



Estimation of saturation in grid connected induction generator

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ABSTRACT : Prediction of the saturation level and henceforth finding the value of magnetizing reactance ' X_m ' is the first need for accurate estimation of steady state performance of grid connected induction generator (GCIG). Study reveals that most of the research persons adopt the unsaturated value for magnetizing reactance for the steady state analysis of such machines. Whereas in this paper an iterative technique is proposed to predict the saturated values of magnetizing reactance with change in operating conditions. The comparison between experimental and simulated results proves the validity of technique proposed. Further efforts have been made to predict the operating limits of machine using proposed modeling. Analysis has been extended to identify effectiveness of the machine parameters to improve the operating performance of the generator. The results are presented and inferences are drawn to suggest guidelines for real design problems in GCIG.

Keywords : Asynchronous Generator, Grid Connected Induction Generator, Iterative Technique, Steady State Analysis, Wind Energy Conversion

NOMENCLATURE

E_1	=	Air gap voltage per phase
I_1	=	Stator current per phase
I_{1real}	=	Real part of I_1
I_{1imag}	=	Imaginary part of I_1
I_2	=	Rotor current per phase
I_{2real}	=	Real part of I_2
I_{2imag}	=	Imaginary part of I_2
I_m	=	Magnetizing current per phase
pf	=	power factor
P_{fw}	=	Friction and windage losses
P_g	=	Air gap power
P_{in}	=	Input Power
P_m	=	Mechanical Power
P_{out}	=	Output power
P_r	=	Rotational losses (friction, windage and core losses)
P_{rcu}	=	Rotor copper losses
P_{score}	=	Stator core losses
P_{scu}	=	stator copper losses
R_1	=	Stator resistance per phase
R_2	=	Rotor resistance per phase referred to stator
s	=	Slip
V_1	=	Terminal voltage per phase
X_1	=	Stator leakage reactance per phase
X_2	=	Rotor leakage reactance per phase referred to stator
X_m	=	Magnetizing reactance per phase

I. INTRODUCTION

Recently considerable attention is being focused on environmentally clean and safe renewable energy sources like wind, solar, hydro etc. The fast depletion of fossil fuels and our over dependence on them is believed to soon bring the wheels of our civilization to screeching halt. Henceforth at this juncture the need is being felt for relevant technological efforts in order to tap the vast potential energy

of hydro, wind etc. available in isolated locations. The use of an induction generator [1] in general and squirrel cage induction generator in particular for such applications in remote, unattended and maintenance free sites is earning more favors over that of the synchronous alternators. 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, reduced maintenance, rugged and brushless rotors, absence of a separate d.c. source for excitation, absence of moving contacts, inherent overload protection, improved performance due to low transient impedance, natural protection against short circuit etc.

Two modes of operation can be employed for an induction generator. One is through self-excitation and other is through external-excitation. In first mode, the induction generator takes its excitation from VAR generating units, generally realized in the form of capacitor banks. With suitable capacitors connected across the terminals and with rotor driven in either direction by a prime mover, voltage builds up across the terminals of the generator due to self excitation phenomenon leaving the generator operating under magnetic saturation at some stable point. Such generator is known as self-excited induction generator (SEIG) [2-6]. In second mode it draws the reactive power for its operation from the grid to which it is connected. Such generator is known as externally excited generator or grid connected induction generator (GCIG) [7-11].

In GCIG the grid regulates voltage and frequency automatically. Thus GCIG has no voltage regulation problem and henceforth eliminates the need of voltage regulators as in case of SEIG. The synchronous machines already connected to grid and running in parallel with an induction generator provides the reactive power, while generator output is decided by its operating slip. Therefore a bottleneck in the application of GCIG remains the requirement of inductive

VAR for both induction generator as well as the load, which has to be fed by the generator.

The custom designed induction generator seems unnecessary because an induction motor gives corresponding performance as induction generator. The fact that induction machines are readily available from several manufacturers makes them very competitive for just in time installation. However there is a scope to improve the performance by proper designing of machine.

