EXCITATION REQUIREMENTS FOR STAND ALONE THREE-PHASE INDUCTION GENERATOR

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Abstract— **Self excitation in induction machine depends on appropriate combination of speed, load and excitation capacitance. This paper presents direct methods derived from Loop and Nodal analyses to find different criteria for maintaining self excitation. Unlike available techniques, the inverse– model for the steady state equivalent circuit has been used. This is found to be of much assistance in the analysis. Besides determination of speed limits for fixed terminal parameters, and capacitance requirement under varying speed and load, a method to test the possibility of self excitation for known speed, load and terminal capacitance has also been presented.**

I. INTRODUCTION

In a stand alone 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]-[9]. These studies have mainly given emphasis on the methods (direct or indirect) to obtain minimum capacitance values for sustained self excitation. Grantham et. al. [7] and Tandon et. al. [5] studied the onset of self excitation and minimum capacitance requirements based on the characteristic polynomial obtained from transient representation of the machine. This method requires sets of results,obtained from the numerical solution to the characteristic polynomial satisfying certain criteria, before inferring on the minimum capacitance at which self excitation occurs for a particular speed and load.

Malik and Mazi [3] suggested an indirect procedure, based on the steady state equivalent circuit model, to test the self-excitation of an induction generator. The indirect methods involve solutions requiring some initial guess in a trial and error procedure.

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Al-Jabri and Alolah [8] and Chan [9] presented direct methods to test the self-excitation of an induction generator and compute the minimum capacitance for self-excitation. However, without detailed computation, both the methods do not suggest any criterion to test the self-excitation for any combination of speed, load and excitation capacitor, and also do not present the cut-off speed for given terminal parameters, viz. load and excitation capacitor, though an expression for a threshold speed is given, below which the generator fails to excite irrespective of the value of capacitance used.

In a different publication Al-Jabri and Alolah [10] dealt with different limiting aspects based on per phase steady state T-form equivalent circuit.

II. OBJECTIVES

This paper re-examines the self-excitation requirements and in the process presents, in a direct way, various criteria that have to be satisfied to initiate voltage build up under various combinations of speed, load and terminal capacitances. These criteria involve no trial and error procedure. In their approaches for steady state analysis and for computing minimum capacitance requirement for self excitation earlier investigators [1]-[10] have used the conventional representation of the machine by the familiar T-form equivalent circuit and the load by a R-L series circuit. The T-form circuit models are actually more complex than necessary. They can be transformed to simpler models [11]. Since actual rotor variables are not required, the inverse-Γ model, can be applied for analysis of self excited induction generators with no loss of information and accuracy. This inverse-Γ circuit model conveniently leads to the formulation of requirements for self-excitation and the limits of operation, besides yielding the minimum capacitance requirements and the corresponding output frequency under both load and no-load conditions. Closed form expressions are provided for such purposes. Besides, the cut-off speed below which the machine fails to build up irrespective of the capacitance used, the speed dependent critical load and load dependent critical speed below which the excitation is not possible, exist. It is shown further that at a particular speed there exists a limit of the ratio of effective capacitance to load, below which the excitation is not possible.

Furthermore, for the non-unity power factor load, all publications consider a series R-L circuit. Not only does it lead to tedious elaboration of the equations but also makes closed form equations difficult to obtain. Since a generator load can also be represented by an equivalent parallel

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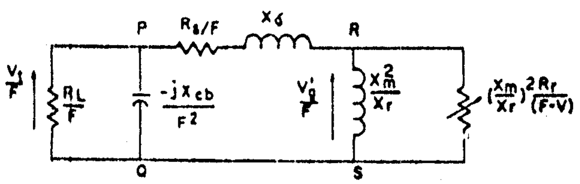

Fig.1 Per phase steady state equivalent circuit (Inverse-Γ model).

R-L circuit, it is sufficient to derive equations for resistive load only. Then all the results arising from non-unity power factor can easily be extracted from the net capacitive reactance required for the supply of leading VAR. This simplifies the procedure very much for analysis.

III. STEADY STATE EQUATIONS

A. Circuit Models

The per phase steady-state inverse-Γ circuit model [11] for self excited induction generator, supplying a balanced resistive load is shown in Fig.1. Machine parameters are referred to the stator and mapped in terms of base frequency (f_b). All parameters are assumed to be constant except the magnetizing reactance X_m, which is affected by saturation. L_σ, the transient inductance of the machine, very closely equals the sum of the stator and the rotor leakage inductances.

