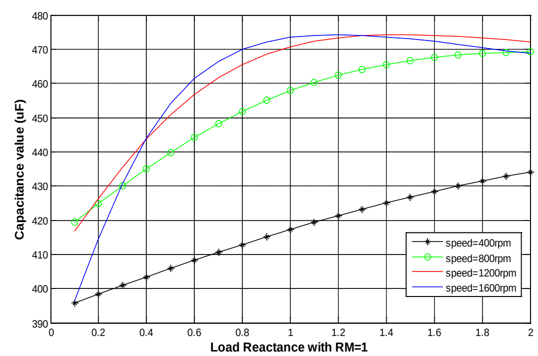

Fig.6 **c- R_M=1**

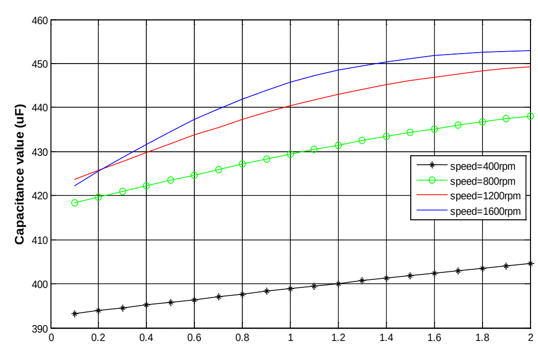

Fig.6 **d- R_M=2**

Fig.6 Variation Of Capacitance Required With Load Reactance For Several Value Of Speed

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Effect of R_M

Figures 5 a, b, c, d and e shows the variation of capacitance required with load resistance when the reactance X_M varies for different values of rotor speed (i .e 400, 800, 1200, 1600 rpm). It is noted that increasing in load reactance requires decreasing capacitance value.

Figures 6 a, b, c and d shows the variation of capacitance required with load reactance when the resistance R_M varies for different values of rotor speed (i .e 400, 800, 1200, 1600 rpm). It is noted that increasing load resistance requires decreasing capacitance value.

In both cases, we also find that the value of the required capacitance also increases with rotor speed.

We see from the figures 4, 5 and 6 that the value of the required capacitance is strongly influenced by the nature of load impedance (resistive, inductive or both).

4. CONCLUSION

Self excitation in induction machine depends on appropriate combination of speed, load and excitation capacitance. In this paper we have shown the relationship between the required capacitance, the rotor speed and the nature of load impedance using a computer program. This program gives typical results without any iteration or divergence problem.

Firstly taking into account the parameters that influence the choice of required capacitance, on the other hand due to their simplicity, ruggedness and low cost of construction, squirrel-cage induction machine is a relatively inexpensive alternative to ac generation using wind power for voltage and frequency insensitive loads.

APPENDIX

TABLE II
INDUCTION GENERATOR PARAMETERS

Rated power	3 KW
Voltage	380V Y
Frequency	50 Hz
Pair pole	2
Rated speed	1400 rpm
Stator resistance	2.2 Ω
Rotor resistance	2.68 Ω
Inductance stator	229 mH
Inductance rotor	229 mH
Mutual inductance	217 mH
Moment of Inertia	0.046 kg.m^2

Table III: Induction Motor Parameters

Rated power	1.5 KW
Voltage	380V Y
Frequency	50 Hz
Pair pole	2
Rated speed	1440 rpm
Stator resistance	4.85 Ω
Rotor resistance	3.805 Ω
Inductance stator	274mH
Inductance rotor	274 mH
Mutual inductance	258 mH
Moment of Inertia	0.031 kg.m^2

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