To incorporate design modifications, there is a need for prior estimation of steady state performance of the machine. Prediction of the saturation level and hence finding the value of magnetizing reactance of induction generator is first step in the steady state analysis of GCIG. A review of the available literature reveals that although a lot of work has been reported on analysis of GCIG using the philosophy of fixed value of magnetizing reactance (X_m) but no attempt seems to have been made in using the saturated values of X_m with corresponding change in air gap voltage (E_1). Computation of the magnetic reactance is done using thevenin equivalent circuit [7], while in [8] the value of X_m is found by carrying out variable voltage no load tests. [1], [9-11] uses the fixed value of X_m and [12] calculates the value of X_m corresponding to induced electromotive force (EMF) by using a software package of MathCAD.

In the present paper it has been shown that there is a considerable variation in X_m with load/slip and hence there is need to compute saturated value of X_m corresponding to any operating load. Therefore, a new iterative technique has been proposed to compute the corresponding values X_m with change in operating conditions. Further the analysis is extended to identify the effectiveness of various design parameters in order to improve the performance characteristics of a machine working as a generator.

II. STEADY STATE MODELING

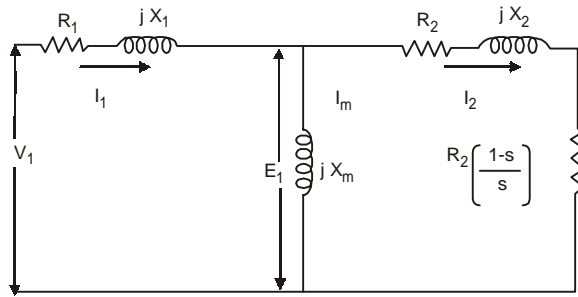


Fig.1(a). Equivalent circuit representation of an induction machine.

Analysis of equivalent circuit representation of an induction machine as given by Fig.1(a), with any value of slip (negative for generator operation) results in to the following mathematical expressions :

$$Z = R_1 + jX_1 + \frac{\left(\frac{R_2}{s} + jX_2\right)(jX_m)}{\left(\frac{R_2}{s}\right) + j(X_2 + X_m)} \quad \dots(1)$$

Unknown and saturated value of X_m for generator operation may be obtained using iterative technique, as explained in section III.

$$Z = Z_{\text{real}} + jZ_{\text{imag}} \quad \dots(2)$$

Where

$$Z_{\text{real}} = R_1 - \frac{\frac{R_2}{s} X_m^2}{\left(\frac{R_2}{s}\right)^2 + (X_2 + X_m)^2} \quad \dots(3)$$

' Z_{real} ' is negative for generator operation

$$Z_{\text{imag}} = X_1 + \frac{\left(\frac{R_2}{s}\right)^2 X_m + X_2 X_m (X_2 + X_m)}{\left(\frac{R_2}{s}\right)^2 + (X_2 + X_m)^2} \quad \dots(4)$$

$$I_1 = \frac{V_1}{Z} \quad \dots(5)$$

$$I_1 = I_{1\text{real}} + jI_{1\text{imag}} \quad \dots(6)$$

Where,

$$I_{1\text{real}} = \frac{V_1 Z_{\text{real}}}{\left(Z_{\text{real}}^2 + Z_{\text{imag}}^2\right)} \quad \dots(7)$$

$$I_{1\text{imag}} = -\frac{V_1 Z_{\text{imag}}}{\left(Z_{\text{real}}^2 + Z_{\text{imag}}^2\right)} \quad \dots(8)$$

$$E_1 = V_1 - I_1 (R_1 + jX_1) \quad \dots(9)$$

$$I_m = \frac{E_1}{jX_m} \quad \dots(10)$$

$$I_1 = I_2 - I_m \quad \dots(11)$$

$$P_{\text{out}} = 3V_1 I_{1\text{real}} \quad \dots(12)$$

This results in negative power for negative slip in case of generator.