B. Loop Impedance Method

There is no emf source, and hence, for the stator current to exist under self excited state, the sum of the impedances around the loop PRSQ in Fig.1 must be zero, i.e.,

$$Z_{PQ} + Z_{PR} + Z_{RS} = 0 \tag{1}$$

By equating the real and imaginary parts of (1) to zeros, the following two equations are obtained

$$\frac{R_s}{F} + \frac{R_r X_m^2 (F-v)}{R_r^2 + (F-v)^2 X_r^2} + \frac{\tau X_{cb}}{F(F^2+\tau^2)} = 0 \tag{2}$$

$$X_\sigma + \frac{R_r^2 X_m^2}{X_r[R_r^2 + (F-v)^2 X_r^2]} - \frac{X_{cb}}{(F^2+\tau^2)} = 0 \tag{3}$$

where

$$\begin{aligned} \tau &= \frac{X_{cb}}{R_L}, \\ X_\sigma &= X_{ls} + (\frac{X_m}{X_r})X_{lr}, \\ and X_r &= X_m + X_{lr} \end{aligned}$$

C. Nodal Admittance Method

The key unknown in determining the performance of an induction generator for given speed and load is the stator frequency. Without simultaneous iterative solution of the two equations, viz. (2) and (3), F, and X_{cb} can not be obtained for an assumed value of X_m. By the nodal admittance method the load and the excitation capacitance branch can be decoupled [8],[9], and the p.u. frequency F can be determined from a single equation without any reference to the reactance of the capacitive branch.

At the node P of the equivalent circuit in Fig.1,the sum of the currents equals to zero,

$$(Y_L + Y_C + Y_{PS})V_P = 0 \tag{4}$$

where

$$\begin{aligned} Y_L &= \frac{1}{R_L} \\ Y_C &= J\left(\frac{F}{X_{cb}^2}\right) \\ Y_{PS} &= \frac{1}{\left[\frac{R_s}{F} + jX_\sigma + \left(j\frac{X_m^2}{X_r} || \left(\frac{X_m^2}{X_r^2}\frac{R_r}{F-v}\right)\right)\right]} \end{aligned}$$

V_P cannot be equal to zero for successful voltage build up, it follows

$$(Y_L + Y_C + Y_{PS}) = 0 \tag{5}$$

Equating the real and imaginary parts independently to zero, the following equations are obtained

$$\frac{F}{R_L} + \frac{R_{PS}}{R_{PS}^2 + X_{PS}^2} = 0 \tag{6}$$

$$\frac{F^2}{X_{CB}} - \frac{X_{PS}}{R_{PS}^2 + X_{PS}^2} = 0 \tag{7}$$

where

$$\begin{aligned} R_{PS} &= \frac{R_S}{F} + \frac{(F-v)R_r' X_m'^2}{R_r'^2 + (F-v)^2 X_r'^2} \\ X_{PS} &= X_\sigma + \frac{R_r'^2 X_m'}{R_r'^2 + (F-v)^2 X_r'^2} \end{aligned}$$

in which

$$\begin{aligned} X_m' &= \left(\frac{X_m^2}{X_r}\right) \\ R_r' &= \left(\frac{X_m^2}{X_r^2}\right) R_r \end{aligned}$$

Equation (6) after much elaboration reduces to a 6th degree polynomial in F

$$A_6F^6 + A_5F^5 + A_4F^4 + A_3F^3 + A_2F^2 + A_1F + A_0 = 0 \tag{8}$$

The detailed expressions for the coefficients (A_0 to A_6) are available in the Appendix.

Equation (8) can be solved numerically. Only the positive real roots will indicate the excitation frequency. Substitution of these values of F in equation (9) (a re-arranged form of equation (7)), gives the corresponding set of capacitor values to make the induction generator operate at these frequencies. Minimum value of capacitance corresponds to the largest of the positive roots and gives feasible capacitor size. Other value is impractical in the sense that the excitation current goes well beyond the rated current of the machine.

$$X_{cb} = \left(\frac{R_{PS}^2 + X_{PS}^2}{X_{PS}}\right) F^2 \tag{9}$$

IV. CRITICAL COMBINATION OF SPEED, LOAD AND EXCITATION CAPACITANCE

A. Development of Relations

For successful self excitation, the machine has to operate in the saturated zone. The minimum value of the magnetizing KVA corresponds to the magnetization that just keeps the machine in the unsaturated zone ($X_m = X_{mu}$). Equations (2) and (3), when combined, yield the following quadratic equation in F

$$s_2F^2 + s_1F + s_0 = 0 \qquad (10)$$

where

$$\begin{aligned} s_2 &= bX_r^3 + R_rX_m^2X_r \\ s_1 &= -v(2bX_r^3 + R_rX_m^2X_r) \\ s_0 &= b(v^2X_r^3 + R_r^2X_r) + \tau R_r^2X_m^2 \end{aligned}$$

in which

$$b = \tau X_\sigma + R_s$$

Equation 10) has two roots given by

$$F_1, F_2 = \frac{-s_1 \pm \sqrt{s_1^2 - 4s_2s_0}}{2s_2} \qquad (11)$$

Roots will be real when

$$(s_1^2 - 4s_2s_0 \geq 0 \qquad (12)$$

Upon substitution of the expressions for s_2, s_1 and s_0, the inequality (12), after proper algebraic manipulation assumes the form

$$\tau^2 + (K_1 + K_2)\tau - (K_3 - K_1K_2) \leq 0 \qquad (13)$$

The expression for K_1, K_2 and K_3 are as follows.

