Reactive Power Requirements of Grid Connected Induction Generator in a Weak Grid

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Abstract -: Induction generators are gaining the popularity due to its simplicity and no synchronization problem. However the major drawback of this machine is its additional reactive burden on the system, where it is connected. In this paper an attempt is made to explore the performance of a grid connected induction generator (GCIG) due to weak grid conditions i.e. voltage and frequency fluctuations. Iterative model developed by the authors is used to predict the reactive burden of the generator due to voltage and frequency fluctuations. The comparison between experimental and simulated results proves the validity of technique proposed. Further proposed modeling is also used to include the effects of saturation.

Key-Words-: Grid connected induction generator, Iterative technique, Magnetizing reactance, Saturation, Weak grid

Nomenclature

E_1=Air gap voltage per phase
f_s=System frequency
I_1 = Stator current per phase
I_2= Rotor current per phase
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_{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=Operating Slip
V_1=Rated terminal voltage per phase or grid voltage
X_1= Stator leakage reactance per phase
X_2= Rotor leakage reactance per phase referred to stator
X_m= Saturated magnetizing reactance per phase
X_{mu}=Unsaturated magnetizing reactance per phase.

1 Introduction

Energy pervades every part of our lives. 87% of total energy is generated from fossil fuels (coal, oil and natural gas), 6% is generated in nuclear plants, and the remaining 7% comes from renewable sources (mainly hydro and wind power). Unfortunately the world has limited amounts of fossil fuel and nuclear power resources and our over dependence on these non-renewable sources of energy is causing global warming, ozone depletion, smog, acid rain, and mercury contamination. Global warming is real and has major implications. It systematically alters climate, which results in more extreme, more damaging weather conditions such as longer dryer summers, longer hurricane seasons, and increased flooding. Air pollution is affecting everything from forests to the quality of human life. Henceforth at this juncture, people are turning more and more to environmentally clean and safe renewable energy sources like wind, hydro, photovoltaic and fuel cells. Conservation techniques, energy-efficient appliances, and renewable sources of energy can lead us towards a future powered by fuels that are sustainable and clean. Renewal energy is expected to create maximum impact in the production of electricity. Projections indicate that by the end of the first decade of the new century, generation and supply of renewable electricity will become cost effective. Besides grid supply augmentation, renewable electrical technologies offer possibilities of distributed generation near consumer ends. This will reduce peak loads and save upon the costly up gradation and maintenance of transmission and distribution networks.

Of all the renewable sources, wind energy has become the workhorse around the world. Man is utilizing wind power for the last 3000 years. Earlier it was used to provide mechanical power to pump water or to grind grains. In early 1970s with a sharp rise in oil prices, interest in wind power remerged. However by the end of 1990s, wind power became as one of the sustainable energy resource. No other technology based on renewable energy electricity production has attained the same level of maturity as wind power. There are no major technical barriers to large-scale penetration of wind power. It also offers an attractive investment option to the private sector for power generation. It is observed that wind carry enormous amount of energy and could meet sufficient energy needs of the world. The regions in which strong wind prevails for a sufficient time during the year may use wind energy profitably for different purposes. It has been found that cost of wind generation is comparable to that of hydro and thermal plants. A state of art has been established in wind harnessing and has far outpaced any previously imagined bounds. There is a little doubt that while the cost of wind generation would become lower in the coming years; the prices of fossil fuels used by thermal plants would definitely go up. Induction Generators with cage rotors are by far the most common type of mechanical-electrical energy conversion devices used in wind turbines. The preference of induction generators [1-5] over synchronous generators in such applications are attributed owing to its inherent advantages such as low unit cost, reduced maintenance, rugged and brushless rotors, absence of a separate dc source for excitation, absence of moving contacts, inherent overload protection, natural protection against short circuit etc. These technical reasons accounts for many fold application of induction machines in various sectors such as agriculture, manufacturing processes, power generation etc. [6-7] describes the general theory and other related aspects of induction machine when operated as generator.

