http://dx.doi.org/10.11142/jicems.2012.1.4.464
Journal of International Conference on Electrical Machines and Systems vol. 1, no. 4, pp. 464~471 , 2012

Design and simulation of an RCN Controller to improve steady state behavior of a self-excited induction generator

Anjali Garg *, K.S. Sandhu ** and L.M. Saini**

Abstract – Self-excited induction generators (SEIG) are gaining importance as compared to conventional generators due to their capability toconvert wind energy into electrical energy for a wide range of variation in operating speed. The performance of such a generator depends upon the load, rotor speed and excitation capacitance. Therefore, depending upon the operating conditions, the output voltage and frequency of this machine goes on changing and this imposes a restriction on its usage. In order to maintain constant voltage and frequency, it need controllers, which make the circuit complicated and also increases the overall cost of power generation. This paper presents a simple controller to regulate the output voltage and frequency of SEIG for variation in its operating conditions due to any change in load, rotor speed and excitation capacitance (R, N, C) and their combination. The controller presented is simple in design, user friendly and is also less expensive, as the elements used in the controller are only resistors, inductors and capacitors. A block of SEIG for steady state operation is also modeled and presented in this paper. SEIG, Controller and other components are modeled and simulated using Matlab/Simulink.

Keywords: Self-excited induction generator, Wind energy, RCN controllers, Matlab.

1. Nomenclature

R_1 & R_2 : stator and rotor resistances per phase respectively referred to stator.
X_1 & X_2 : stator and rotor leakage reactance per phase respectively referred to stator.
R : resistive load per phase
X_m : magnetizing reactance per phase
C : exciting capacitance per phase
$\overline{E_1}$: air gap voltage per phase
$\overline{V}$: load voltage per phase
a : ratio of generated frequency to rated frequency
b : ratio of actual rotor speed to synchronous : speed corresponding to rated frequency
Ns : synchronous speed

P_D : total dump load power
I_L : load current
I_D : dump current
R_D : dump resistance
X_{LD} : dump inductance
X_{CD} : dump capacitance
Z_{LD} : dump impedance
V' : output voltage using RCN controller
f' : per unit frequency using RCN controller
d_1 : % deviation of output voltage from the rated value without using controller
d_2 : % deviation of per unit frequency from the rated value without using controller
d_3 : % deviation of output voltage from the rated value using RCN controller
d_4 : % deviation of per unit frequency from the rated value using RCN controller

* Dept. of Electrical and Electronics Engineering, ITM University, Gurgaon, India. (anjaligarg@itmindia.edu)
** Dept. of Electrical Engineering, National Institute of Technology, Kurukshetra ,India (kjssandhu@yahoo.com,lmsaini@rediffmail.com
Received 18 January 2012; Accepted 05 May 2012

2. Introduction

Renewable energy sources are now the matter of great concern for power generation due to their pollution free nature of generation as compared to emission of gases caused by conventional energy sources. Out of all the renewable sources, wind energy sources are gaining more prominence due to its abundant presence in nature, low cost of generation and lack of threat to global warming. Renewable energy systems using wind energy can be used to supply power either directly to a utility grid or to an isolated load. The stand alone systems are found to have wider applications in areas which are far away from a utility grid in order to meet the local needs [1]-[12].

An induction machine generates power when enough excitation is provided and its rotor is driven at a speed above synchronous speed. The required excitation is provided by connecting appropriate excitation capacitors [6]-[7] across the terminals. Out of all the advantageous features of induction generators, the most prominent one is its generating capacity at the varying speed which operates the induction generators in self-excited/isolated mode.

However, in reality self-excited induction generators (SEIG) have certain limitations in implementation for renewable energy applications. These are reactive power consumption and poor voltage regulation. Steady state behavior of a self-excited induction generator [8]-[10] is also analyzed by researchers; but, with these bottlenecks, the machine faces restricted applications.

In order to provide quality power with constant terminal voltage and frequency to the consumer, a control scheme is required to compensate for any changes in load, excitation-capacitance or rotor speed. Research has shown that one of the alternatives to controlling terminal voltage and frequency is usage of an electronic load controller (ELC) with SEIG [11]-[12]. The ELC used normally consists of an uncontrolled rectifier, a filtering capacitor, dump load and a controller.

In this paper, an RCN controller is modeled in Matlab/Simulink to control the variations in terminal voltage and frequency. It will act like a dump load and will provide control on variations of individual or a combination of load resistance, rotor speed and excitation capacitance to output a constant terminal voltage and frequency. The controller will switch ON the dump load circuit connected in parallel with the consumer load at the output terminals, whenever there is variation in the terminal conditions due to any reason.