The input to rotor is

$$P_{\text{in}} = P_{\text{out}} + 3I_1^2 R_1 + 3I_2^2 R_2 + P_r \quad \dots(13)$$

Equation (12) and (13) gives efficiency (η) of the generator as;

$$\eta = \frac{P_{\text{out}}}{P_{\text{in}}} \quad \dots(14)$$

III. ITERATIVE TECHNIQUE

Iterative procedure for the computation of magnetizing reactance X_m in generating mode is summarized as following :

Step 1. Assume X_m^0 corresponding to E_1^0 as 1.0 p.u. from the relationship between E_1 and X_m depicting the magnetic characteristics of induction machine.

Step 2. Compute E_1^1 using (1) to (9)

Step 3. Find out the new value of magnetizing reactance X_m^1 corresponding to air gap voltage computed in Step 2

Step 4. If $|X_m^1 - X_m^0| \leq \epsilon$

Then the value of X_m^1 may be used as the final magnetizing reactance needed for further computation the

performance of the induction generator. Otherwise X_m^0 may be replaced by the new value of X_m^1 and the procedure may be repeated unless until the difference between successive values of magnetizing reactance comes out as desired.

IV. GENERATOR OPERATIVE LIMITS

It is found that for generator operation I_{1real} in (7) becomes negative in contrast to motor operation. This is the indication for reversal of active power in generating mode. Now real power flows from machine to grid system, which is opposite in case of motoring mode. However as indicated by I_{1imag} in (8), direction of reactive power flow remains same irrespective of operating mode. Such observations leads to a new representation for the grid connected induction generator as shown in Fig.1(b).

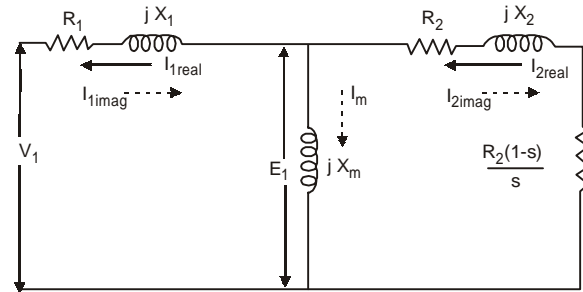


Fig.1(b). Equivalent circuit representation of grid connected induction generator.

Further for generator operation I_{1real} is negative only if Z_{real} is negative quantity. This results in the generating condition as given below;

$$s \left[\left(\frac{R_2}{s} \right)^2 + (X_2 + X_m)^2 \right] > R_1 \quad \dots(15)$$

Equation (15) with boundary conditions results in a quadratic equation

$$as^2 + bs + c = 0$$

$$\text{Where, } a = R_1 (X_2 + X_m)^2, b = -R_2 X_m^2, c = R_1 R_2^2$$

Solution of quadratic equation gives the operating slip of machine in generating zone as;

$$s = \frac{R_2 X_m^2 \pm \sqrt{R_2^2 X_m^4 - 4R_1^2 R_2^2 (X_2 + X_m)^2}}{2R_1 (X_2 + X_m)^2} \quad \dots(16)$$

Out of the two solutions as obtained by (16), only one feasible value can be selected as operating slip corresponding to boundary conditions *i.e.*, s_{mg} . Therefore s_{mg} is the maximum value of slip up to which generator is possible. However operating slip (s_{mt}) corresponding to maximum value of torque generated ($-ve$ in case of generator) comes out to be;

$$s_{mt} = \frac{R_2}{\sqrt{R_e^2 + (X_2 + X_e)^2}} \quad \dots(17)$$

Where,

$$R_e = \frac{R_1 [X_m (X_1 + X_m) - X_1 X_m]}{R_1^2 + (X_1 + X_m)^2}$$

$$X_e = \frac{R_1^2 X_m + X_1 X_m - (X_1 + X_2)}{R_1^2 + (X_1 + X_m)^2}$$

Comparison of two expressions as given by (16) and (17) yields the following deductions;

1. $s_{mt} \neq s_{mg}$
2. $s_{mt} > s_{mg}$
3. s_{mt} and s_{mg} are dependent upon saturated values of magnetizing reactance ' X_m ' in addition to machine parameters.
4. Operating range of the machine can be controlled by proper handling of magnetic circuit *i.e.*, ' X_m ' and machine parameters.