$$\begin{aligned} K_1 &= \frac{\left[R_s + R_r\left(\frac{X_m}{X_r}\right)^2\right]}{X_\sigma} \\ K_2 &= \frac{R_sX_r}{X_rX_\sigma + X_m^2} \\ K_3 &= \frac{X_m^4v^2}{4(X_rX_\sigma + X_m^2)X_\sigma X_r} \end{aligned}$$

K_1, K_2 and K_3 are all positive quantities. As τ has to be positive quantity the inequality (13) requires

$$K_1K_2 \leq K_3 \qquad (14)$$

Substituting the expressions for K_1, K_2 and K_3 yields

$$v \geq \left[\frac{4R_s(R_sX_r^2 + R_rX_m^2)}{X_m^4}\right]^{1/2} \qquad (15)$$

Inequality (15) reveals that there exists a cut-off speed below which the generator will never excite irrespective of any combination of R_L and X_{cb}. This cut-off speed is thus

$$v_c = \left[\frac{4R_s(R_sX_r^2 + R_rX_m^2)}{X_m^4}\right]^{1/2} \qquad (16)$$

Incidentally, this expression for cut-off speed v_c agrees with that given in [8]. Inequality (15) is a necessary condition but not sufficient. Inequality (13) implies that to ensure voltage build up the terminal resistance, capacitance and inductance combination at a given speed must satisfy the condition

$$K_3 > \tau^2 + \tau(K_1 + K_2) + K_1K_2 \qquad (17)$$

i.e.,

$$v^2 > \frac{4[\tau^2 + \tau(K_1 + K_2) + K_1K_2](X_rX_\sigma + X_m^2)X_\sigma X_r}{X_m^4} \qquad (18)$$

The minimum p.u. speed v_{min} above which the induction generator will self excite for specific ratio of effective capacitive reactance (at base frequency) to load resistance is thus given by

$$v_{min} = \left[\frac{4[\tau^2 + \tau(K_1 + K_2) + K_1K_2](X_rX_\sigma + X_m^2)X_\sigma X_r}{X_m^4}\right]^{\frac{1}{2}} \qquad (19)$$

Equation (19) specifies the minimum speed required for a given value of τ for the machine to self-excite, and by (11) the stator terminal frequency at this minimum speed takes the value

$$F = -s_1/(2s_2) \qquad (20)$$

τ is not a direct physical variable. The same value of τ may be had with different combinations of X_{cb} and R_L, hence $\tau = \tau_m$ does not furnish the critical values of X_{cb} or R_L. τ equals zero indicates either $X_{cb} = 0$ or $R_L = \infty$. As $X_{cb} = 0$ means a short circuit condition, hence this is not applicable for study of self excitation. So τ equals zero describes the no load condition, frequency and capacitance of which may be obtained from Fig.2 and 3 respectively.

The computational procedure to separate X_{cb} and R_L for an assumed value of τ for the machine to just build up voltage (i.e. $X_m = X_{mu}$) at a given speed v is as follows:
Step:1 Assume a value of τ and determine F by (20).
Step:2 Use the assumed value of t and the corresponding values of F in (2) or (3) to obtain X_{cb}.
Step:3 Evaluate R_L from τ and X_{cb}.

B. Application of Equations

Based on the computational procedure, outlined above for separation of X_{cb} and R_L for a given τ, the limiting loci of operation (w.r.t. X_{mu}) were calculated for Machine-1 whose parameters are listed in Appendix. The results are shown in Figs.2 through 4. The plots give the ranges of p.u. frequency(F), capacitance (in terms of X_{cb}), and load resistance(R_L) for assumed speeds of 0.8, 1.0 and 1.2 p.u. In all the three cases magnetizing reactance (X_m) is made equal to X_{mu}, the independent variable being τ. From the plots it is evident that τ varies over a limited range. In other words for the machine to build up voltage there is a maximum value of τ (τ_{max}) i.e. the ratio $\frac{X_{cb}}{R_L}$, above which self excitation will not occur. The limiting frequency at (τ_{max}) is given by (20). τ_{max} depends on the parameters and speed of the machines. τ_{max} increases with

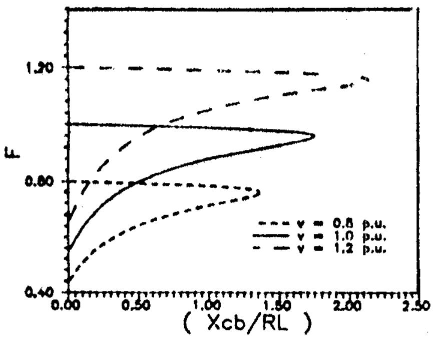

Fig.2 F vs. τ for different speeds.