3. System description

A schematic representation of the proposed system is shown in Fig. 1. It consists of a three phase star connected squirrel cage induction motor working as a self-excited induction generator when driven by a constant speed prime mover with suitable value of excitation capacitance across its stator terminals. Excitation capacitors are selected in such a manner that it results in rated terminal voltage and frequency at the rated load. Fig. 2 represents the steady state model of a self-excited induction generator simulated as an embedded block in a Matlab/ Simulink environment. The induction generator block has inputs for the combined effect of load resistance and dump resistance, dump circuit element values, excitation capacitance and rotor speed and output as per unit frequency, load current, output voltage and dump current. The dump circuit (controller) block contains resistive, inductive and capacitive elements.

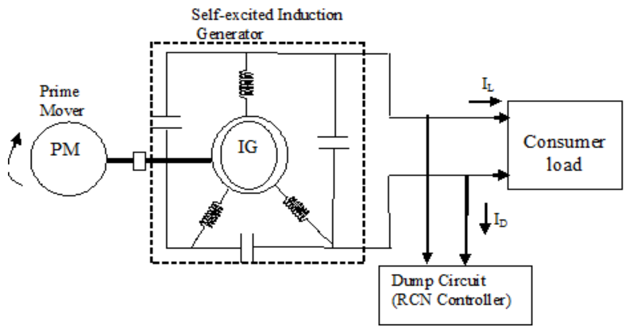

Fig. 1. Schematic representation of the self-excited induction generator

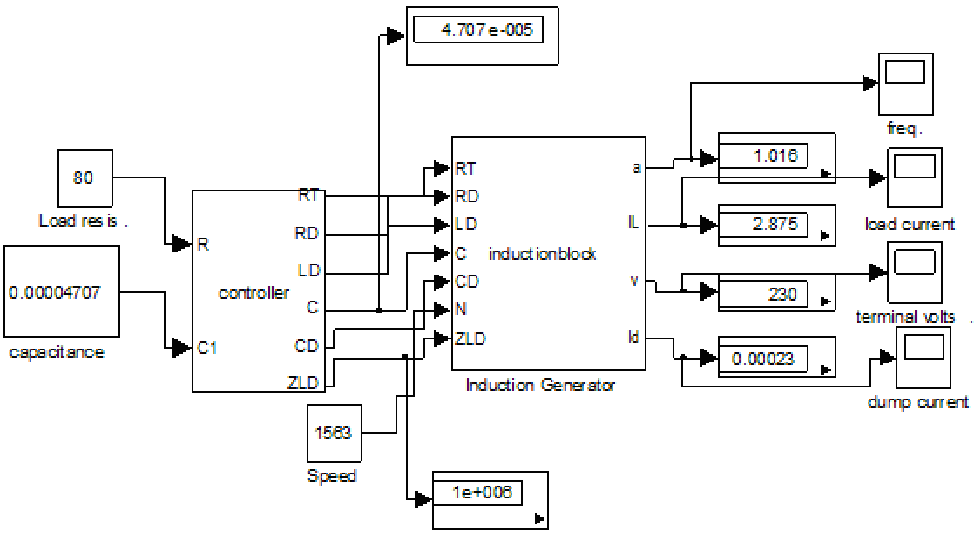

Fig. 2. Schematic representation of proposed system in Matlab/Simulink

4. Steady state modeling

The conventional equivalent circuit of an induction machine can be used for finding out steady-state operational characteristics of SEIG, with the exception that the shunt branch contains only the magnetizing reactance X_m. In the presence of the dump circuit, this conventional equivalent circuit representation may be modified as shown in Fig. 3, where all the parameters are referred to as the rated frequency, assuming that all the inductive reactances are proportional to the frequency.

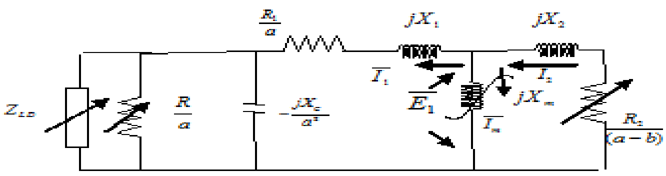

Fig. 3. Per phase equivalent circuit for steady state operation of SEIG using dump impedance

The dump impedance Z_{LD} is shown in Fig.4.