Power flow diagram for the induction generator has been shown in Fig.2

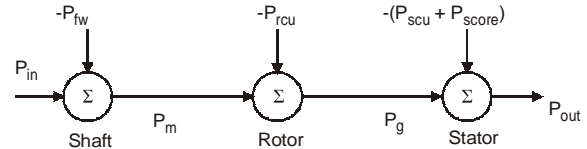


Fig.2. Power flow diagram of induction generator.

Fig.3 gives the flow chart for performance evaluation of the generator and this has been programmed in MATLAB

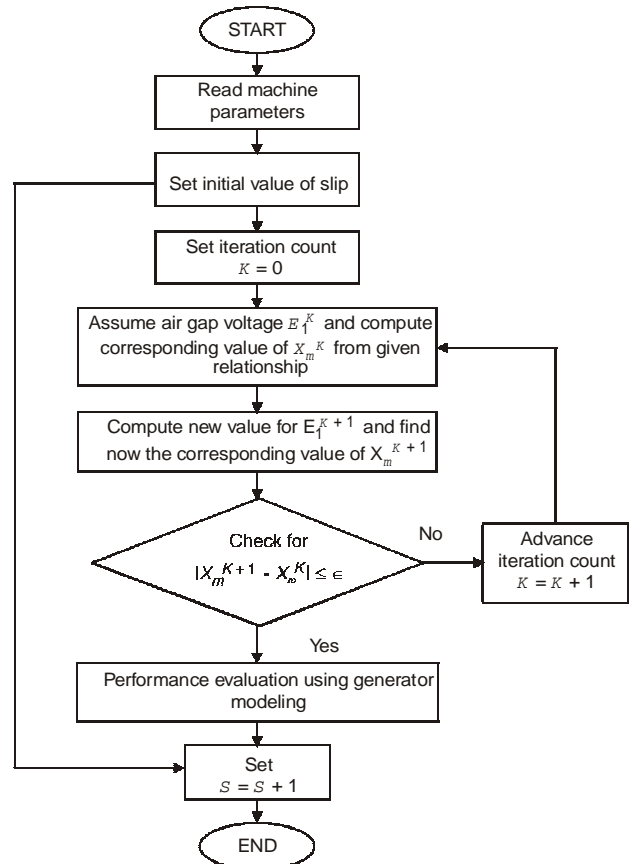


Fig.3. Flow chart for performance evaluation.

V. RESULTS AND DISCUSSIONS

Proposed iterative technique is adopted to simulate the results on Machine-1 [Appendix-I]

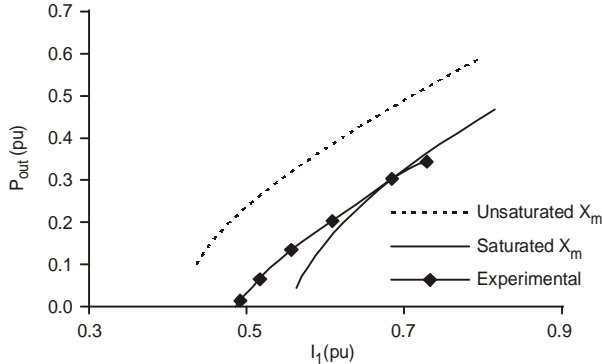


Fig.4. Variation of output power with stator current.

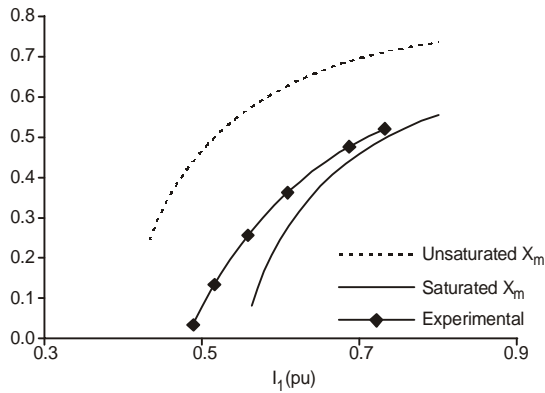


Fig.5. Variation of power factor with stator current.