Two modes of operation can be employed for an induction machine. The first one is through regeneration and second one is through self-excitation. In first mode, the induction generator takes its excitation in terms of lagging magnetizing current from the power source of known voltage and frequency, to produce its rotating magnetic field necessary for regeneration. Such generators are known as externally excited generation or grid connected induction generators (GCIG). In this way induction machine basically being single excited, draws the reactive power for it's operation from the grid to which it is connected. In second mode the VAR generating unit has to be connected across the terminals of induction machine, which are 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 machine due to self excitation phenomenon leaving the machine operating under magnetic saturation at some stable point. Such machines are known as self excited induction generators (SEIG).Estimation of steady state performance of the machine in self excited mode is taken by Quazene etal [8]. It is observed that the terminal voltage of self excited induction generator falls sharply with application of load and results into poor voltage regulation. Therefore the only drawback of this machine is unregulated power generation in the absence of regulating devices. [9-11] describes the operation of self excited induction generator with regulated power supply.

A wind turbine with self-excited induction generator may be a very worthwhile proposition for an isolated and remote area. To feed such an area from power grid, long transmission lines are required. It needs huge investment. Diesel plants best serve such areas and a wind turbine generator may be installed to work in combination with diesel plant to meet the local demands. Such an operation will lead to saving in fuel and economy.

In induction generator the saturation state of the magnetic circuit has a significant influence over its performance. Asynchronous machines fall significantly further into the saturation state in generator operation than in motor operation. High magnetic saturation usually results in high no-load losses. However in wind turbines no-load losses are generally undesirable, firstly because they make it more difficult to convert low wind speeds into electrical output and also increase the standstill time of the plant. Secondly for the wind turbines operated independently, the generator excitation normally occurs after turbines have run up. No-load losses caused in this manner cannot be covered at high saturation in the lower wind-speed range; thus the turbine speed can drop to the point where the generation is de-excited. Furthermore, the permissible current density of the generator is significantly increased due to high magnetic energy content and thus wind turbines with increased generator saturation operated as part of grid, faces high in rush currents which can even trip the fuses and significantly load windings.

Predicting the saturation level and hence finding the value of magnetizing reactance is the first need in accurately analyzing the grid connected induction generators. A review of the available literature reveals that although a lot of work has been reported on analysis of grid connected induction generators using the philosophy of fixed value of magnetic 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 [12], while in [13] the value of X_m is found by carrying out variable voltage no load tests. [14-16] used the fixed value of X_m and [17] calculated the value of X_m corresponding to induced electromotive force (EMF) by using a software package of MathCAD. In this paper an attempt is made to explore the performance of a grid connected induction generator due to weak grid conditions i.e. voltage and frequency fluctuations. Further proposed modeling is used to analyze the affects of saturation on the steady state performance of grid connected induction generator.

2 Steady State Analysis

The equivalent circuit representation for induction machine is given by Figure 1.

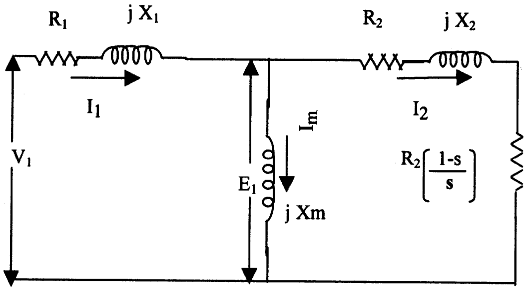

Fig. 1 Equivalent circuit of induction machine.

Analysis of conventional induction machine with any value of slip (negative for generator operation) and saturated magnetizing reactance Xm [calculated using an iterative technique (Appendix-1)] results in to the following mathematical expressions:

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

$$Z = Z_{real} + jZ_{imag} \tag{2}$$

Where

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

Z_{real} turns to be negative for generator operation.

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

$$I_1 = \frac{V_1}{Z} \tag{5}$$

$$I_1 = I_{1real} + jI_{1imag} \tag{6}$$

Where

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

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

$$E_1 = V_1 - I_1\left(R_1 + jX_1\right) \tag{9}$$

$$I_m = \frac{E_1}{jX_m} \tag{10}$$

$$I_2 = I_1 - I_m \tag{11}$$

$$P_{out} = 3V_1 I_{1real} \tag{12}$$

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

The input to rotor is

$$P_{in} = P_{out} + 3I_1^2 R_1 + 3I_2^2 R_2 + P_{fw} \qquad (13)$$

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

$$E_{ff} = \frac{P_{out}}{P_{in}} \qquad (14)$$

The reactive power requirement is given by equation (15);

$$Q = 3V_1 I_{1imag} \qquad (15)$$

Power flow diagram for the induction generator is as shown in Fig.2

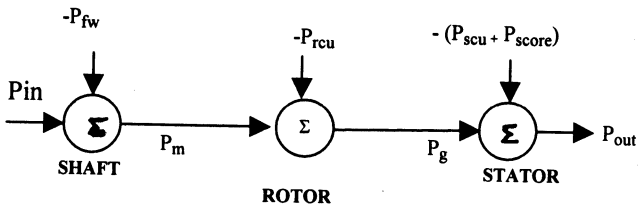

Fig.2 Power flow diagram of induction generator.

