DYNAMIC SIMULATION, ANALYSIS AND CONTROL OF SELF-EXCITED INDUCTION GENERATOR USING STATE SPACE APPROACH

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Abstract: *The Based upon state space approach, this paper presents a Matlab model which may be used to describe the transient behaviour of self-excited induction generator. An attempt has been made to design an electronic load controller with resistive as well as inductive elements as dump load to absorb excessive real and reactive power during mismatch of power generated and power required by the consumers. These It has also been observed that terminal voltage of the machine may be maintained, even in the absence of excitation and speed controllers.*

Key words: *Renewable energy source, Wind, Self-excited induction generator, Matlab*

1. Nomenclature

V_{ds} , V_{dr} , V_{qs} , V_{qr} : stator and rotor d, q axis voltages
i_{ds} , i_{dr} , i_{qs} , i_{qr} : stator and rotor d, q axis currents
V_{ld} , V_{lq} : d,q axis terminal voltage per phase
i_{ld} , i_{lq} : d,q axis load current per phase
V_{cd} , V_{cq} : d,q axis voltage across excitation capacitor per phase
i_{cd} , i_{cq} : d,q axis current in excitation capacitor per phase
L_m : magnetizing inductance
I_m : magnetizing current
Ψ_m : magnetizing flux
w_r : rotor angular speed in rad/sec
C : exciting capacitance per phase
R_s, R_r : stator and rotor resistance
L_{ls}, L_{lr} : Stator leakage reactance
R : resistive load per phase
L : inductive load per phase
P : differential operator

2. **Introduction**

Due to rapid decrease in conventional power generating sources and radical increase in fuel cost, power generation through non-conventional sources using self-excited induction generator (SEIG) is gaining importance over the years. Besides low cost and pollution free power generation, wind is preferred for power generation due to its presence in abundance. SEIG is an externally driven induction machine with a capacitor bank connected across its terminals for self-excitation. Along with other features, SEIG has the scope to generate power for broad range of speeds which let the induction generator to get operated in self-exited/isolated mode [1-20]. This feature of SEIG is helpful to meet local energy demands of remote areas like Islands, river banks, remotely located villages, hilly areas where extension of grid is either not possible or un-economical.

There are two approaches for analysis of SEIG: a) Steady state equivalent circuit approach wherein loop impedance method and nodal admittance method is used b) Generalized machine theory based approach which uses d-q modeling for analysis. The two approaches are not compatible with each other and the equations hence obtained cannot be used interchangeably [14]. The transient analysis of SEIG is presented by many authors [6-9]. For transient analysis, state space approach seems to be quite simple and has better way of representation of transient analysis of SEIG [18-19].

The major bottleneck in the usage of power generated by SEIG is poor voltage and frequency regulation. Researchers have proposed many control techniques to regulate voltage and frequency of SEIG [10-16]. Electronic load controller (ELC) is one of the methods to regulate voltage and frequency for constant power applications [15-17]. An electronic load controller is a set up connected in parallel to the consumer load and work in such a way to control the terminal voltage and frequency for any load variation. An ELC normally consist of uncontrolled rectifier bridge, a chopper circuit and a resistor as dump load which enables to control real power of the machine. An excitation capacitance along with assistance in self-excitation process will also provide reactive power required by the load [5-6]. It has been assumed that total power generated by induction machine remain constant. So, the rating of capacitor bank in that case will be large and hence reduces overall efficiency of the system.

In this paper transient analysis of SEIG using d-q modeling of SEIG has been proposed with classical state space approach. All the non-linear parameters like main and cross flux are considered while determining the solutions of the equations in state space which otherwise has not been taken into consideration by many of the previous reported studies [8-9].

In this paper, for the first time an attempt has been also made, to develop an 'ELC comprising of resistive and inductive elements' as dump load to control both real and reactive power.

3. SEIG Modeling

Equivalent circuit of SEIG supplying inductive load, using d-q modeling is shown in Fig.1. Matrix representation using classical state space approach for representation of generator dynamics is given by equation (1) and (2). This matrix represents the instantaneous voltage and current obtained during the self-excited process and also during the load variations [19].

The generalized dynamic SEIG model consists of eight differential equations in terms of i_{ds}, i_{dr} , i_{qs} , i_{qs} , i_{qr} , v_{ld}, v_{lq} , i_{ld} and i_{lq} as given by equation (2).

