STEADY-STATE ANALYSIS OF AN ISOLATED SELF-EXCITED INDUCTION GENERATOR DRIVEN BY AN UNREGULATED TURBINE USING MATLAB

SUNIL SINGH[1], ROHIT KUMAR[1] and YOGESH KUMAR[2]
[1]Department of Electrical Engineering, G.B. Pant University of Agriculture & Technology, Pantnagar, Uttarakhand
[2]Department of Electrical Engineering, Gurukula Kangri Vishwavidyalaya, Haridwar, Uttarakhand

Abstract— Capacitor-excited induction generator offers certain advantages over a conventional synchronous generator as a source of isolated power supply. Main advantages are reduced cost, less maintenance, self protection from short-circuit and overload condition. It is used as variable speed generator for different applications such as wind energy conversion, micro hydropower generation. Therefore it is now a key interest to develop an efficient and viable generator for harnessing the energy from renewable sources. Steady state analysis is important for the design and control point of view to develop an efficient, viable economic and controllable induction generator; we must know the overall performance of the generator. In this work, the steady-state performance of a capacitor excited induction generator driven by an unregulated turbine is analysed both incuding and excluding the iron-losses. The speed is considered as a variable for the unregulated turbine case. The steady-state equivalent circuit is solved using the node admittance method, and the shaft torque is expressed in terms of the rotor current. The newton raphson method is used to solve the system nonlinear equations. For the present investigation, a linear speed-torque characteristic is considered, but the method of analysis applies equally well to nonlinear characteristics.

Index Terms— Self-excited induction generator, renewable energy, isolated power supply, newton raphson method, MATLAB.

◆

1 INTRODUCTION

THE ascending rates of fossil-fuel depletion over the last two decades combined with a growing concern about pollution of the environment have led to an accelerated search for renewable energy generation systems. This accelerated drive has led to a tremendous technical progress in the field of renewable energy systems over the last two decades. It has also led to an increasing utilization of wind and mini-hydro energy available at isolated locations. The capacitor-excited induction generator is reliable, robust, cheap, low maintenance machine and suitable for these applications. The induction generator in self-excited mode is preferred over synchronous generator because of its ruggedness, simple construction, absence of DC source, brushless rotor and self-protection against short circuits[1].

Application of SEIG in rural plants has been rigorously studied in recent years as the source is generally water or wind, and the generator is normally not connected to the grid. Therefore, the excitation of the generator is usually provided by connecting capacitors across the induction machine, which generates required emf is known as ‘capacitor self excitation’and can be used to generate the power from constant as well as variable speed prime movers. The self excited induction generator must deliver power to the consumer with acceptable quantity in terms of voltage, frequency, and waveform. This requires suitable controllers to be developed for SEIG[1-3].

PROBLEMS FACED BY SEIG

The drawback of SEIG is that both voltage and frequency varies with load even if rotor speed is constant. The rise in rotor speed will result in proportional rise in frequency which is often accompanied with over-voltages. This type of operation requires active and reactive power balances every time. The other drawback is that the machine demagnetizes and stops generation if the rotor speed falls below or the load rises beyond certain limits. Afterwards, even if the rotor speed and the load return to the rated values, the SEIG cannot start working again without the help of an auxiliary source and a controller. Therefore these drawbacks should be considered during the design phase[4-7].

In the recent years, due to increasing cost of conventional energy and environmental problems, research in the field of non-conventional energy has been intensified. Therefore, the SEIG has become a possible source of low cost power generation from renewable energy systems. Intensive research work on SEIG has been undertaken by many researchers and is well documented in the literature. Attention has been mainly focused on the constant speed mode of operation. In constant speed mode, solutions are tedious algebraic derivations of nonlinear equations which must be solved numerically[4-7].

Electricity generation for commercial purpose needs constant frequency and this work is done analysis SEIG operation with

---

- *Sunil Singh is faculty of Department of Electrical Engineering, G.B. Pant University of Agriculture & Technology, Pantnagar, US Nagar, Uttarakhand. E-mail: sunilsingheed@gmail.com.*
- *Rohit Kuma is PG scholar at Department of Electrical Engineering,G.B. Pant University of Agriculture & Technology, Pantnagar, US Nagar, Uttarakhand. E-mail: kumar_rohit31416@yahoo.co.in*
- *Yogesh Kumar is faculty of Department of Electrical Engineering, Gurukula Kangri Vishwavidyalaya, Haridwar. E-mail: yksehgal20012@gmail.com*

unregulated turbine (variable speed). In used model, iron losses have been included and R load is considered. Certain assumptions are made that circuit parameters, magnetization characteristic, excitation capacitance and load impedance are specified. For the present investigation, a linear speed-torque characteristic, which is typical for a Hydro-turbine at constant water head, is considered[1,5].