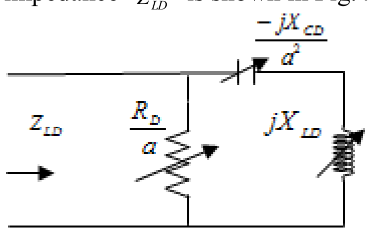

Fig. 4. Dump impedance Z_{LD}

The circuit is further transformed into Fig. 5

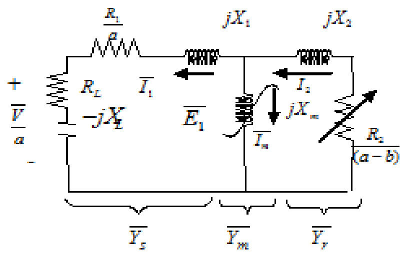

Fig. 5. Modified per phase equivalent network of SEIG

where $R_L - jX_L$ is the impedance due to contribution of $\frac{R}{a}, \frac{R_D}{a}, \frac{-jX_{CD}}{a^2}, jX_{LD}$ and $-\frac{jX_C}{a^2}$. The quantities R_L and X_L are given as:

$$R_L = \frac{R_T X_{CT}^2}{a(a^2 R_T^2 + X_{CT}^2)}, X_L = \frac{R_T^2 X_{CT}}{a^2 R_T^2 + X_{CT}^2}$$

where R_T is the parallel resultant resistance due to R and R_D and X_{CT} is the net reactance due to X_C in parallel with series combination of X_{CD} and X_{LD}.

Using admittance method of solving the circuit, the sum of admittances of the three branches of the circuit shown in Fig. 5 must be zero, as there is no emf source or current source present in the circuit.

$$\overline{Y}_S + \overline{Y}_m + \overline{Y}_r = 0 \quad (1)$$

Equating the real and imaginary part of (1) to zero, two non-linear equations are obtained which are the function of per unit frequency 'a'.

$$\frac{(R_L + R_1/a)}{(X_1 - X_L)^2 + (R_L + R_1/a)^2} + \frac{R_2/(a-b)}{X_2^2 + (R_2/(a-b))^2} = 0 \quad (2)$$

$$-\frac{1}{X_m} - \frac{X_2}{X_2^2 + (R_2/(a-b))^2} - \frac{(X_1 - X_L)}{(X_1 - X_L)^2 + (R_L + R_1/a)^2} = 0 \quad (3)$$

Equations (2) and (3) may be solved to determine the unknown p.u. frequency i.e. 'a' and magnetizing reactance i.e. 'X_m' for given values of operating speed, excitation capacitance and load. Then, air gap voltage 'E_1' can be read using 'X_m' from the magnetization characteristics of the given machine.

The output voltage in terms of reduced frequency 'a' and air gap voltage 'E_1' at rated frequency is given by:

$$V = \frac{aE_1}{([1 - a^2(X_1/X_C)]^2 + a^2[(X_1/R)^2 + (R_1/X_C)^2] + [1 + (R_1/R)]^2 - 1)^{1/2}} \quad (4)$$

An induction generator block for steady state analysis of SEIG has been developed as an embedded block in Matlab/Simulink wherein the output voltage of SEIG is obtained using (1)-(4).

The observations on the test machine (Appendix-1) are taken in Matlab/Simulink and some of the values are given in Table 1. - Table 3. It is noticeable that the total effective resistance, total capacitance at the output terminals and rotor speed should be 80 Ω,, 47.1µF and 1563 rpm respectively to obtain the rated output.

Table 1. Effect of load resistance R

Load resistance(Ω)	Output voltage(V)	Load current(A)	Per unit frequency
80	230.12	2.87	1.0159
100	243.51	2.43	1.0205
120	251.47	2.09	1.0236
140	256.75	1.83	1.0259
160	260.52	1.62	1.0276

Table 2. Effect of excitation capacitance C

Excitation capacitance(μF)	Output voltage(V)	Load current(A)	Per unit frequency
46.8	229.07	2.86	1.0159
47.0	229.77	2.87	1.0159
47.1	**230.01**	**2.88**	**1.0159**
47.4	231.15	2.88	1.0159
47.6	231.83	2.89	1.0158

Table 3. Effect of rotor speed N

Rotor speed(rpm)	Output voltage(V)	Load current(A)	Per unit frequency
1558	228.45	2.85	1.0127
1562	229.78	2.87	1.0153
1563	**230.01**	**2.88**	**1.0159**
1570	232.45	2.90	1.0204
1574	233.78	2.92	1.0230