Figure 3 gives the phasor representation for induction generator.

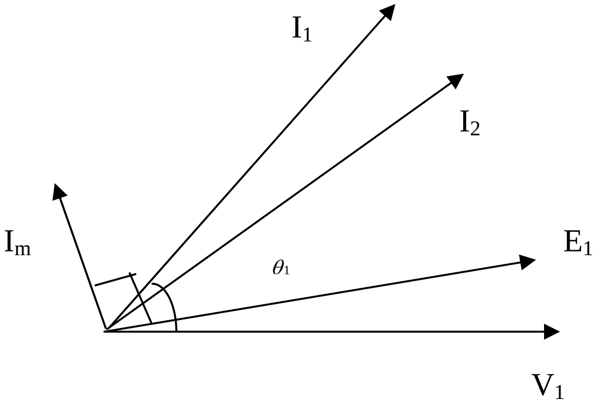

Fig. 3 Phasor diagram for induction generator

Fig.4 gives the flow chart for performance evaluation of the generator, which has been programmed in MATLAB

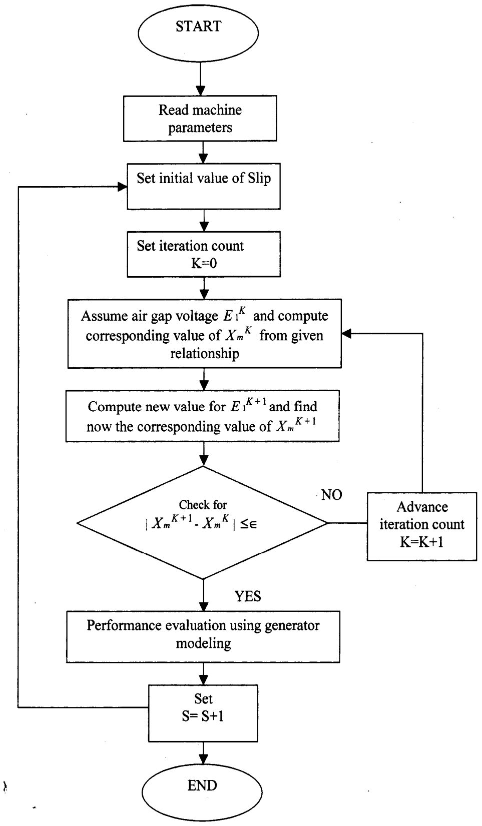

Fig.4 Flow chart for performance evaluation.

3 Results and Discussions

Proposed iterative technique is adopted to simulate the results on machine [Appendix-2]