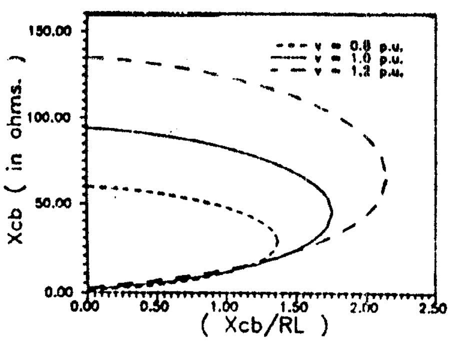

Fig.3 X_{cb} vs. τ for different speeds.

the increase in speed. Fig.4 further reveals that for a given speed there is a minimum value of R_L (R_{Lmin}) below which self excitation fails and this R_{Lmin} increases with increase in speed. Although the machine could go into self excitation mode for $X_m = X_{mu}$ the reliability of operation demands that the magnetizing state of the machine should be well within saturation. Figs.5 through 7 show the variation of F, X_{cb} and R_L as a function of τ for increased saturation at 1.0 p.u. speed. With the decrease in X_m, i.e. with increased saturation level, the range of τ for the machine to build up shrinks and at $\tau = \tau_{max}$ the single value of F is again given by (20).

V. SPEED LIMITS FOR SELF EXCITATION UNDER FIXED TERMINAL PARAMETERS

A. Formulation of basic equations and its solutions

It may not always be feasible to continuously vary the excitation capacitor value to cope up with changing operating condition, and load may even remain fixed while the machine speed changes. Under such condition it is necessary to investigate the speed limits between which the machine is capable to build up voltage for given load and excitation capacitor. Basic steady state equations (2) and (3), or (8) and (9), are not in the appropriate forms to bring out this limiting features. It is therefore necessary to develop equations in a suitable form for the purpose of carrying out such investigations.

Elimination of the terms involving $R_r^2 + (F-v)^2X_r^2$ from (2) and (3) yields the following quadratic equation in F^2

$$F^4 + p_1F^2 + p_0 = 0 \tag{21}$$

where

$$\begin{aligned} p_1 &= \tau^2 - \tau - R_sR_r/(X_\sigma X_r) - X_{cb}/X_\sigma \\ p_0 &= \gamma X_{cb}/X_\sigma - R_rX_{cb}\tau/(X_\sigma X_r) \\ &\quad - \tau^2(R_sR_r/(X_\sigma X_r) + \gamma) \end{aligned}$$

in which the quantity γ is defined as

$$\gamma = Fv \tag{22}$$

Replacing v in (10) by $\frac{\gamma}{F}$ leads to the following quadratic equation in F^2

$$F^4 + q_1F^2 + q_0 = 0 \tag{23}$$

where

$$q_0 = \frac{(\tau X_\sigma + R_s)X_r^3\gamma^2}{(\tau X_\sigma + R_s)X_r^3 + R_rX_rX_m^2}$$

$$q_1 = \frac{(\tau X_\sigma+R_s)X_rR_r^2+\tau R_r^2X_m^2-2(\tau X_\sigma+R_s)X_r^3\gamma-R_rX_rX_m^2\gamma}{(\tau X_\sigma+R_s)X_r^3+R_rX_rX_m^2}$$

Equations (21) and (23) are not identical equations. They must have a common positive root in the case of self excitation of the induction generator. If α be the common root, it follows that

$$\begin{aligned} \alpha^2 + p_1\alpha + p_0 &= 0 \\ \alpha^2 + q_1\alpha + q_0 &= 0 \end{aligned} \tag{24}$$

where

$$\alpha = F^2$$

Eliminating α from the set in (24) gives

$$p_1^2q_0 + q_1^2p_0 - p_1q_1(p_0q_0) - 2p_0q_0 + p_0^2q_0^2 = 0 \tag{25}$$

Upon substitution of the expressions for p's and q's, as given by (21) and (23), and after much elaboration the following cubic equation is obtained

$$b_3\gamma^3 + b_2\gamma^2 + b_1\gamma + b_0 = 0 \tag{26}$$

The detailed expressions of the coefficients (b_0 to b_3) are available in Appendix.

Further it follows from (24) that the common root α is

$$\alpha = \frac{p_0 - q_0}{q_1 - p_1} \tag{27}$$

which is in fact, the square of p.u. frequency. Solution to (26) for given R_L and X_{cb} determines γ, while (27) gives α, i.e. F^2. Knowing the values of F and γ, speed can be obtained from (22).