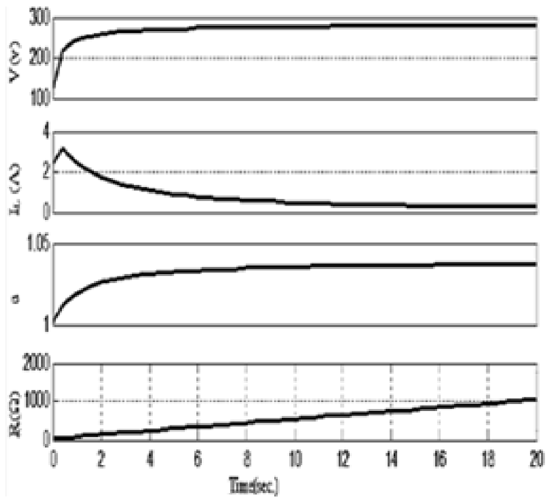

Fig. 6. Output of SEIG without controller with variation in load resistance R

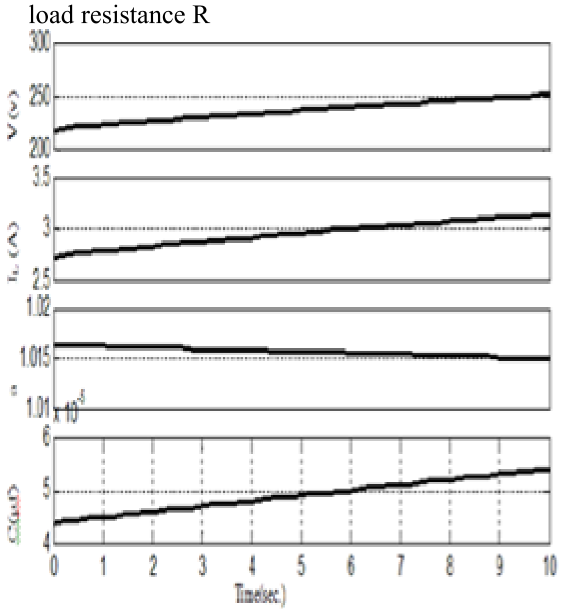

Fig. 7. Output of SEIG without controller with variation in excitation capacitance C

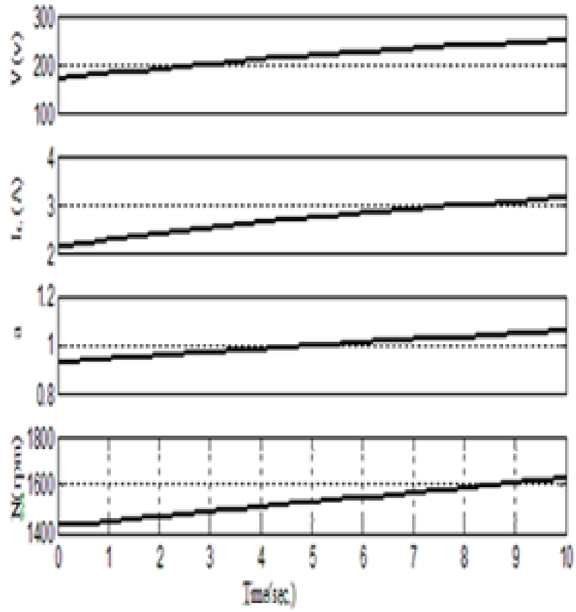

Fig. 8. Output of SEIG without controller with variation in rotor speed N

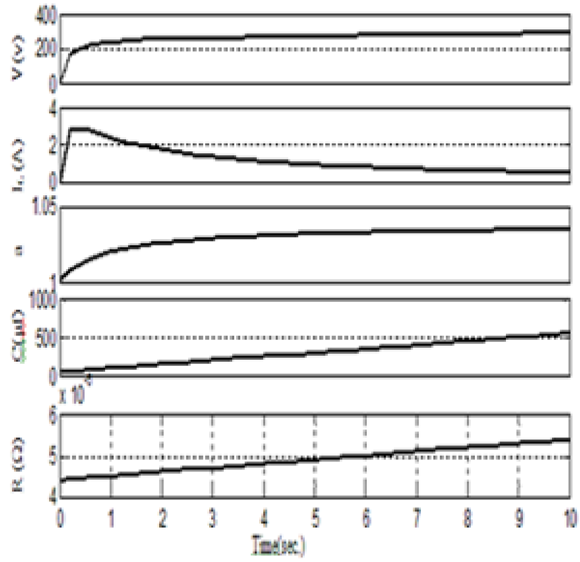

Fig. 9. Output of SEIG without controller with variation in R-C

The result of steady state analysis of SEIG without using a controller is shown in Fig 6 to Fig. 8 for variation in load resistance(R), excitation capacitance(C) and rotor speed (N) while variations of combination of R-C-N are shown in Fig. 9 to Fig. 12.

It is clear from these figures that the variation in R, C, N and their combination have appreciable effect on the terminal voltage and per unit frequency of the machine. The variation in the output leads to restricted usage of the machine.