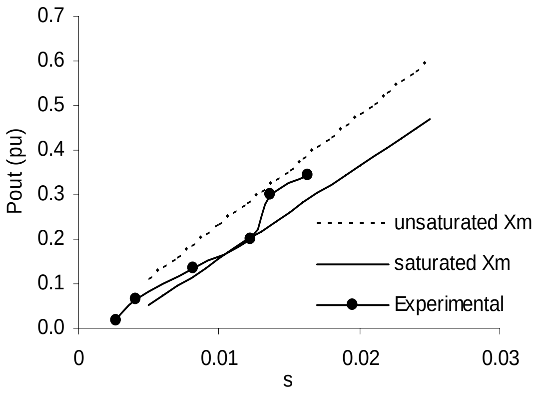

Fig.5 Variation of output power with slip

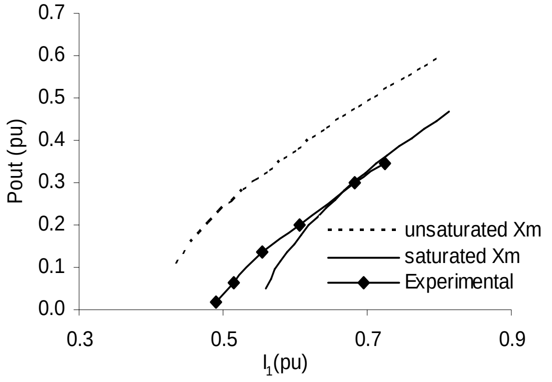

Fig.6 Variation of output power with stator current

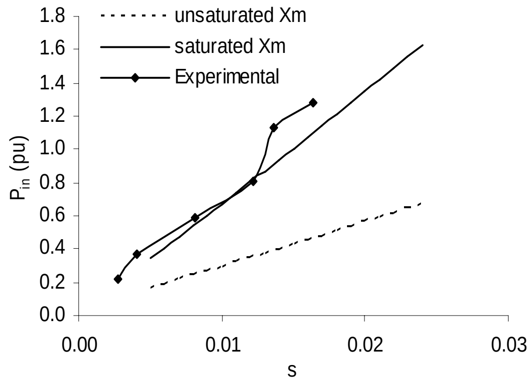

Fig.7 Variation of input power with slip

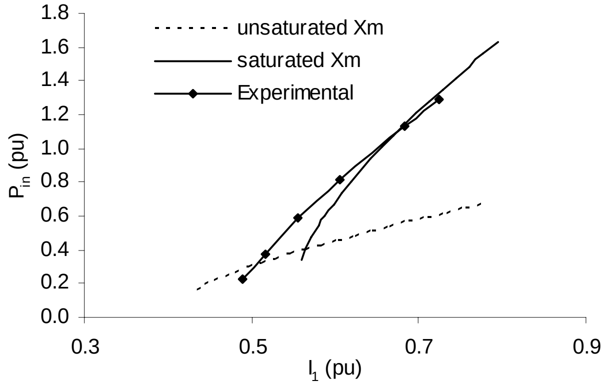

Fig.8 Variation of input power with stator current

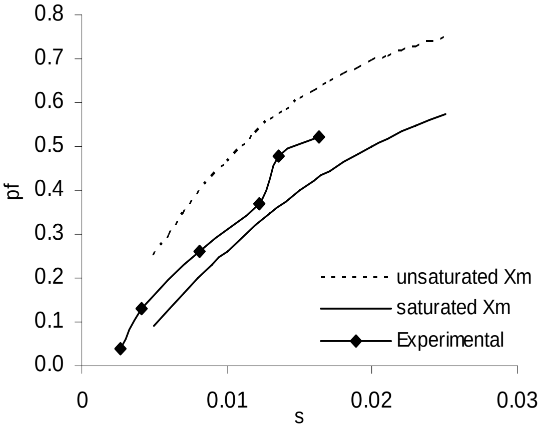

Fig.9 Variation of power factor with slip

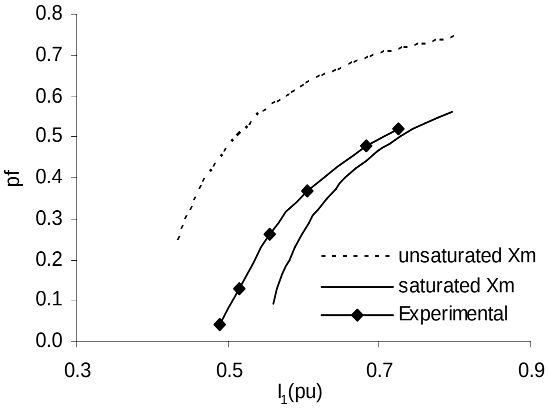

Fig.10 Variation of power factor with stator current

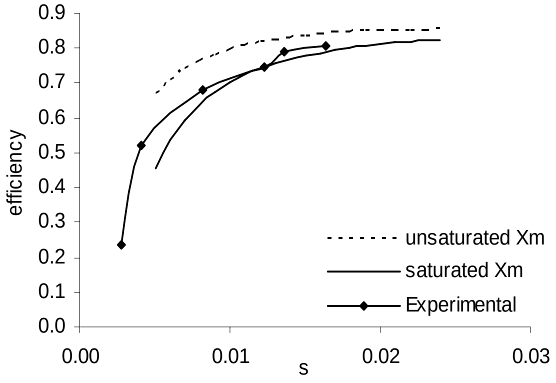

Fig.11 Variation of efficiency with slip

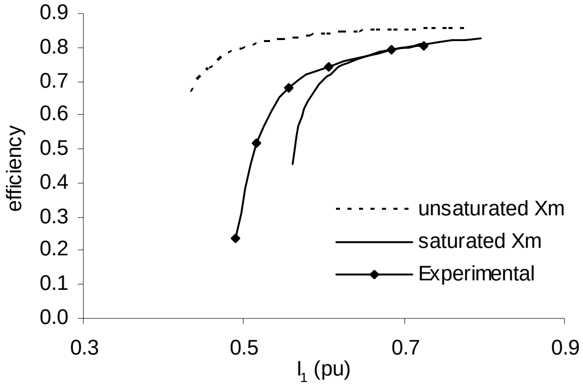

Fig.12 Variation of efficiency with stator current

Fig 5 to Fig. 12 shows the comparison of computed and experimental results for output power, input power, operating power factor and efficiency of the generator. Comparison in tabular form has been shown in Appendix-3. A close comparison indicates that the simulated results using proposed techniques (with saturated value of Xm) falls closer to experimental results. This proves the validity of proposed iterative technique. Further closeness of simulated results using proposed modeling in comparison to the results obtained from unsaturated value of Xm, indicates the need to compute saturated value of Xm. Henceforth accounting for saturation in magnetic circuit, which was generally omitted by research persons, has been incorporated in this paper.