B. Application of Equations

For the same machine Fig.8 and 9 show the variation of speed and per unit frequency with R_L respectively for 30μF, 60μF and 120μF capacitances connected across the load. Plots show that for any combination of load and excitation capacitor there exists speed range ("cd"s in Fig.8) which shrinks with increase in load. At any speed between

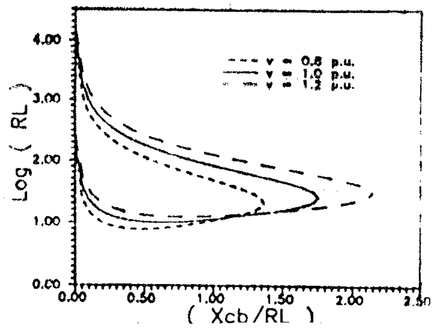

Fig.4 R_L vs. τ for different speeds.

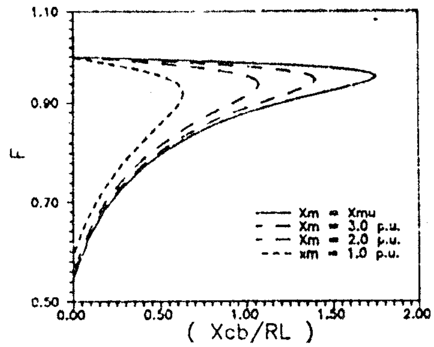

Fig.5 F vs. τ for different X_m.

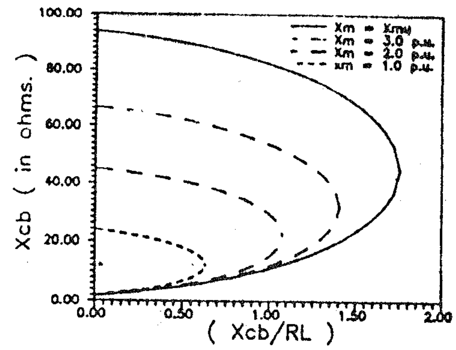

Fig.6 X_{cb} vs. τ for different X_m.

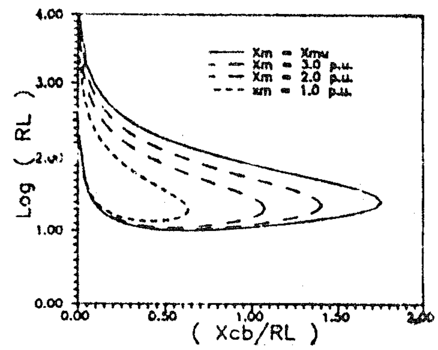

Fig.7 R_L vs. τ for different X_m.

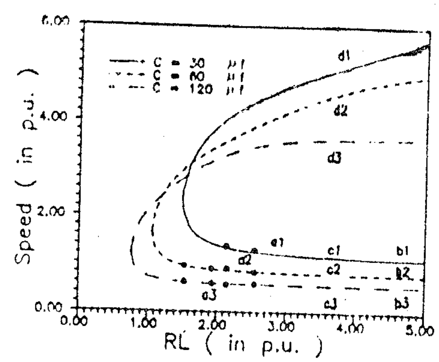

Fig.8 Speed vs. R_L for different excitation capacitance. experimental points

these limits self excitation will be sustained and the magnetizing reactance will be set at a value below X_{mu}. This is revealed in Fig.10. Working at increased saturation level, i.e. at lower value of X_m, affects the lower value of speed range but hardly influences the upper speed limit. The upper speed limit is found abnormally high and is thus of theoretical interest only.

Fig.8 further reveals that for a definite value of capacitance there exists a critical value of load resistance (R_{Lccap}), below which self excitation is not possible. R_{Lccap} decreases with the increase in capacitance. Except close to R_{Lccap} "ab" portions of the plots indicate that the minimum speed to maintain excitation is mainly dependent on capacitance and is not significantly affected by the load and this lower bound of speed decreases with increases in the value of excitation capacitance.

Figs.11 and 12 present the plots of speed limits and p.u. frequency respectively as a function of capacitance for three different load resistances. It gives load dependent critical value of capacitance (C_{cl}) below which self excitation would not occur at any value of speed. C_{cl} decreases with increase in the load resistance. It further exposes a minimum excitation speed for a given load resistance below which voltage build-up will not take place irrespective of the size of the capacitor. Lower traces of the plots in Fig.11 become asymptote to the straight line curve given by $v = v_c$ (vide (16)).

VI. SELF EXCITATION WITH SPECIFIC LOAD RESISTANCE

Results of study in the two sections above do not explicitly bring out the bounds in respect of speed, if there be any, for the machine to remain self excited with any specific load resistance.