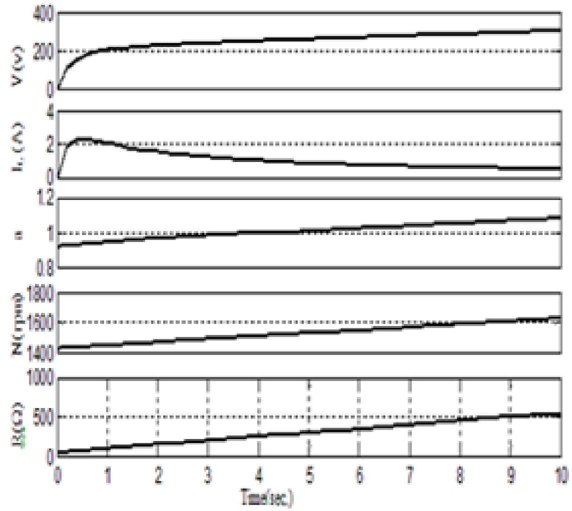

Fig. 10. Output of SEIG without controller with variation in R-N

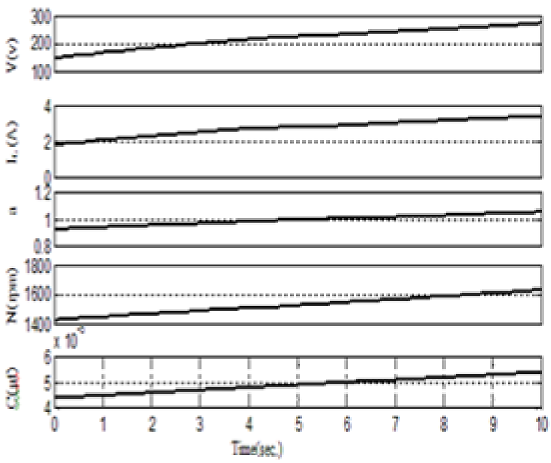

Fig. 11. Output of SEIG without controller with variation in C-N

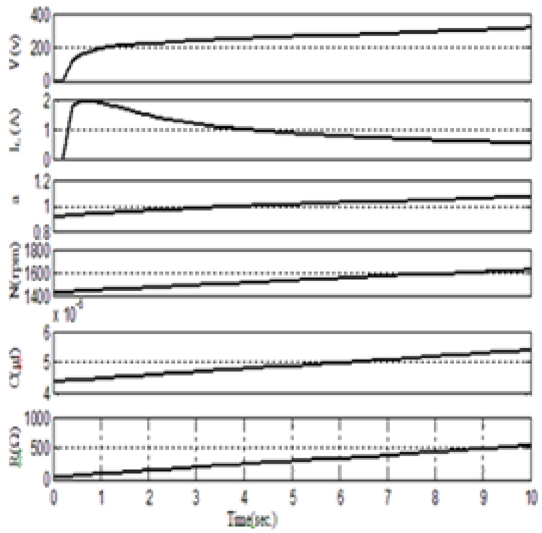

Fig. 12. Output of SEIG without controller with variation in R-C-N

5. RCN Controller

The dump load parameters of Fig. 13 are defined by the following equations:

$$R_D = \frac{80R}{R-80} \quad (5)$$

$$C_D = \frac{C}{0.0000471w^2C+1} \quad (6)$$

$$L_D = \frac{1}{w^2(0.0000471+C)} \quad (7)$$

The block diagram of SEIG using RCN controller is shown in Fig.13.

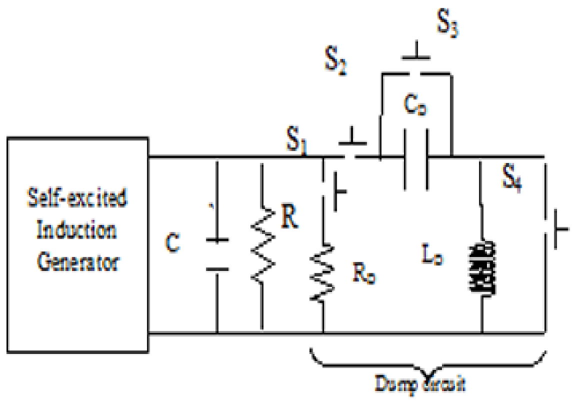

Fig.13. Block diagram of RCN controller (dump circuit)

It has been observed that for the machine mentioned in Appendix-1, Table 4 shows the controlling action taken by the RCN controller using switches S_1, S_2, S_3, S_4 shown in Fig. 13, for different cases of variation in load resistance, excitation capacitance and rotor speed, in order to obtain rated voltage and per unit frequency as mentioned in Table1 to Table3.