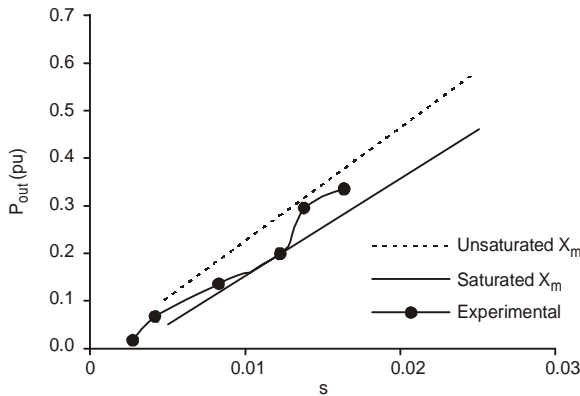


Fig.6. Variation of output power with slip.

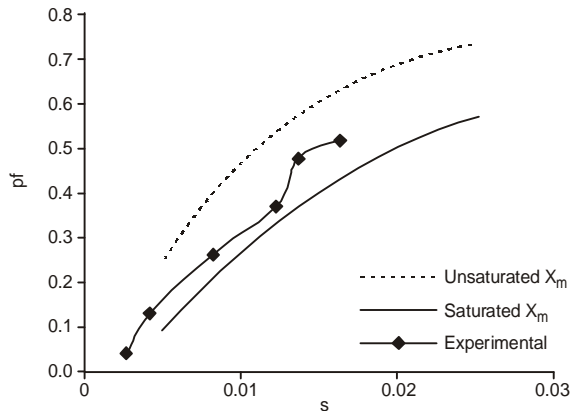


Fig.7. Variation of power factor with slip.

The computed and experimental results for the variation of output power and operating power factor with stator current and slip are shown in Fig.4 to Fig.7. The simulated results using the saturated value of X_m in contrast to unsaturated value of X_m are far closer to experimental results. This closeness of simulated results with experimental ones establishes the validity of proposed iterative technique. This paper lays an emphasis on computing saturated value of X_m , accounting for saturation in magnetic circuits, which was generally neglected by research persons earlier.

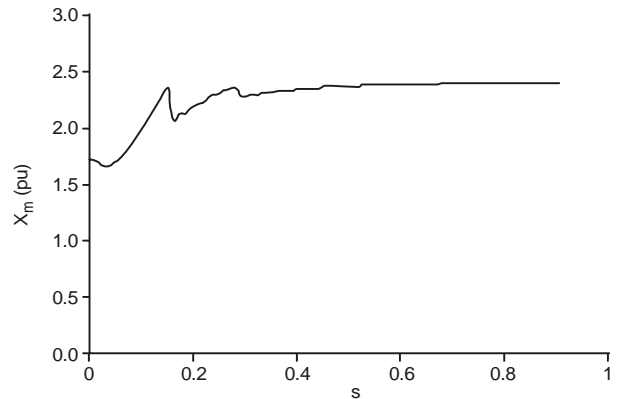


Fig.8. Variation of magnetizing reactance with slip.

Fig.8 shows the simulated results for variation of magnetizing reactance with operating slip. This variation in X_m is due to the saturation effect.

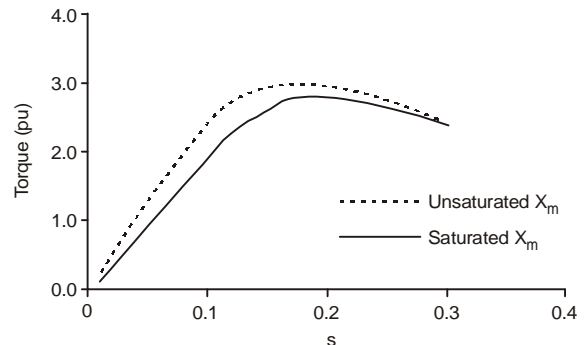


Fig.9. Variation of torque with slip.