2 METHODOLOGY

EQUIPMENT USED:
1. Three-Phase Squirrel-Cage Induction Machine: 3.7 kW, 415V, 8 A, 1440 rpm, 50 Hz, delta connected, 4 pole Induction motor.
2.D.C. Shunt Machine as a Prime Mover: 220 V, 3 kW, 1500 rpm.
3. Other equipments: Voltmeter, Ammeter, Wattmeter, etc.
SOFTWARE USED: MATLAB
DETERMINATION OF MACHINE PARAMETERS

Shunt branch parameters of induction machine have been calculated by conducting synchronous running test, block rotor test and stator resistance measurement test and with test data following parameters were calculated which are as follows:
R1=5.18Ω, R2=6.42Ω, X1=X2=12.97Ω, Xm=232.3 Ω, Rc=1768.89Ω

SYSTEM MODELLING:
In this case of unregulated turbine both frequency and speed are variable.the frequency and the speed are solved simultaneously using three non-linear equations[1]. The third equation comes from System Modeling. The system consists of a three-phase SEIG driven by a turbine whose speed w (T_d) depends on the shaft torque Td according to a given speed-torque characteristics and the SEIG is supplying a static three-phase balanced load[1][5][9-12]. The system layout is shown in Figure 1.

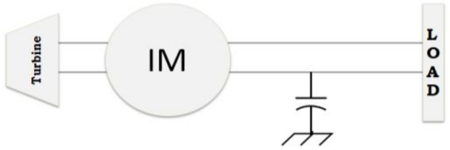

Fig 1. SEIG-Turbine system

For a stable excitation the machine is normally operated in the saturated state. Therefore the magnetizing reactance X_m, at base frequency depends nonlinearly on the air-gap voltage V_g.

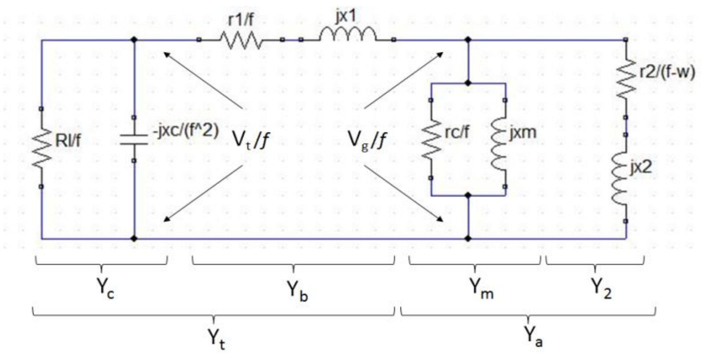

Fig. 2 SEIG per-phase equivalent circuit

The steady-state equivalent circuit is shown in Fig. 2, in which normal frequency reactance values are retained while the stator and rotor resistance and the capacitive reactance values are suitably modified[1].

Generally, with all the machine parameters including magnetization characteristics, load and capacitance parameters at base frequency specified, the circuit in Fig.2 can be solved for f (per unit frequency) and V, if w is specified, or alternatively, for w (per unit speed) and V, if f is specified. Applying node admittance method, the node equation at the magnetizing node may be written as:

$$V_g[Y_a(f,w,V_g)+Y_t(f)]=0 \quad (1)$$

Hence,

$$Y_a(f,w,V_g)+Y_t(f)=0 \quad (2)$$

Since Vg is not equal to 0. Where,

$$Y_a(f,w,V_g)=1/[r_2/(f-w)+jx_2]+1/[jX_m(V_g)]+1/[rc/f] \quad (3)$$

And

$$Y_t(f)=Y_b(f)Yc(f)\ /\ [Yb(f)+Yc(f)] \quad (4)$$

Where

$$Y_b(f)=1/[(r_1/f)+jx_2] \quad (5)$$

And

$$Y_c(f)=(f/R_l)+(f^2/jXc) \quad (6)$$

The electrical torque in per-unit is equal to the gross rotor input power, therefore