Table 4. Controlling action of RCN Controller

R(Ω)	C (µF)	N (rpm)	S_1	S_2	S_3	S_4
Var.	Const	Const	ON	OF F	OFF	OFF
Const.	Var., > 47.1	Const.	OFF	ON	ON	OFF
Const.	Var., < 47.1	Const.	OFF	ON	OFF	ON
Const.	Const.	Var.< 1563	OFF	ON	OFF	ON
Const.	Const.	Var.> 1563	OFF	ON	ON	OFF
Var.	Var.> 47.1	Const.	ON	ON	ON	OFF
Var.	Var.< 47.1	Const.	ON	ON	OFF	ON
Var.	Const.	Var.< 1563	ON	ON	OFF	ON
Var.	Const.	Var.> 1563	ON	ON	ON	OFF
Const.	Var.> 47.1	Var.> 1563	OFF	ON	ON	OFF
Const.	Var.< 47.1	Var.> 1563	OFF	ON	OFF	ON
Const.	Var.> 47.1	Var.< 1563	OFF	ON	OFF	OFF
Const.	Var.< 47.1	Var.>1563	OFF	ON	OFF	OFF
Var.	Var.	Var.	ON	ON	OFF	OFF

6. Results and Discussions

The simulated model of the proposed system in Matlab/Simulink is shown in Fig. 2. The controller will take input as load resistance R, excitation capacitance C and rotor speed N, will apply controlling action as discussed in section 5 and will output R_T, R_D, C_D, L_D and Z_{LD}. This output of controller will act as input to the SEIG which will work as per modeling described in section 4 to deliver the output as shown in Fig 14, Fig.15 and Fig.16 for different cases. Fig. 14 to Fig. 16 shows that with any change in consumer load, rotor speed and excitation capacitance, the variation in output voltage and per unit frequency remains within the tolerable limits.

The reason is that as the load resistance increases, the value of the current drawn by the load decreases and the difference between generated current and load current will flow in the dump circuit to maintain output nearly constant at the rated value. Similarly, as the excitation capacitance or the rotor speed increases, the power generated increases and the extra current will flow in the dump circuit in order to maintain output nearly constant at the rated value.

Comparison between output of SEIG without a controller and with an RCN controller is given in Table 5 to Table 7. The table shows that the percentage deviation of the output voltage and per unit frequency from the rated value mentioned in Appendix-1 decreases drastically with the use of the controller.