These equations can be solved simultaneously using Runge-Kutta 4th order integration method.

Following assumptions are made during dynamic analysis of SEIG: 1) Except the magnetizing inductance (L_m), all the machine parameters are assumed to be constant. 2) Mechanical and core losses in the machine are neglected. 3) Load, stator windings and excitation capacitors are connected in star.

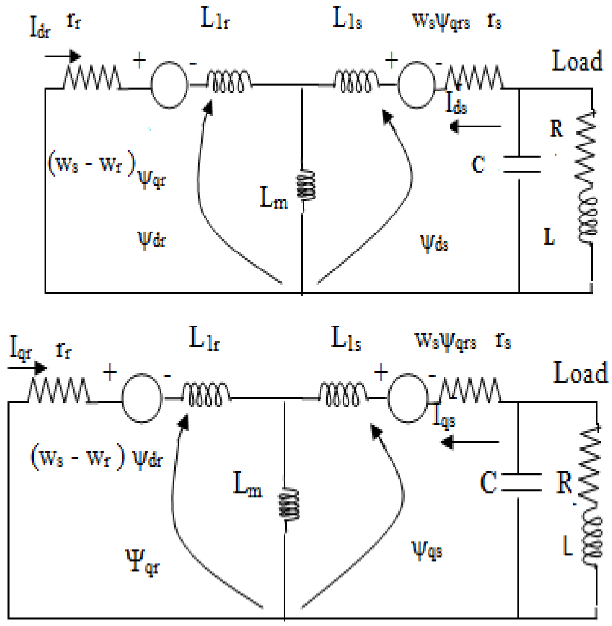

Fig.1 d-q axes based equivalent circuit of SEIG

The non-linear relation of magnetizing inductance with magnetizing current can be obtained using synchronous speed test.

$$\begin{bmatrix} v_{ds} \\ v_{qs} \\ v_{dr} \\ v_{qr} \end{bmatrix} = \begin{bmatrix} R_s + L_s p + (\frac{R+Lp}{RCp + LCp^2 + 1}) & 0 & L_m p & 0 \\ 0 & R_s + L_s p + (\frac{R+Lp}{RCp + LCp^2 + 1}) & 0 & L_m p \\ L_m p & \omega_r L_m & R_r + L_r p & \omega_r L_r \\ -\omega_r L_m & L_m p & -\omega_r L_r & R_r + L_r p \end{bmatrix} \begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \end{bmatrix} \quad (1)$$

$$p\begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \\ v_{Ld} \\ v_{Lq} \\ i_{Ld} \\ i_{Lq} \end{bmatrix} = K\left\{\left[\begin{array}{cccc|cc|cc} R_s L_r & -\omega_r L_m^2 & -R_r L_m & -\omega_r L_m L_r & L_r & 0 & 0 & 0 \\ \omega_r L_m^2 & R_s L_r & \omega_r L_m L_r & -R_r L_m & 0 & L_r & 0 & 0 \\ -R_s L_m & \omega_r L_m L_s & R_r L_s & \omega_r L_s L_r & -L_m & 0 & 0 & 0 \\ -\omega_r L_m L_s & -R_s L_m & -\omega_r L_s L_r & R_r L_s & 0 & -L_m & 0 & 0 \\ \hline 1/CK & 0 & 0 & 0 & 0 & 0 & -1/CK & 0 \\ 0 & 1/CK & 0 & 0 & 0 & 0 & 0 & -1/CK \\ \hline 0 & 0 & 0 & 0 & 1/LK & 0 & -R/LK & 0 \\ 0 & 0 & 0 & 0 & 0 & 1/LK & 0 & -R/LK \end{array}\right] \begin{bmatrix} i_{ds} \\ i_{qs} \\ i_{dr} \\ i_{qr} \\ v_{Ld} \\ v_{Lq} \\ i_{Ld} \\ i_{Lq} \end{bmatrix} + \begin{bmatrix} -L_r & 0 & L_m & 0 \\ 0 & -L_r & 0 & L_m \\ L_m & 0 & -L_s & 0 \\ 0 & L_m & 0 & -L_s \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} v_{ds} \\ v_{qs} \\ v_{dr} \\ v_{qr} \end{bmatrix}\right\} \quad (2)$$

For machine-1 given in Appendix-1, the magnetization curve is represented as below:

L_m = -6.89x 10^{-6} I_m^4 +1.38x 10^{-4} I_m^3 -1.22x 10^{-3} I_m^2 +1.28x 10^{-3} I_m +4.62x 10^{-2} henrys (3)

where:

$I_m = \sqrt{(I_{ds} + I_{dr})^2 + (I_{qs} + I_{qr})^2}$ (4)

The residual magnetism is also taken into account, without which self-excitation seems to be impossible and hence initial voltage across excitation capacitance is also considered.