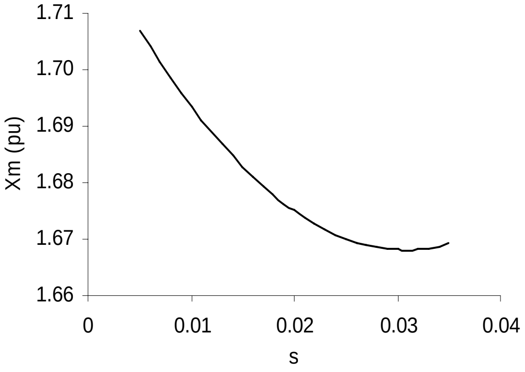

Fig.13 Variation of magnetizing reactance with slip

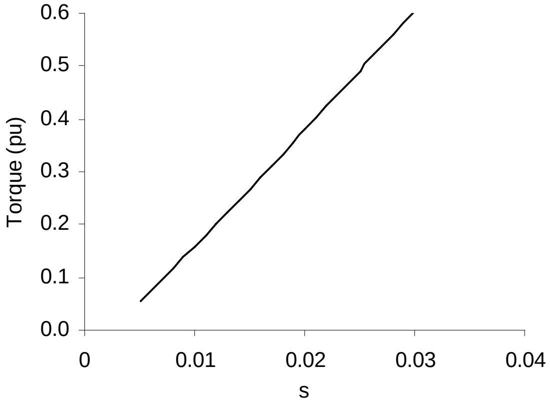

Fig.14 Variation of torque with slip

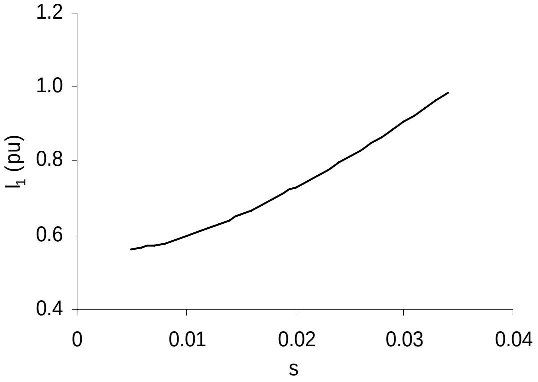

Fig.15 Variation of stator current with slip

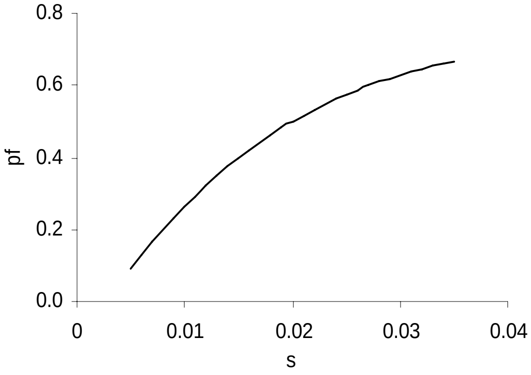

Fig.16 Variation of power factor with slip

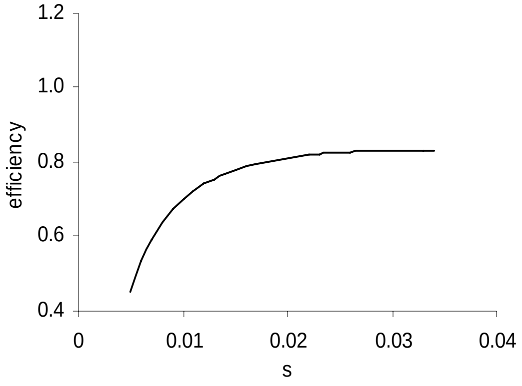

Fig.17 Variation of efficiency with slip

Fig.13 shows the simulated results for variation of magnetizing reactance with operating slip. This variation in Xm is due to the saturation affect. It clearly shows the reduction in Xm with operating slip accounted due to the loading affects on generator. Fig.11 to Fig.17 shows the simulated results for variation of torque, stator current, power factor, and efficiency with operating slip.

Fig. 18 and Fig. 19 show the affects of variation in grid voltage on the requirement of reactive power and efficiency of the generator.

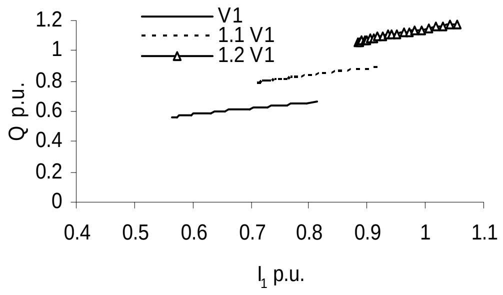

Fig. 18 Variation of reactive power with stator current

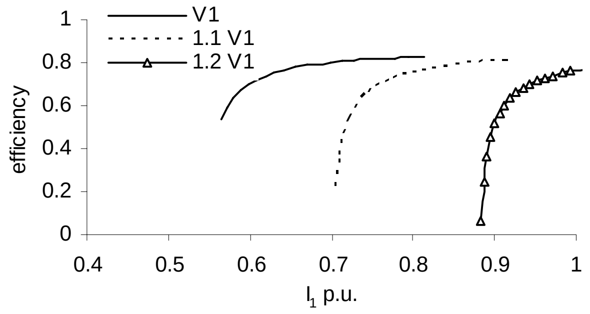