Analyses and computational procedures outlined under section IIIC are of much assistance in this regard. Plots in Fig.13 based on (8) and (9) show the minimum capacitor values, just required for voltage build up, against speed for a few specific load resistances.It is seen that for each load resistance there exists a minimum and maximum speed beyond which voltage build up with that specific terminal resistance is not possible irrespective of capacitor sizes. Upper bound increases with increase in the load resistance. A critical value of speed exists below which no excitation is possible for any combination of load and capacitance. This is the cut-off speed and is in agreement with the value

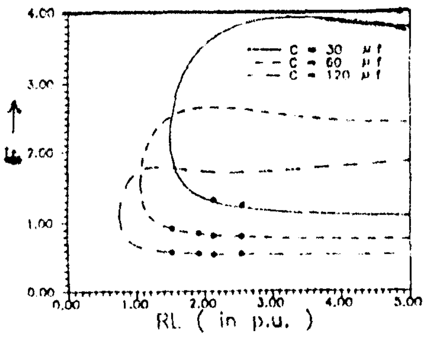

Fig.9 F vs. R_L for different excitation capacitance.
• experimental points

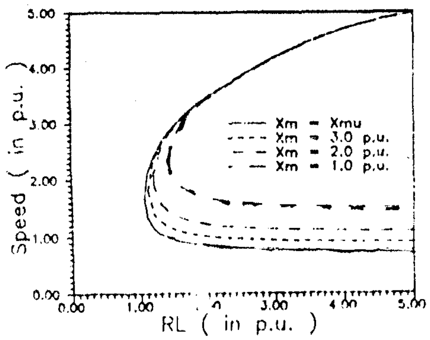

Fig.10 Speed vs. R_L for different X_m.

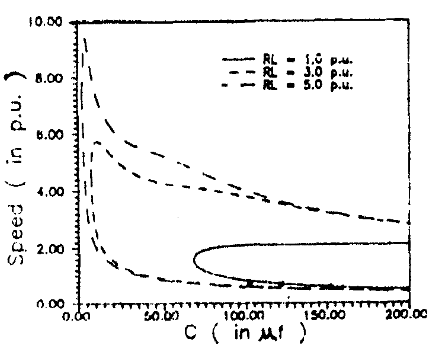

Fig.11 Speed vs. Capacitance for different R_L.
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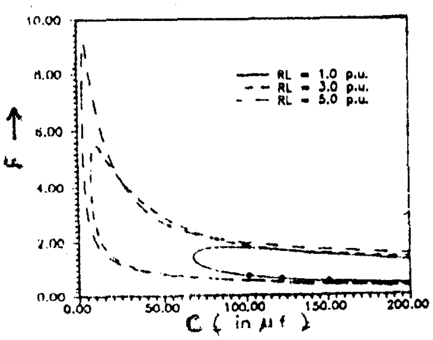

Fig.12 F vs. capacitance for different R_L.
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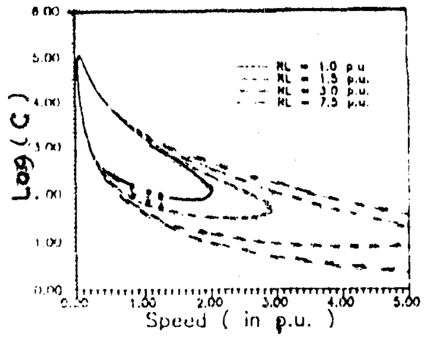

Fig.13 Capacitance vs. speed for different R_L.
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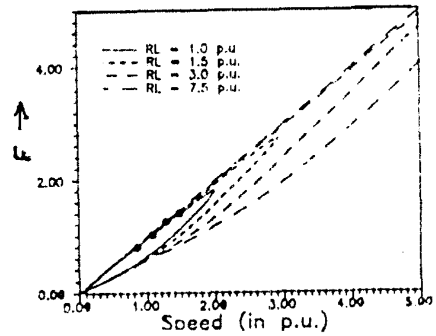

Fig.14 F vs. speed for different R_L.
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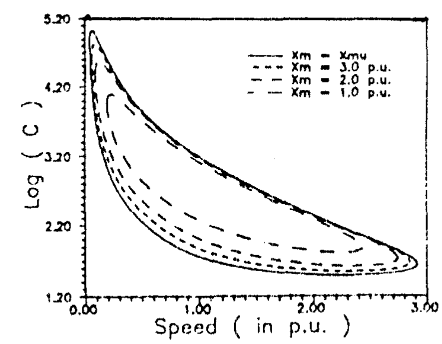

Fig.15 Capacitance vs. speed for different X_m.

given by (16). However, this speed being very low is of no practical interest. The terminal frequency corresponding to Fig.13 is shown in Fig.14. Fig.15 shows the effect of increasing the minimum allowable saturation state of the machine on the speed and capacitor bounds within which the machine can sustain self excitation. Operating speed and capacitor ranges decrease.