3.1 Self-excitation and load modeling

The capacitor voltages and currents in terms of d-q axes are given by equation (5) - (8) [19].

$$V_{cd} = V_{ds}; V_{cq} = V_{qs} \quad (5)$$

$$i_{ds} = i_{cd} + i_{ld}; i_{qs} = i_{cq} + i_{lq} \quad (6)$$

$$V_{cd} = \frac{1}{C}\int i_{cd}\,dt + V_{cd}\,|_{t=0} \quad (7)$$

$$V_{cq} = \frac{1}{C}\int i_{cq}\,dt + V_{cq}\,|_{t=0} \quad (8)$$

where $V_{Cd}\,|_{t=0}$,$V_{Cd}\,|_{t=0}$ are the initial voltages of capacitors used for self-excitation, without which the voltage will not build up in SEIG. d-q axis load voltage and current is given by equation (9) - (12).

$$V_{ld} = L\frac{d}{dt}i_{ld} + Ri_{ld} \quad (9)$$

$$V_{lq} = L\frac{d}{dt}i_{lq} + Ri_{lq} \quad (10)$$

$$\frac{d}{dt}i_{ld} = \frac{1}{L}V_{ld} - \frac{R}{L}i_{ld} \quad (11)$$

$$\frac{d}{dt}i_{lq} = \frac{1}{L}V_{lq} - \frac{R}{L}i_{lq} \quad (12)$$

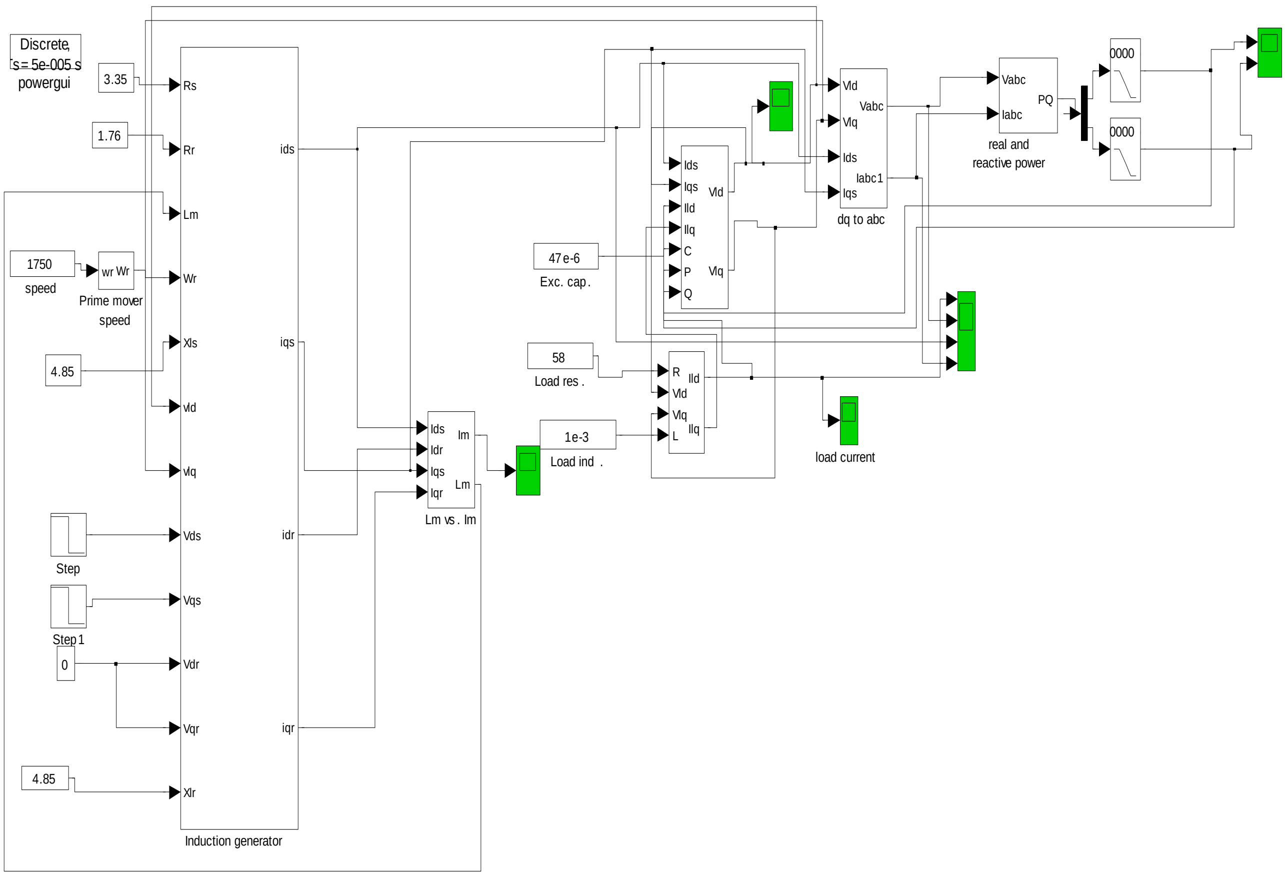

Fig. 2 MATLAB SIMULINK model of Self-Excited Induction Generator

Fig. 3 and Fig. 4 show the simulated results for voltage, current, active and reactive power, without any controller.

It is clear from Fig. 3 that terminal voltage varies with load variation. There is sudden rise or dip in terminal voltage when the load varies from full load to no load and vice-versa. Such variation in voltage at the load end is not permissible and it needs some control to maintain the power quality. These are due to the changes in real and reactive power of the load (Fig. 4).

5. Controller concept and model