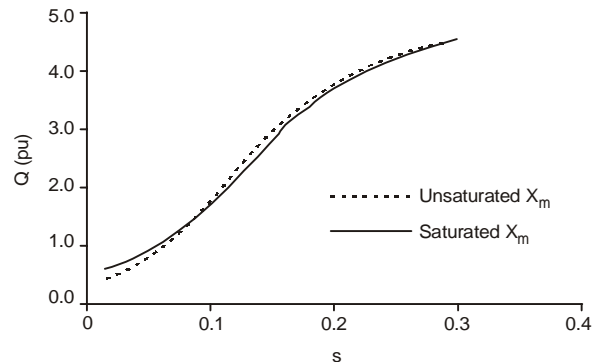


Fig.10. Variation of reactive power with slip.

The variation of torque and reactive power with slip for saturated and unsaturated values of X_m are shown in Fig.9 and Fig.10 respectively. It is observed that accounting of saturation for analysis purpose affects the generating torque and reactive power consumption of the machine.

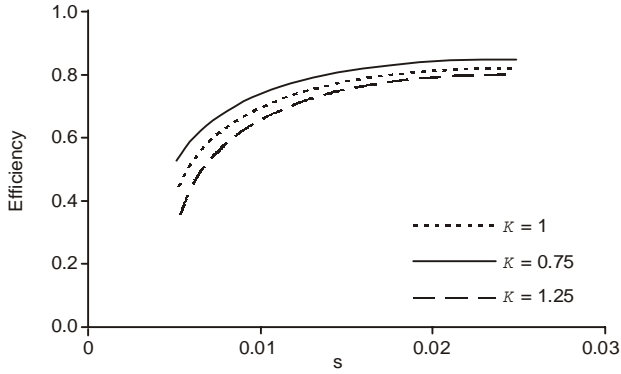


Fig.11. Variation of efficiency with slip, stator resistance = KR_1 .

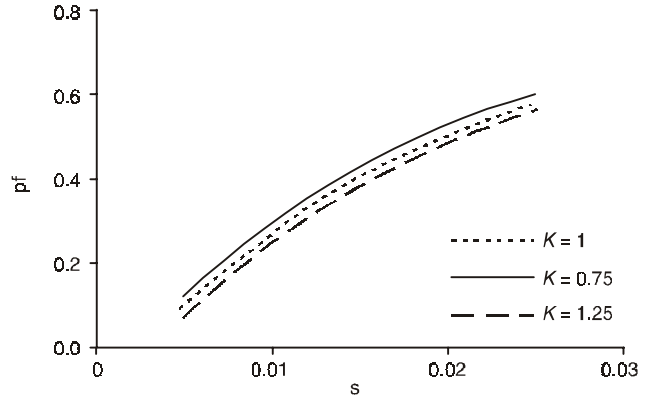


Fig.15. Variation of power factor with slip, stator resistance = KR_1 .

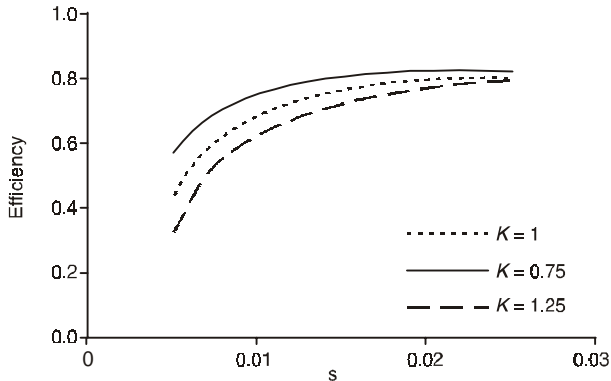


Fig.12. Variation of efficiency with slip, rotor resistance = KR_2 .