The capacitance vs. R_L plot is shown in Fig.16, which reflects the existence of speed dependent critical resistance (R_{Lcspd}). Machine with load resistance less than this will not build up. This is in agreement with the investigation in [9] and plots in Fig.8. It is interesting to note that R_{Lcspd} increases with increase in speed. The corresponding value of frequency (F) may be obtained from Fig.17. The effect

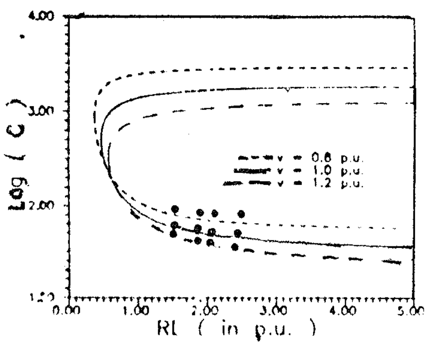

Fig.16 Capacitance vs. R_L for different speeds.
• experimental points

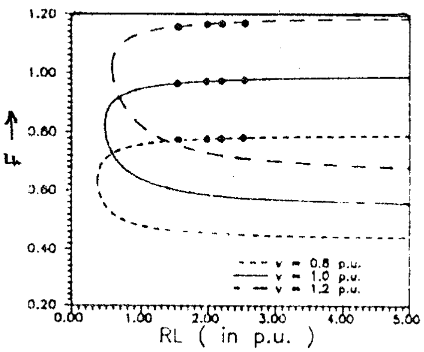

Fig.17 F vs. R_L for different speeds.
• experimental points

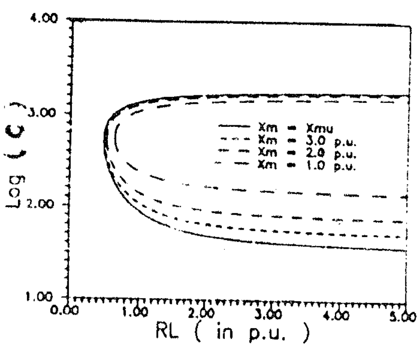

Fig.18 Capacitance vs. R_L for different X_m.

of saturation is studied in Fig.18 for a speed of 1 p.u. As is obvious capacitance demand increases with the increase in saturation for a constant value of speed and R_L.

VII. CONCLUSION

The paper has described an application of the inverse-Γ model of the induction machine to study its excitation criteria as a three-phase induction generator. The analytical results obtained are verified with the experimentally obtained curves. It has been shown that a proper combination of speed, load and terminal capacitance can only guarantee self excitation in induction machines. The novel approach reveals different limiting features that can be summerised as follows:

- For any combination of terminal parameters and speed, it has been shown that the ratio of effective capacitance to load resistance should be lower than the corresponding maximum value.
- The range of operating speed for different values of load resistance and terminal capacitance has been found. For a constant value of capacitance, the speed range decreases with decrease in load resistance and also there exists a critical value of load resistance below which self excitation fails. The value of this critical resistance decreases with the increase in capacitance. From the plot of speed vs. capacitance, the load dependent critical value of capacitance below which self excitation is not possible is also found. This critical capacitance value decreases with increase in the value of load resistance.
- The capacitance vs. speed plot reveals the existence of load dependent critical value of speed below which no value of capacitance could excite the machine. The capacitance vs. load resistance plot reflects the existence of speed dependent critical resistance, which increases with the increase in speed.

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APPENDIX

Co-efficients of (8) are

$$A_0 = g_3^2 + R_L g_3 f_3$$

$$
\begin{aligned}
A_1 &= 2g_2g_3 + R_L(g_2f_3 + g_3f_2)\\
A_2 &= g_2^2 + h_3^2 + 2g_1g_3 + R_L(g_1f_3 + g_2f_2 + g_3f_1)\\
A_3 &= 2g_1g_2 + 2h_2h_3 + R_L(f_2g_1 + g_2f_1)\\
A_4 &= g_1^2 + h_2^2 + 2h_1h_3 + R_Lg_1f_1\\
A_5 &= 2h_1h_2\\
A_6 &= h_1^2
\end{aligned}
$$

where

$$
\begin{aligned}
g_1 &= R_sf_1 + f_4 & h_1 &= X_\sigma f_1\\
g_2 &= R_sf_2 + f_5 & h_2 &= X_\sigma f_2\\
g_3 &= R_sf_3 & h_3 &= X_\sigma f_3 + f_6\\
f_1 &= \left(\frac{X_m^2}{X_r}\right)^2 & f_2 &= -2v\left(\frac{X_m^2}{X_r}\right)^2
\end{aligned}
$$

$$
\begin{aligned}
f_3 &= R_r^2\left(\frac{X_m}{X_r}\right)^2 + v^2\left(\frac{X_m^2}{X_r}\right)^2\\
f_4 &= R_r\left(\frac{X_m}{X_r}\right)^2 + \left(\frac{X_m^2}{X_r}\right)^2\\
f_5 &= -vf_4 \qquad f_6 = R_r'^2\left(\frac{X_m}{X_r}\right)^2\left(\frac{X_m^2}{X_r}\right)
\end{aligned}
$$