The variation in terminal voltage and frequency is due to the imbalance in the power generated by generator and power absorbed by the load. The controller will regulate the terminal voltage and frequency of the generated power by balancing the real and reactive power produced and absorbed. The controller must be able to divert the extra power to the alternative load which is not absorbed by the consumer load.

In this paper an ELC is used as a controller connected in parallel with the load connected to SEIG. The ELC used consists of resistive and inductive elements as dump load along with uncontrolled rectifier-chopper system. The power absorbed by the dump load is controlled by duty cycle of the chopper to maintain the generated power equal to power consumed by the consumer load and the dump load. The duty cycle of the chopper depends on the difference between the reference terminal voltage and the actual voltage at the load end. The chopper will generate the gating signal to the insulated gate bipolar transistor (IGBT) which acts as a switch to control power input to dump load in ELC.

The control strategy of the IGBT's used in controller is based on measuring the real and reactive power absorbed by the consumer load. The strategy is shown in Fig. 5. There are present five IGBT's acting as switches. Fig. 6 depicts the steps of switching ON and OFF of IGBT's using flow chart.

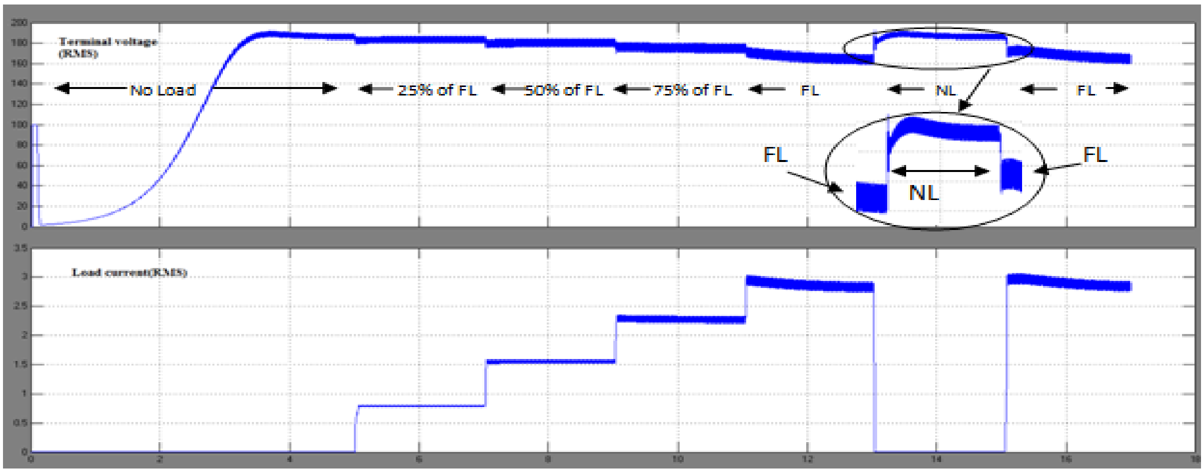

Fig. 3 Variation in terminal voltage and load current (without controller)