$$Te= |I_2|^2 r_2\ /(f-w) \quad (7)$$

From the equivalent circuit, the rotor current is given by

$$I_r=V_g/f[r_2/f-w) + jx_2] \quad (8)$$

Therefore,

$$T_e = (V_g)^2 r_2/\ f^2[r_2^2/(f-w) + x_2^2(f-w)] \quad (9)$$

The total shaft retarding torque is

$$T_d= T_e+T_r \quad (10)$$

where Tr is the rotational loss torque. For the present investigation, it is assumed that the SEIG is driven by a hydro-turbine at constant water head. The turbine speed-torque characteristic in this case is linear and is given by the following equation-

$$w(T_d) = w_o - kT_d \quad (11)$$

where w_o and k are constants.

Equation (2) has complex coefficients; thus it can be separated into real and imaginary parts which are both equated to zero. Let the real part of (2) be denoted by f 1,

$$f1 = Re\{Y_a\} + Re\{Y_t\} = 0 \quad (12)$$

and let its imaginary part be denoted by f2.

$$f2 = Im\{Y_a\} +Im\{Y_t\} = 0 \quad (13)$$

where Re and Im are the 'real part' and 'imaginary part' operator respectively.

Equation (1 1) is real and it can be written in the form

$$f3 = w_o - w - kT_d = 0 \quad (14)$$

Equations (12), (13) and (14) are solved using the Newton-Raphson method which is very suitable for solving this type of problem. The elements of the resulting Jacoubian matrix J are formed as follows:

$$\begin{bmatrix} \delta f1/\delta f, & \delta f1/\delta w & \delta f1/\delta Vg \\ \delta f2/\delta f & \delta f2/\delta w & \delta f2/\delta Vg \\ \delta f3/\delta f & \delta f3/\delta w & \delta f3/\delta Vg \end{bmatrix}$$

The above solution method can also be used if the SEIG is driven by a turbine having non-linear speed-torque characteristics. Equation (11), however, should be modified according to the actual turbine characteristics.

The per-unit parameters of the test machine are calculated as follows:

r1=.1, r2=.123, x1=x2=.25, rc=34.148, Rl=1, xc=1.86, k=.1, w0=1

From the measurement data of stator voltage and current, the desired relationship was obtained using regression analysis. For the test machine X_m, in per-unit at base frequency was found as:

$$Xm(Vg) = -5.386(Vg)^3+7.13(Vg)^2-2.662Vg+3.721$$

3 RESULTS AND DISCUSSION

MAGNETIZATION CURVE OF SEIG

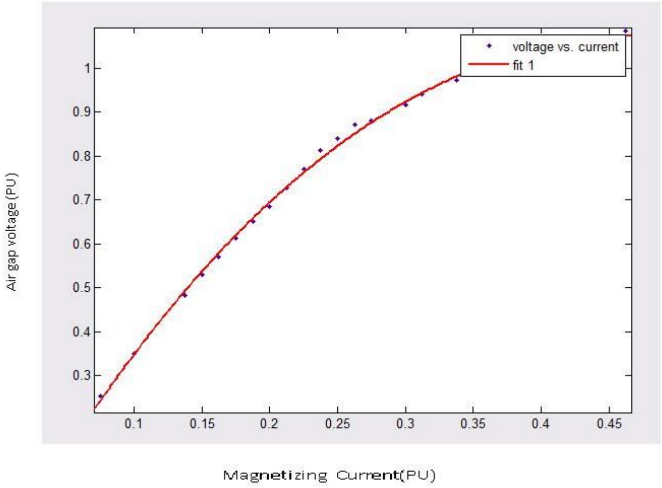

Fig 3 Magnetization characteristics

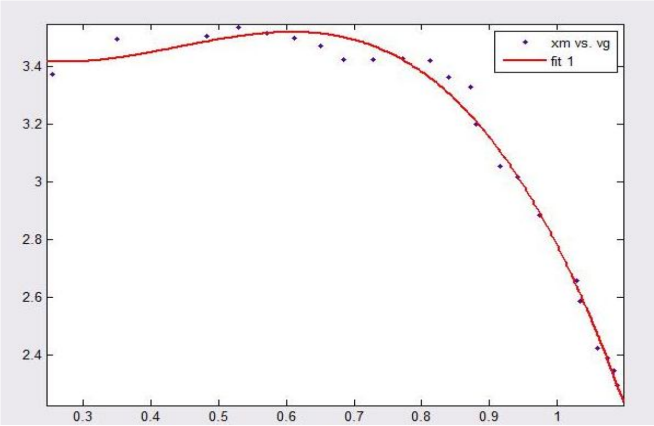

Fig 4 Curve between voltage and Xm at synchronous speed

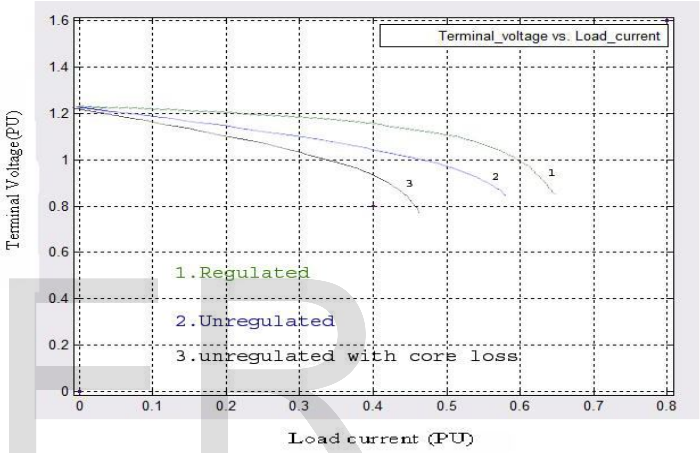

Fig 5 Variation of terminal voltage with load

From the above characteristic it is clear that terminal voltage is decreasing with increase in load current. The fall of characteristic is minimum in case of regulated case compare to unregulated case. In unregulated case including core losses, The fall of voltage characteristic is more compare to regulated case and unregulated without core loss case.

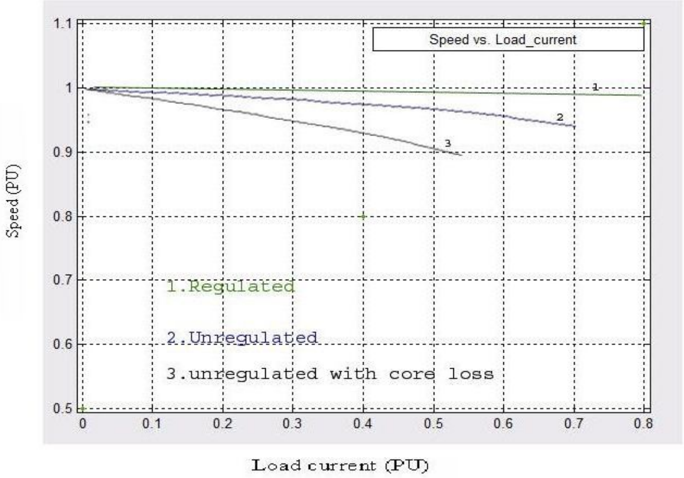

Fig 6. Variation of speed with load current

Above characteristic shows the variation of speed with load current. From the above characteristic it is clear that speed is constant in case of regulated case. There is a slight fall in speed vs load-current characteristic with increase in load current in case of unregulation. The fall is steep if core losses are included with unregulated case.

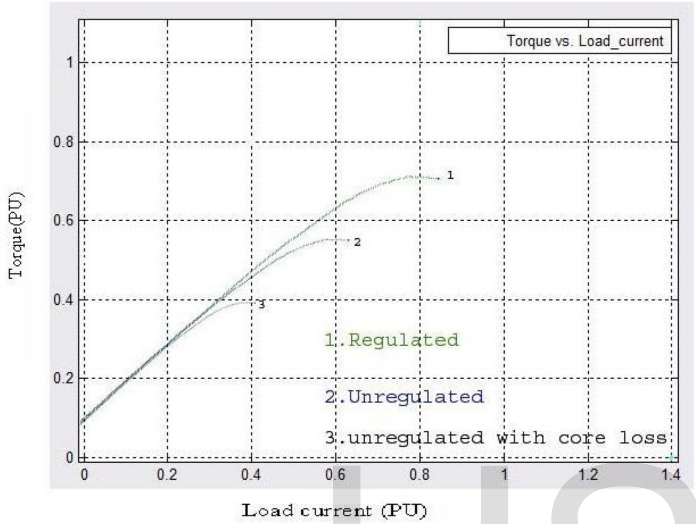

Fig 7 Variation of torque with load current

Above characteristic shows the variation of torque with load current. From the above characteristic it is clear that torque is decreasing with increase in load current. The fall of characteristic is minimum in case of regulated case compare to unregulated case. In unregulated case including core losses, The fall of voltage characteristic is more compare to regulated case and unregulated without core loss case.