Fig. 19 Variation of efficiency with stator current

Fig. 18 and 19 depicts that with an increase in terminal voltage:

- The reactive power requirement of the generator increases. This is due to operation of the machine in deep saturation.
- Whereas the efficiency of the generator decreases.
- Also in both cases the operating range of induction generator shifts with a change in grid voltage.

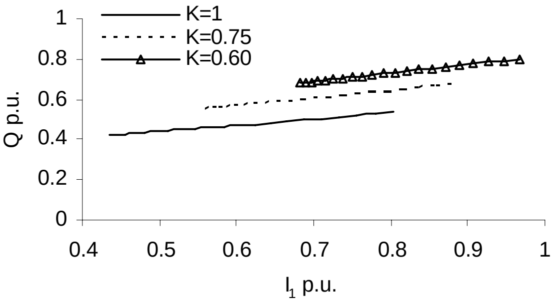

Fig. 20 Variation of reactive power with stator current, terminal voltage = V_1, magnetizing reactance=K Xmu

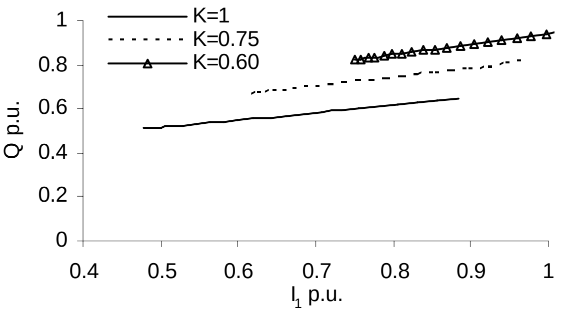

Fig. 21 Variation of reactive power with stator current, terminal voltage =1.1 V_1, magnetizing reactance=K Xmu

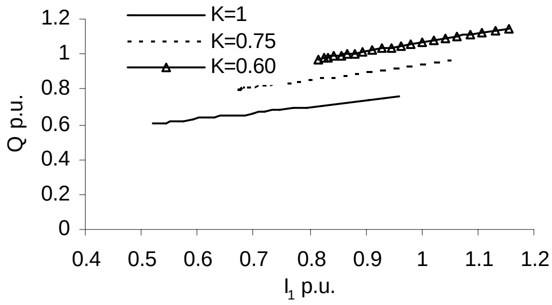

Fig. 22 Variation of reactive power with stator current, terminal voltage =1.2 V_1, magnetizing reactance=K Xmu

From Fig. 20 and 22 the following observations can be made:

- Increase in terminal voltage causes increase in reactive power requirement.
- Also the reactive power requirement increases as the generator moves in saturation region.