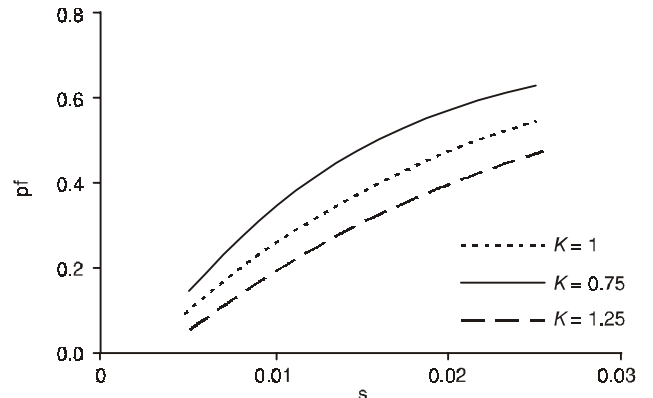


Fig.16. Variation of power factor with slip, rotor resistance = KR_2 .

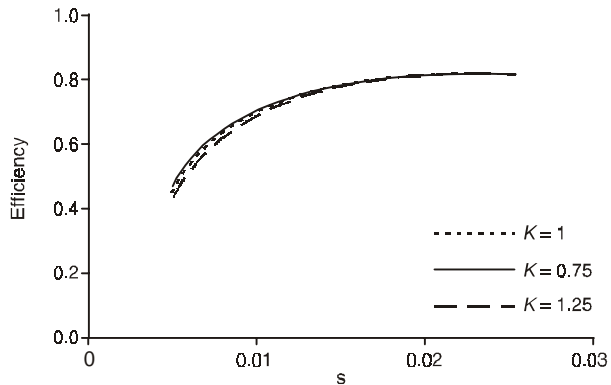


Fig.13. Variation of efficiency with slip, stator reactance = KX_1 .

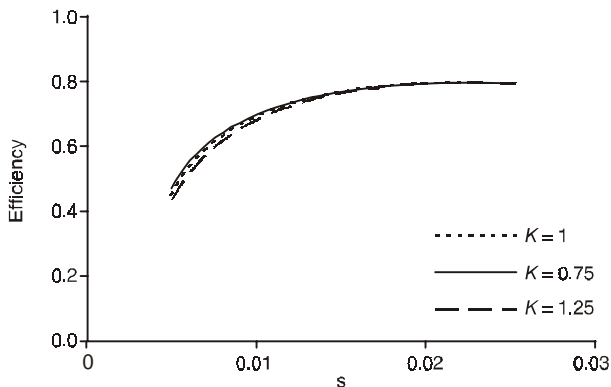


Fig.14. Variation of efficiency with slip, rotor reactance = KX_2 .

Fig.11 to Fig.14 shows the effects of variations in machine parameters on the operating efficiency of the generator. It is observed;

1. Variations in stator and rotor resistances will affect the operating efficiency of the generator. This effect is more pronounced at low operating slips.
2. The stator or rotor reactance doesn't play much role in the enhancement of efficiency of induction generator.
3. Rotor resistance is more effective to control efficiency in comparison to stator resistance.

Similarly Fig.15 and Fig.16 indicate that any change in stator and rotor resistance affects the operating power factor of the machine. However this effect is large, for same variation of resistance, in case of rotor as compared to stator. These discussions leads to the conclusion that stator and rotor resistance may be selected as main design parameters for the induction machines to be operated as generators.

VI. CONCLUSION

For the analysis of grid connected induction generators, estimation of saturated magnetizing reactance is very important in contrast to motor operation (may be considered

as unsaturated value), due to the fact that loading of generator shifts the operation in to saturated region of magnetization curve whereas it is not so for motor operation. Study reveals that most of the research persons adopt the unsaturated value for magnetizing reactance for the analysis of such machines, which may lead to inaccurate performance estimation.