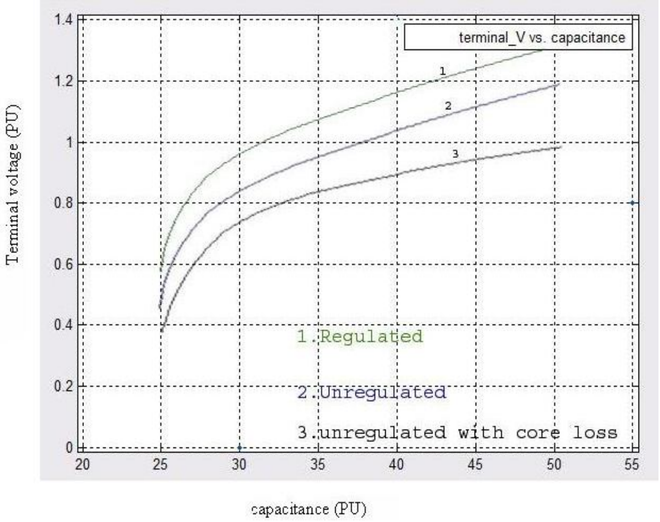

Fig 8. Variation of voltage with capacitance

Above characteristic shows that the voltage increases with capacitance. Terminal voltage is higher if regulation is provided. The terminal voltage also rises in case of unregulation, but this increment is less compare to regulated case and this increment is minimum in case of unregulation including core losses.

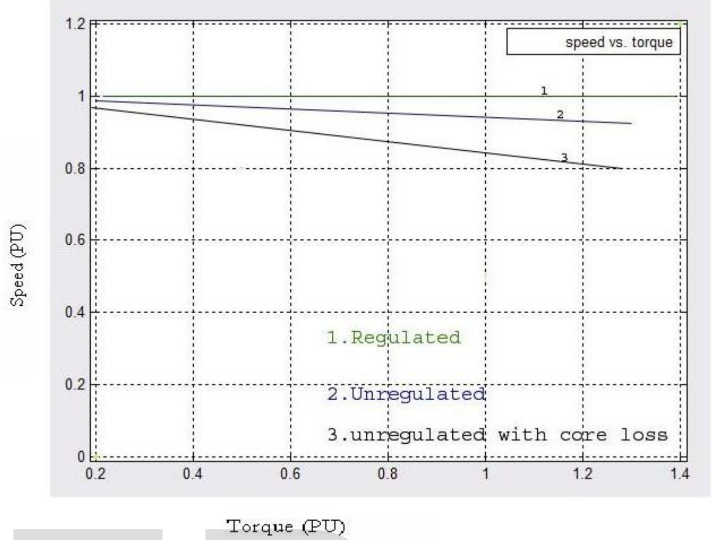

Fig 9. Variation of speed with torque

Above characteristic shows the variation of speed with torque. From the above characteristic it is clear that speed is constant irrespective of torque when regulation is provided. and the other two characteristics confirms linear relationship between speed and torque according to assumed speed torque characteristic.and the fall of speed vs torque characteristic is more in case of unregulation including core loss.

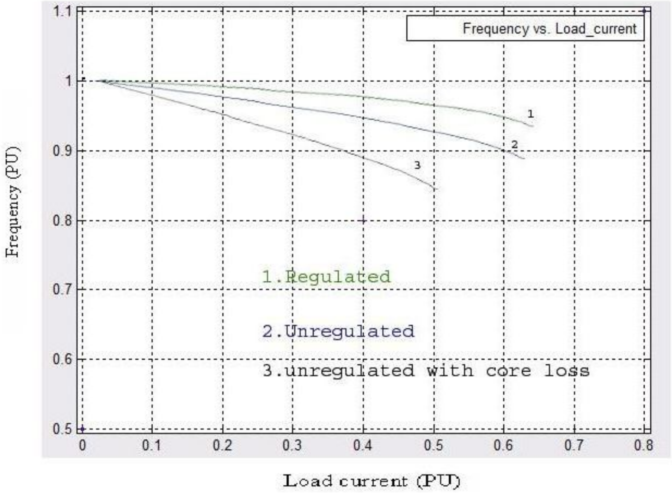

Fig 9 Variation of frequency with load current

Above characteristic shows the variation of frequency with load current. From the above characteristic it is clear that frequency is slightly falling in case of regulated case. The fall in frequency vs load-current characteristic with increase in load current is more in case of unregulation compare to the case when regulation is provided. The fall is steep if core losses are included with unregulated case.