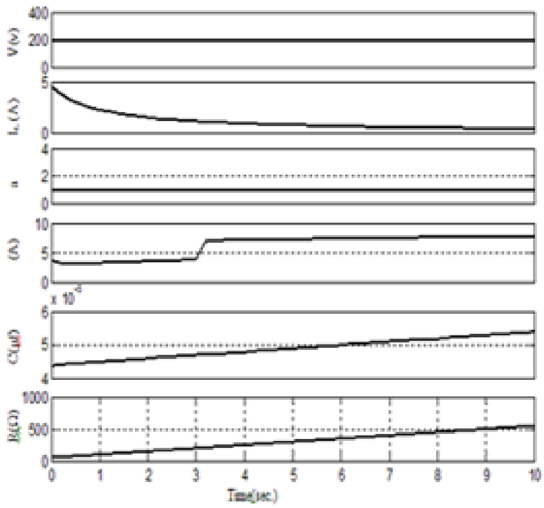

Fig. 14. Output of SEIG for variations in R-C with controller

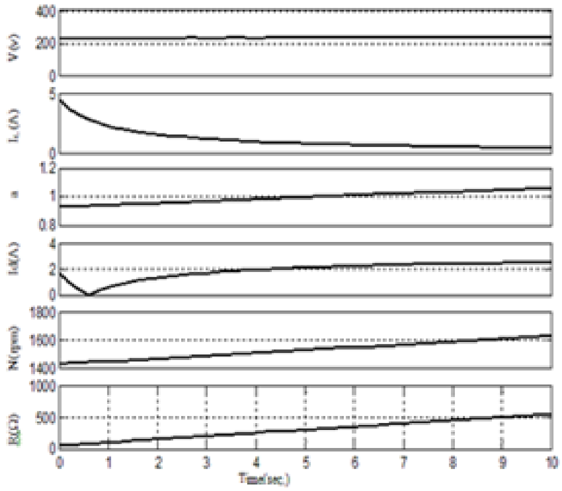

Fig.15. Output of SEIG for variations in R-N with controller

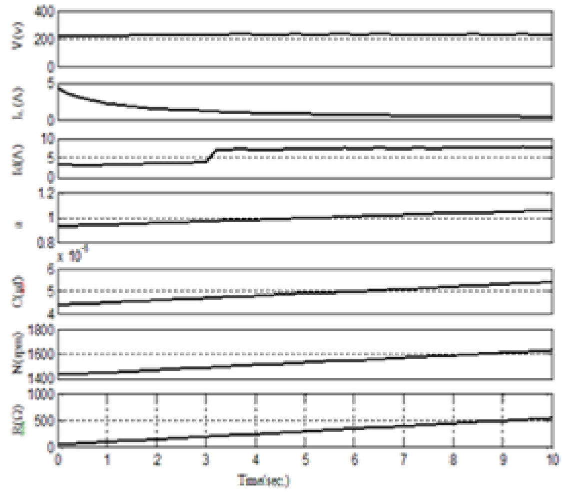

Fig. 16. Output of SEIG for variations in R-C-N with controller

Table 5. Performance comparison of SEIG output for variation in R, C with and without controller

R(Ω)	C(μF)	Output voltage(V)			Per unit frequency		
		V	d_1	V	f	d_2	f'
80	44.6	221.0	3.9	230	1.01	0.06	1.01
120	45.4	246.0	7.0	230	1.02	0.8	1.01
160	46.2	257.8	12.0	230	1.02	1.16	1.01
200	47.0	265.3	15.3	230	1.03	1.4	1.01
300	49.0	277.1	20.5	230	1.03	1.7	1.01
400	51.0	285.2	24	230	1.03	1.85	1.01
500	53.0	291.8	26.9	230	1.03	1.94	1.01

Here d_3 and d_4 is zero as v' and f' is equal to rated value.

Table 6. Performance comparison of SEIG output for variation in R, N with and without controller

R (Ω)	N (rpm)	Output voltage(V)				Per unit frequency			
		V	d_1	V	d_3	f	d_2	f'	d_4
80	1442	177.9	22.7	225.9	1.8	0.93	6.2	0.93	6.3
120	1458	215.7	6.5	226.6	1.5	0.95	4.5	0.94	5.3
160	1474	230	0.0	226.9	1.3	0.96	3.1	0.95	4.2
200	1490	240.4	4.5	227	1.3	0.98	1.8	0.96	3.2
300	1530	260.4	13.2	228.6	0.6	1.01	1.2	0.99	0.6
400	1570	277.2	20.5	235.5	2.4	1.03	4.0	1.02	2
500	1610	293	27.4	234.4	1.9	1.06	6.7	1.04	4.7

Table 7. Performance comparison of SEIG output for variation in R, C, N with and without controller

R (Ω)	N (rpm)	C (μF)	Output voltage(V)				Per unit frequency			
			v	d_1	v'	d_3	f	d_2	f'	d_4
80	1442	44.6	159.4	30.7	219.2	4.7	0.93	6.2	0.93	6.3
120	1458	45.4	210.2	8.6	223.7	2.7	0.95	4.5	0.94	5.3
160	1474	46.2	227.2	1.2	225.7	1.9	0.96	3.1	0.95	4.2
200	1490	47.0	240.1	4.4	227.5	1.1	0.98	1.8	0.96	3.2
300	1530	49.0	265.6.	15.5	227.8	0.9	1.01	1.2	0.99	0.5
400	1570	51.0	287.7	25.1	228.3	0.7	1.03	3.9	1.02	2.1
500	1610	53.0	308.3	34.0	230.1	0.0	1.06	6.7	1.04	4.7

6. Conclusion

In this paper an embedded block of induction generator for steady state analysis along with an RCN controller is modeled and simulated in Matlab\Simulink, for controlling the terminal voltage and frequency of SEIG under condition of varying load resistance, excitation capacitance and rotor speed. This SEIG block reduces the efforts in solving complex and higher order polynomial equations which otherwise becomes very cumbersome. Also the RCN controller designed is a low cost controller as it uses only resistive, inductive and capacitive elements. It has been observed that using the RCN controller as dump circuit, any one or all the three variables viz. R, C and N can be varied at a time and output voltage and frequency can be maintained within the tolerable limits.

References

[1] Lahcene Quazene, George McPherson, "Analysis of the isolated induction generator," *IEEE Transaction on PAS*, Vol. PAS-102, No. 8, pp. 2793-2798,August 1983.

[2] K.S.Sandhu, "Iteractive model for the analysis of self-excited induction generators," *Electric power components and systems*, vol.31,No.10, pp. 925-939, Oct.2003.