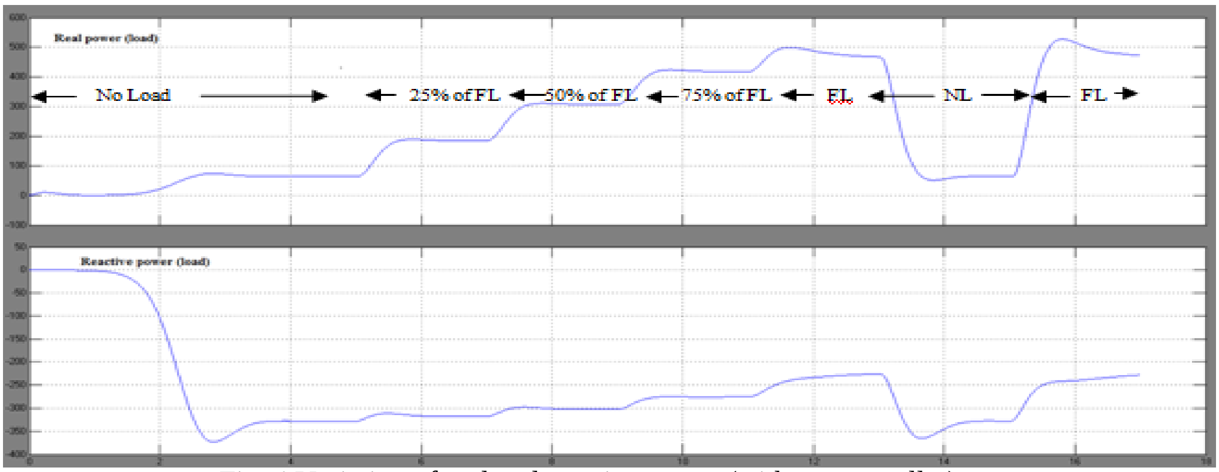

Fig. 4 Variation of real and reactive power (without controller)

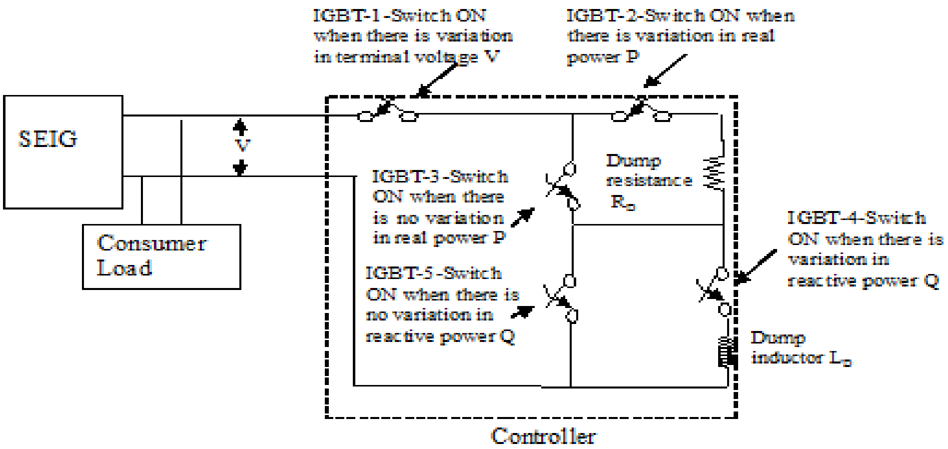

Fig.5 Control strategy of Electronic Load controller

6. Results and discussion

It is clear from Fig. 3 that as the load varies, variation in terminal voltage appears and it results in variation of real or reactive power or both. This variation in terminal voltage can be controlled by varying excitation capacitance, rotor speed or load impedance. Increasing capacitance will increase the size of the system and reduces the overall efficiency of the system. The rotor speed range of such generators is limited. The electronic load controller will maintain the load on the machine and it is due to consumer and dump load. Hence it maintains the total power generated equal to total power absorbed by controlling resistive and inductive element present as dump load in the controller. The rms value of variation in terminal voltage and load current in SEIG with variation in load, using controller is shown in Fig. 7. Real and reactive power variation in load is shown in Fig. 8.