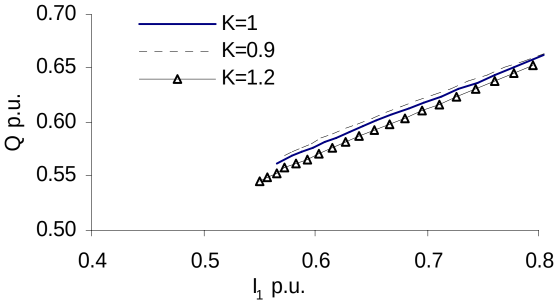

Fig. 23 Variation of reactive power with stator current, terminal voltage = V_1, frequency=K f_s

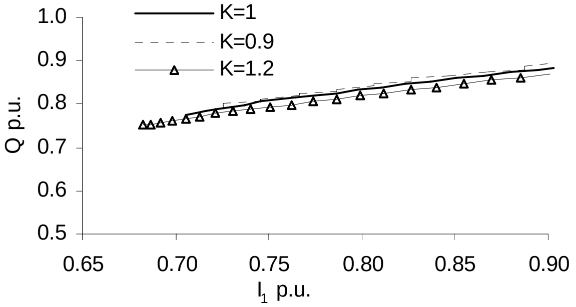

Fig. 24 Variation of reactive power with stator current, terminal voltage =1.1V_1, frequency=K f_s

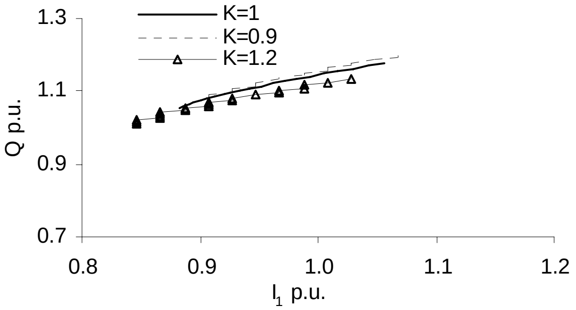

Fig. 25 Variation of reactive power with stator current, terminal voltage =1.2 V_1, frequency=K f_s

Fig. 23 to 25 shows the effects of change in frequency on reactive power requirement of the generator for constant voltages. Further the figures show that:

- As the frequency increases the reactive power requirement decreases

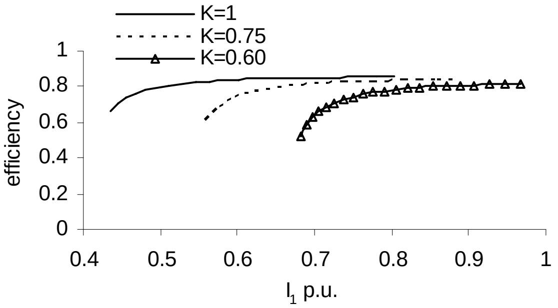

Fig. 26 Variation of efficiency with stator current, terminal voltage=V_1, magnetizing reactance=K Xmu

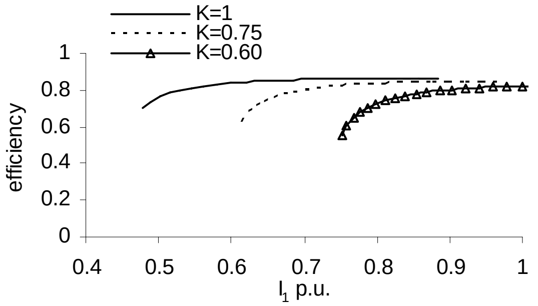

Fig. 27 Variation of efficiency with stator current, terminal voltage=1.1V_1, magnetizing reactance = K Xmu

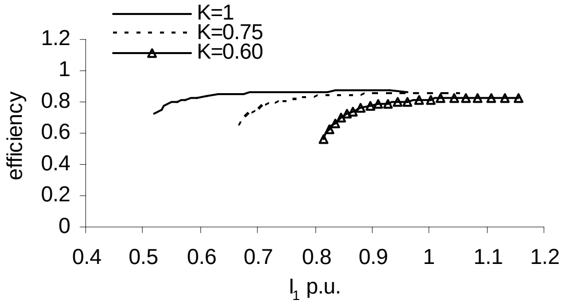

Fig. 28 Variation of efficiency with stator current, terminal voltage =1.2 V_1, magnetizing reactance= K Xmu

Fig. 26 to 28 realizes us with the fact that:

- Change in terminal voltage causes no significant change in efficiency of generator.
- Where as efficiency of generator is affected by saturation level. The efficiency decreases as saturation level of generator increases.