[3] S.Rajakaruna, R.Bonert, "Self-excited Induction generator with excellent voltage and frequency control," *IEEE Proc.-Gener. Transm. Distrib*., Vol. 145, No.1, pp. 33-39, 1998.

[4] S.S.Murthy, O.P Malik and A.K.Tandon, "Analysis of self excited induction Generators," in *Proc. IEEE*, Vol. 129, no.6, pp. 260-265,Nov. 1982.

[5] G. Raina, O.P.Malik, "Wind energy conversion using self-excited induction generator," *IEEE Trans., Power App. Syst*., Vol. PAS-102,no.12, pp.3933-3936, Dec. 1983.

[6] T.F. Chang, "Capacitance requirements of Self-Excited Induction Genertor," *IEEE Trans. on Energy Conversion*, Vol. 8, No. 2, pp. 304-310, June 1993.

[7] N.H. Malik and A.A. Mazi, "Capacitance requirements for isolated self excited induction generators," *IEEE trans. on Energy Conversion*, Vol. EC-2, No. 1, pp. 62-68, March 1987.

[8] T.F.Chan, "Steady state analysis of self-excited induction generators," *IEEE Trans. Energy Convers*., Vol. 9, no. 2, pp. 288-296, Jun. 1994.

[9] A.K.tandon, S.S. Murthy and G.J.Berg, "Steady state analysis of capacitor self-excited induction generators," *IEEE Trans. Power Appratus and Systems*, Vol. PAS 103, pp.612-618, March 1984.

[10] Bhim Singh, S.S.Murthy, Madhusudan, Manish Goel, A.K. Tandon, "A steady state analysis on voltage and frequency control of self-excited induction generator in micro-hydro system," *IEEE International Conf. on Power Electronics Drives & Energy Systems*, PEDES, Dec.2006, pp. 1- 6.

[11] Bhim Singh, S.S.Murthy, Sushma Gupta, "Analysis and Design of electronic load controller for self -excited induction generators," *IEEE Transactions on Energy conversion*, Vol.21, No.1, pp.285-93, 2006.

[12] Bhim Singh, S.S.Murthy, Ashish Kulkarni, R. Sivarajan,Sushma Gupta, "Field experience on a novel pico-hydel system using self-excited induction generator and electronic load controller," PEDS 2003, *the Fifth International Conference* Vol. 2, Issue -17-20, Nov. 2003, pp. 842 - 847 .

Appendix-1

Details of Machine

- **Specifications**

  3phase, 4 pole, 50 Hz, delta-connected, squirrel cage induction machine 2.2kW/3.0 hp, 230V, 8.6A

- **Parameters**

  R_1= 3.35 ohm, R_2 = 1.76 ohm, X_1= X_2=4.85 ohms

- **Base Values**

  Base current = 4.96 A, Base speed = 1500 rpm, Base capacitance = 47.1 μF.

- **Air gap voltage**

  The piecewise linearization of magnetization characteristics of the machine gives

$$X_m \langle 82.292 \qquad E_1 = 344.411 - 1.61 X_m$$

$82.292 \le X_m \langle 95.569 \qquad E_1 = 465.12 - 3.077 X_m$

$95.569 \le X_m \langle 108.00$

$E_1 = 579.897 - 4.27 X_m$

$X_m \ge 108.00 \quad E_1 = 0$

Anjali Garg received her B.E degree in Electrical Engineering from State college of Engineering, Murthal, India in 1995 and M.Tech degree in Control and Instrumentation from Delhi College of Engineering, Delhi, India in 2004. She has been pursuing a Ph.D. from National Institute of Engineering, Kurukshetra, India and working as assistant professor in ITM University, Gurgaon, India since 2000. Her area of interests is electrical machines, induction generators, control systems, power electronics and artificial intelligence.

Kanwarjit Singh Sandhu received his B.Sc.Eng. (Electrical), M.Sc. (Electrical), and Ph.D. (Electrical Machines) degrees from Regional Engineering College, Kurukshetra University, Kurukshetra, India, in 1981, 1985, and 2001, respectively. He joined the Electrical Engineering Department of Regional Engineering College, Kurukshetra, as a Lecturer in January 1983. Currently, he is Professor in the Electrical Engineering Department, National Institute of Technology, Kurukshetra. He has more than 120 international & national publications in the area of electrical machines & drives/ induction generators/wind energy conversion/ power quality/ artificial intelligence/ power system.

Lalit Mohan Saini received his B.E.from Panjab University and M.Tech from REC, Kurukshetra and Ph.D. from Kurukshetra University. He is working as faculty of Electrical Engineering, National Institute of Technology, Kurukshetra. One of his main areas of interest is non-conventional energy resources.