Fig. 9 shows variation of real and reactive power absorbed in dump load. It is clear from Fig. 8 and Fig. 9 that the sum of total power absorbed in consumer load and dump load will always remain constant at any instant of time in order to maintain constant terminal voltage. At No load (NL), whole of the power will be absorbed by dump load and in case of full load (FL), the consumer load will take the total power generated by the machine, hence maintaining the relation of power generated equal to power consumed. Fig. 10 and Table 1 gives a comparison of the terminal voltage of SEIG without controller and with controller. It is shown in Table 1 that with the use of controller, the percentage deviation of the terminal voltage of SEIG with the rated terminal voltage (i.e. 240v) is very low (minimum 0f 0 % and maximum of 3.8%) while this percentage deviation rises to very high value (minimum of 2.1% and maximum of 10.8%) in case of SEIG without using controller.

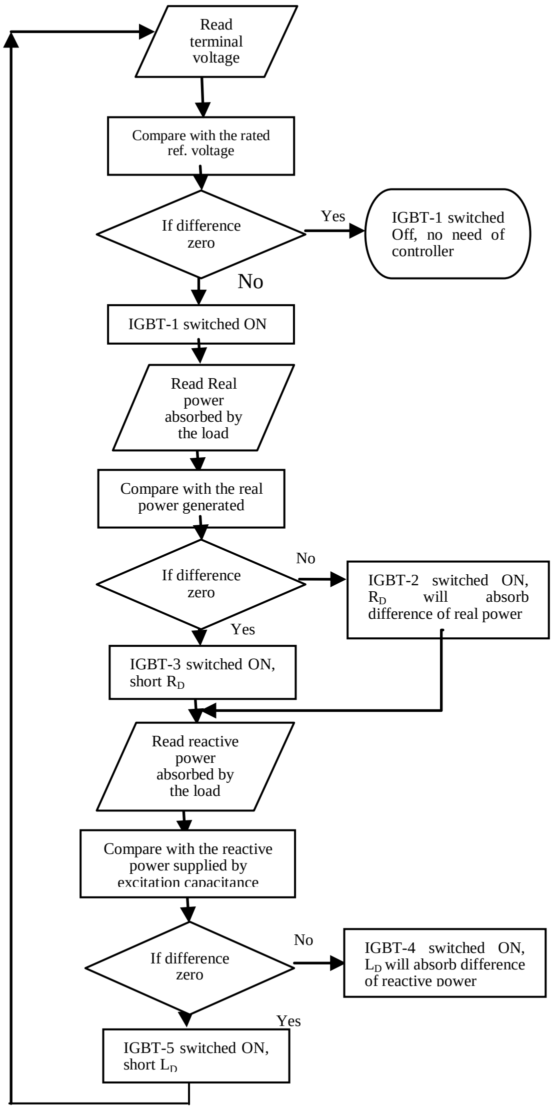

Fig.6 Controller Flow chart

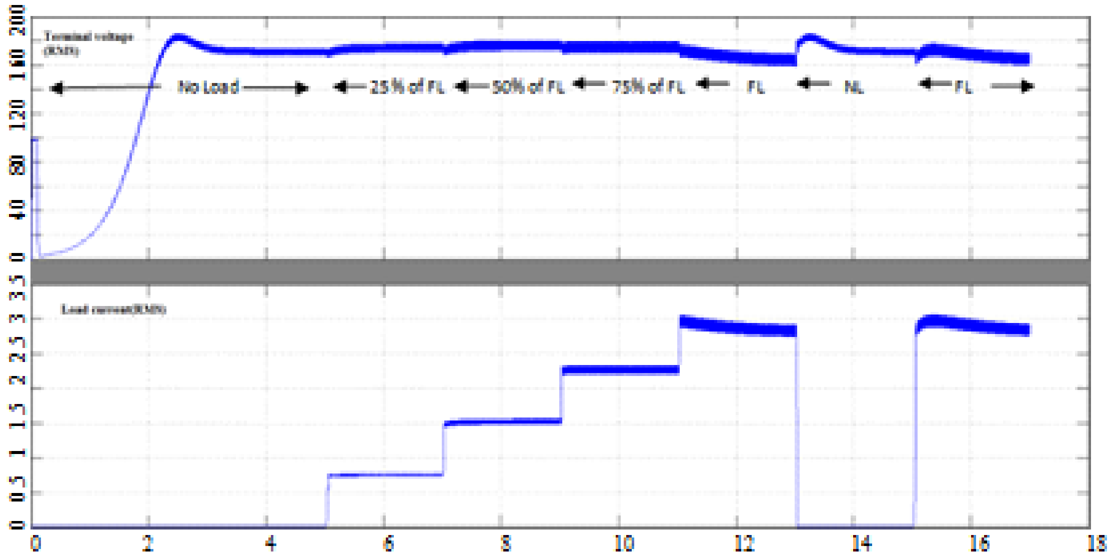

Fig. 7 Variation in terminal voltage and load current (with controller)

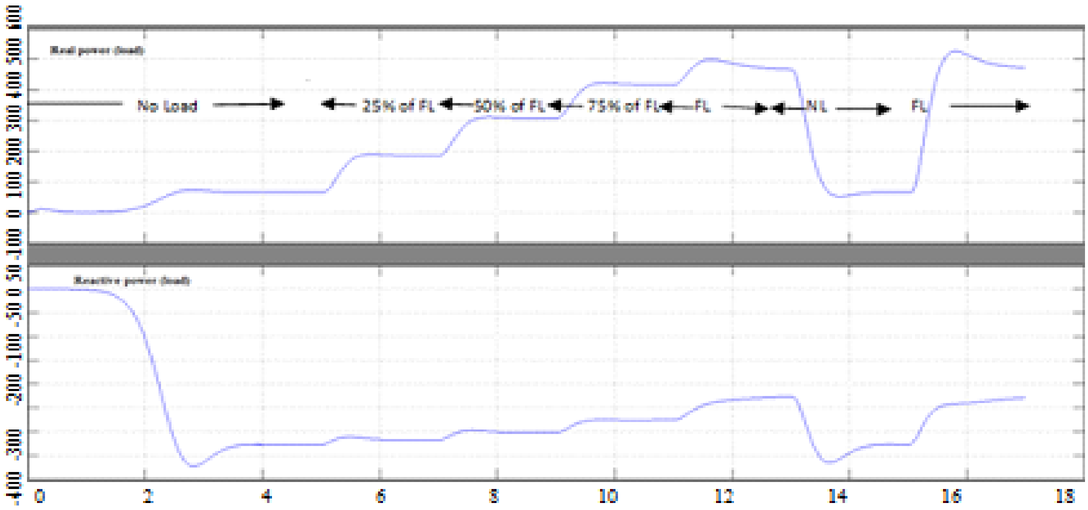

Fig. 8 Variation of real and reactive power in consumer load (with controller)