4 Conclusion

In this paper an attempt is made to explore the performance of a grid connected induction generator

(GCIG) due to weak grid conditions. Finally the following conclusions can be made:

- Saturated values of X_m with corresponding change in air gap voltage (E_1) should be taken in study of grid connected induction generator.
- Change in terminal voltage and frequency of the grid connected induction generator causes change in reactive power requirement and efficiency.

Iterative technique as proposed for the estimation of saturated reactance of grid connected induction generator results into a close agreement of simulated and experimental results. This proves the validity of proposed modeling. The work carried out in the present paper, will attract the focus of power engineers to maintain the grid voltage and frequency for the promotion of grid connected induction generator. It is further proposed to continue the research work related to induction generator in the following areas:

- Optimum design of generator suitable for specific zone under certain operating constraints.
- Investigations of power quality issues related to induction generator and methodologies to control associated problems

Appendix-1

The procedure for the computation of magnetizing reactance Xm in generating mode is summarized as following:

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

Step 2. Compute E_1^1 using (1) to (8)

Step 3. Find out the new value of magnetizing reactance Xm^1 corresponding to air gap voltage computed in Step2

Step 4. If $| Xm^1 - Xm^0 | \leq \in$

Then the value of Xm^1 may be used as the final magnetizing reactance needed for further computation the performance of the induction generator. Otherwise Xm^0 may be replaced by the new value of Xm^1 and the procedure may be repeated unless until the difference between successive values of magnetizing reactance comes out as desired.

Appendix-2

Specifications of Machine ;

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

V_{base} =230 V

I_{base} =4.96 A

N_{base} = 1500 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 Xm with air gap voltage E_1 is

$0 \leq E_1 < 117.87$ $Xm=108$,

$117.87 \leq E_1 < 171.052$ $Xm=135.553-0.2337E_1$,

$171.052 \leq E_1 < 211.919$ $Xm=151.160-0.325E_1$,

$211.919 \leq E_1 < 344.411$ $Xm=213.919-0.621E_1$,

Appendix-3

Table 1. Comparison of results.

Slip (s)	Power Output P_{out}(pu)		Power Input P_{in}(pu)	
	Experimental Results	Proposed Technique	Experimental Results	Proposed Technique
0.003	0.02	0.07	0.22	0.19
0.004	0.06	0.09	0.37	0.31
0.008	0.13	0.17	0.59	0.54
0.012	0.20	0.26	0.81	0.8
0.014	0.30	0.30	1.13	0.94
0.016	0.34	0.34	1.29	1.07

Table 2. Comparison of results.

Slip (s)	Power Factor		Efficiency	
	Experimental Results	Proposed Technique	Experimental Results	Proposed Technique
0.003	0.04	0.12	0.23	0.19
0.004	0.13	0.16	0.52	0.34
0.008	0.26	0.29	0.68	0.64
0.012	0.37	0.39	0.74	0.74
0.014	0.48	0.44	0.79	0.77
0.016	0.52	0.48	0.80	0.79

Table 3. Comparison of results.

I_1(pu)	Power Output P_{out} (pu)		Power Input P_{in}(pu)	
	Experimental Results	Proposed Technique	Experimental Results	Proposed Technique
0.49	0.02	0.01	0.22	0.13
0.52	0.06	0.03	0.37	0.21
0.56	0.13	0.06	0.59	0.34
0.61	0.20	0.18	0.81	0.74
0.68	0.30	0.30	1.13	1.14
0.73	0.34	0.36	1.29	1.35

Table 4. Comparison of results.

I_1(pu)	Power Factor		Efficiency	
	Experimental Results	Proposed Technique	Experimental Results	Proposed Technique
0.49	0.04	0.03	0.23	0.32
0.52	0.13	0.07	0.52	0.32
0.56	0.26	0.09	0.68	0.45
0.61	0.37	0.29	0.74	0.72
0.68	0.48	0.44	0.79	0.79
0.73	0.52	0.50	0.80	0.81

References:

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