4 CONCLUSION

From the present investigation, it was found that the steady-state performance of the SEIG is largely influenced by the slope of the speed-torque characteristics. It was also observed that the voltage and frequency regulation is poor when the corelosses are included and that predicts the actual behavior of the generator.

5 ACKNOWLEDGEMENT

We are thankful to administration and staff of G.B. Pant University of Agriculture & Technology, Pantnagar for their help.

References:

[1] S. M. Alghuwainem, "Steady-state analysis of an isolated self-excited induction generator driven by regulated and unregulated turbine", IEEE Trans. Energy Conversion, vol. 14, no. 3, pp. 718-723, September 1999.

[2] J. E. Barkle and R.W. Ferguson, “Induction generator theory and application,” AIEE Trans., pt. III A, vol. 73, pp. 12–19, Feb. 1954.

[3] E. D. Basset, F. M. Potter, "Capacitive excitation of induction generators," AIEE Trans., vol. 54, pp. 540-545, 1935.

[4] C. Chakraborty, S. N. Bhadra and A. K. Chattopadhyay, "Excitation requirements for stand-alone threephase induction generator", IEEE Trans. Energy Conversion, vol. 13, no. 4, pp. 358-365, 1998.

[5] T.F. Chan, “Self-excited induction generator driven by regulated and unregulated turbines”, IEEE Trans. on Energy Conversion, Vol. 11, No. 2, 1996, pp. 338-343.

[6] R. C. Bansal, "Three-phase self-excited induction generators: an overview", IEEE Trans. Energy Conversion, vol. 20, no. 2, pp. 292-299, 2005.

[7] Boldea, S. Nasar, The Induction Machine Handbook, Boca Raton - London - New York – Washington D.C, CRC Press, 2002.

[8] L. Wang and C. H. Lee, "A novel analysis on the performance of an isolated self-excited induction generator", IEEE Trans. Energy Conversion, vol. 12, no. 2, pp. 109-117, 1997.

[9] C. Chakraborty, S. N. Bhadra and A. K. Chattopadhyay, "Excitation requirements for stand-alone threephase induction generator", IEEE Trans. Energy Conversion, vol. 13, no. 4, pp. 358-365, 1998.

[10] M. H. Haque, "A novel method of evaluating performance characteristics of a self-excited induction generator", IEEE Trans. Energy Conversion, vol. 24, no. 2, pp. 358-365, 2009.

[11] A.K. Tandon, S.S. Murthy and G.J. Berg, “Steady state analysis of capacitor self-excited induction generators”, IEEE Trans. on Power Apparatus and Systems, Vol. 103, No. 3, 1984, pp. 612-618.

[12] S.S. Murthy, O.P. Malik, A.K. Tandon, Analysis of self excited induction generators, IEE Proc., Generation, Transm. Distribution 129 (6) (1982) 260–265.

[13] M.G. Simoes and F.A. Farret, “Renewable energy systems – Design and analysis with induction generators”, CRC Press, New York, USA, 2004.

[14] G.K. Singh, “Self-excited induction generator research – a survey”, Electric Power Systems Research, Vol. 69, 2004, pp. 107-114.

[15] N. H. Malik and S. E. Haque, “Steady state analysis and performance of an isolated self-excited induction generator”, IEEE Trans., 1986, EC- 1, (3). pp. 134-139.

[16] L. Shridhar, B. Shing and C.S. Jha, “A step towards improvements in the characteristics of self-excited induction generator”, IEEE Trans. on Energy Conversion, Vol. 8, No. 1, 1993, pp. 40-46.

[17] S.P. Singh, B. Singh and M.P. Jain, “Performance characteristics and optimal utilization of a cage machine as capacitor excited induction generator”, IEEE Trans. on Energy Conversion, Vol. 5, No. 4, 1990, pp. 679-685.

[18] S.S. Murthy, B.P. Singh, C. Nagamani and K.V.V. Satyanarayana, “Studies on the use of conventional induction motors as self-excited induction generators”, IEEE Trans. on Energy Conversion, Vol. 3, No. 4, 1988, pp. 842-848..