In this paper an iterative technique is proposed to predict the saturated values of magnetizing reactance with change in operating conditions. The comparison between experimental and simulated results proves the validity of technique proposed. Further efforts have been made to predict the operating limits of machine using proposed modeling. Analysis has been extended to identify effectiveness of the machine parameters to improve the operating performance of the generator. It is found that operating performance of the machine may be improved by proper design of stator and rotor parameters.

APPENDIX I

Specifications;

Machine I

Three Phase, 2.2KW\3HP, 230V, 8.6A, 50Hz, Delta connected, Squirrel Cage Induction Machine.

$$V_{\text{base}} = 230 \text{ V}$$

$$I_{\text{base}} = 4.96 \text{ A}$$

$$N_{\text{base}} = 1500 \text{ RPM}$$

The Machine parameters are:

$$R_1 = 3.35\Omega, R_2 = 1.76\Omega, X_1 = 4.85\Omega, X_2 = 4.85\Omega$$

Variation of magnetizing reactance X_m with air gap voltage E_1 is

$0 \leq E_1 \leq 117.87$	$X_m = 108,$
$117.87 \leq E_1 \leq 171.052$	$X_m = 135.553 - 0.2337 E_1,$
$171.052 \leq E_1 \leq 211.919$	$X_m = 151.160 - 0.325 E_1,$
$211.919 \leq E_1 \leq 344.411$	$X_m = 213.919 - 0.621 E_1,$
$344.411 < E_1$	$X_m = 0,$

REFERENCES

- [1] J.E. Barkle, R.W. Ferguson "Induction Generator-Theory and Application" *AIEE Transaction*, **73**: 12-19(1954).
- [2] S.S. Murthy, O.P. Malik, and A.K. Tandon, "Analysis of self-excited induction generators," *Proc. IEE*, **129c**(6): 260-265(1982).
- [3] L. Quazene and G. McPherson, "Analysis of the isolated induction generator," *IEEE Trans. Power Apparatus and Systems*, **102**(8): 2793-2798(1983).
- [4] T.F. Chan, "Analysis of self-excited induction generators using an iterative method," *IEEE Trans. Energy Conversion*, **10**(3): 502-507(1995).
- [5] K.S. Sandhu and S.K. Jain, "Operational aspects of self-excited induction generator using a new model", *Electric Machines and Power Systems*, **27**(2): 169-180(1999).
- [6] K.S. Sandhu, "Iterative model for the analysis of self-excited induction generators," *Electric Power Components and Systems*, **31**(10): 925-939(2003).
- [7] S.S. Murthy, C.S. Jha, P.S. Nagendra Rao, "Analysis of Grid Connected Induction Generator Driven By Hydro/Wind Turbine Under Realistic System Constraints," *IEEE Trans. Energy Conversion*, **15**(1): 1-7(1990).
- [8] A.H. Gorashi, S.S. Murthy, B.P. Singh, Bhim Singh, "Analysis of Wind Driven Grid Connected Induction Generator Under Unbalanced Grid Connections," *IEEE Trans. Energy Conversion*, **9**(2): 217-223(1994).
- [9] S.S.Y. Narayanan, B.K. Murthy, G.S. Rao, "Dynamic Analysis Of A Grid Connected Induction Generator Driven By A Wave-Energy Turbine Through Hunting Networks," *IEEE Trans. Energy Conversion*, **14**(1): 115-121(1999).
- [10] M.A. Abdel-Halem, "Solid State Control of a Grid Connected Induction Generator," *Electrical Power Components and Systems*, **29**(4): 163-178(2001).
- [11] T. Fukami, K. Nakagawa, Y. Kanamaru and T. Miyamoto, "A Technique For The Steady - State Analysis Of a Grid Connected Permanent Magnet Induction Generator," *IEEE Trans. Energy Conversion*, **19**(2): 318-324(2004).
- [12] M.V.A. Nunes, J.A.P. Lopes, H.H. Zurn, V.H. Bezerra, R.G.Almeida, "Influence of The Variable Speed Wind Generators In Transient Stability Margin of The Conventional Generators Integrated In Electrical Grids," *IEEE Trans. Energy Conversion*, **19**(4): 692-701, December (2004).