Co-efficients of (27) are

$$
\begin{aligned}
b_0 &= d_2d_3^2 - d_1d_2d_3 - d_2^2\\
b_1 &= 2c_3d_2d_3 + 2c_2d_2 - c_2d_3^2 + c_3d_1d_2 + c_1d_2d_3 + c_2d_1d_3\\
b_2 &= 2c_2c_3d_3 - 2c_4d_2 + c_4d_1d_3 + c_3^2d_2 - c_4d_1^2 - c_1c_3d_2\\
&\quad - c_2c_3d_1 - c_1c_2d_3 - c_2^2\\
b_3 &= 2c_2c_4 + 2c_1c_4d_1 - c_1c_4d_3 - c_3c_4d_1 - c_2c_3^2 + c_1c_2c_3
\end{aligned}
$$

where

$$
\begin{aligned}
c_1 &= 1 \qquad c_2 = \frac{X_rX_{cb} - X_\sigma X_r\tau^2}{X_\sigma X_r}\\
c_3 &= \frac{2(\tau X_\sigma + R_s)X_r^3 + R_rX_rX_m^2}{(\tau x_\sigma + R_s)X_r^3 + R_rX_rX_m^2}\\
c_4 &= \frac{(\tau X_\sigma + R_s)X_r^3}{(\tau X_\sigma + R_s)X_r^3 + R_rX_rX_m^2}\\
d_1 &= \tau^2 - \frac{R_sR_r + X_rX_{cb}}{X_\sigma X_r}\\
d_2 &= \frac{R_rX_{cb}\tau + R_sR_r\tau^2}{X_\sigma X_r}\\
d_3 &= \frac{(\tau X_\sigma + R_s)X_rR_r^2 + \tau R_r^2X_m^2}{(\tau X_\sigma + R_s)X_r^3 + R_rX_rX_m^2}
\end{aligned}
$$

Machine Rating and Parameters:
Ratings: 400 Volts, 10.9 Amps., 7.5 HP, 4 Poles.
Parameters: $R_s = 1.23\Omega$, $R_r = 1.105\Omega$, $X_{ls} = X_{lr} = 2.756\Omega$, $X_{mu} = 91.2\Omega$

BIOGRAPHIES

Chandan Chakraborty was born on August 17, 1965 in Calcutta. He received B.E.E.(Hons) and M.E.E. degree from Jadavpur University, Calcutta and PhD degree from IIT, Kharagpur in 1987. 1989 and 1996 respectively. Since 1993, he is a Lecturer in Electrical Engineering at the Jadavpur University. Dr. Chakraborty is a Member of IEEE and he has published several papers in reputed Journals and Conference Records, one of which has been awarded the Tata Rao Prize by IE(India). He is now in Japan on a Post Doctoral Scholarship. His main areas of interest are Electric Machines, Power electronics and Electric drives.

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Ajit K. Chattopadhyay (SM'83, F'91) received the B.E.degree in Electrical Engineering from Calcutta University(B.E.College), M.Tech. degree in Elec- trical Machines from the IIT, Kharagpur and the PhD degree from the University of Manchester, England in 1958, 1963 and 1971 respectively.After working for more than one year in GKW Ltd,Howrah and for sometime in the ISI, New Dehli, he joined the Electrical Engineering Department of the IIT,Khragpur in 1960, became a Professor in 1976 and the Head of the Department during 1992-95. During1969-71, he was engaged in research work in the field of thyristor drives at UMIST, Manchester as a Colombo plan Study Fellow. In 1972, he established a Power Electronics Laboratory at IIT, Kharagpur and pioneered M.Tech. course and Ph.D. research programs in this area. He has supervised so far 10 PhD projects, 25 M.Tech projects and authored over 90 research papers in International/National Journals and Conference records in the field of electrical machines, power electronics and microprocessor-based control of dc and ac drives. During 1980-81, he was a Visiting Professor at the University of Technology,Baghdad, Iraq. He has acted as a Consultant-in charge of several sponsored industrial projects and filed four patent applications. He organised a number of continuing education programs on Power Electronics & Drives and was the Co-ordinator of the first National Workshop on Power Electronics-Industry and Academic interaction held at IIT, Kharagpur in May, 1988.

For his outstanding contribution in Power electronics, Dr Chattopadhyay received the Bimal Bose Award in 1986 from IETE(I.He was elected IEEE Fellow in 1991 'for the leadership in the development of Power Electronics Research and Educational programs in India'.He is a Fellow of the National Academy of Engineering,a Life fellow of the IE(I) and the IETE(I).He was awarded the Bhartia Cutler Hammer prize in 1986,the Tata Rao Prize (1993-94) and a Certificate of Merit (1992) from IE(I) for his papers.He has served on the program committes of many international conferences and chaired many technical sessions in India and abroad. He has authored two complete video courses in Machine Drives & Power Electronics. He is listed in several International Biographies.Since July, 1996, Dr Chattopadhyay has joined the Electrical Engineering Department, Bengal Engineering College(Deemed university), Howrah, as an AICTE Emeritus Fellow.