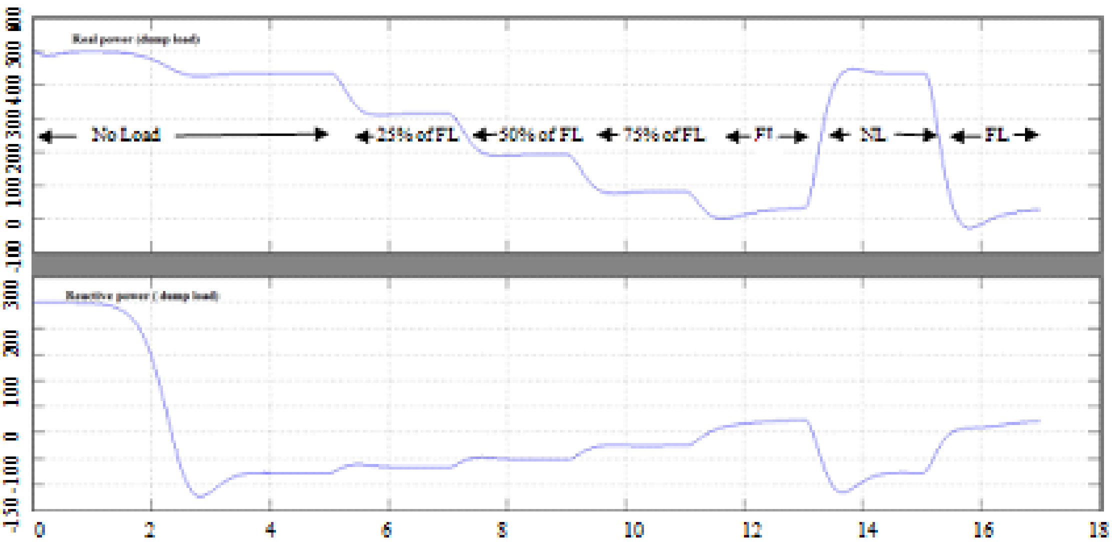

Fig. 9 Variation of real and reactive power in dump load

Table: 1 Comparison of terminal voltage with and without ELC controller

Sr. No.	Time (sec)	Consumer load	Without Controller		With Controller	
			Terminal voltage (v)	% deviation from rated value (240v)	Terminal voltage (v)	% deviation from rated value (240v)
1	0-5	No load	266	10.8 ↑	244(settles down from 254v to 244v in 1.0 sec)	1 ↑
2	5-7	25% of full load	260	8.3 ↑	247	3 ↑
3	7-9	50% of full load	256	6.7 ↑	249	3.8 ↑
4	9-11	75% of full load	249	3.8 ↑	248	3.3 ↑
5	11-13	Full load	235(settles down from 242v to 235v in 2.0 sec)	2.1 ↓	240	0
6	13-15	No load	266	10.8 ↑	244(settles down from 254v to 244v in 1.0 sec)	1 ↑
7	15-17	Full load	235 (settles down from 242v to 235v in 2.0 sec)	2.1 ↓	242(settles down from 246v to 242v in 1.7 sec)	0.8 ↑

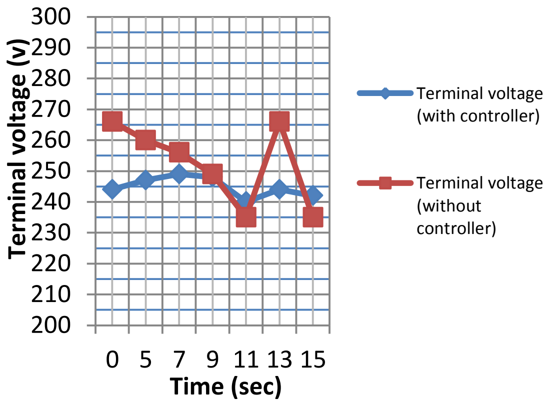

Fig. 10 Comparison of terminal voltage with and without controller

7. Conclusion

The paper proposed a nonlinear generalized state space dynamic modeling of self-excited induction generator for lagging power factor loads. It is shown that using d-q modeling in state space approach for SEIG, the transient analysis becomes an easy task. The terminal voltage obtained varies with the load variation and hence their utility decreases due to poor power quality supply. Here an attempt has been made to design an electronic load controller consisting of dump load having resistive and inductive elements in it, to control real and reactive power in order to maintain power generated equal to power consumed. Using such Electronic Load Controller will significantly reduce the variation in terminal voltage with variation in lagging power factor load.

8. Appendix

Machine-1

Induction machine specifications and parameters:

Rated power	3HP
Rated line to Line voltage	440v
Rated frequency	50 Hz
Number of poles	4 poles
Stator resistance R_s	0.32Ω
Rotor resistance R_r	0.41Ω
Stator leakage reactance X_{ls}	0.8Ω
Rotor leakage impedance X_{lr}	0.8Ω

References

1. Quazene, L., McPherson, G.: *Analysis of the isolated induction generator*. In: IEEE Transaction on Power Apparatus and Systems, PAS-102(1983), No. 8, pp. 2793-2798, August 1983.
2. Sandhu, K.S.: *Iterative Model for the analysis of self-excited induction generators*. In: Electric power Components and Systems, Vol.31 (2003), No.10, pp. 925-939, October 2003.
3. Rajakaruna, S., Bonert, R.: *Self-excited Induction generator with excellent voltage and frequency control*. In: IEE Proceedings-Generation Transmission Distribution, Vol. 145, No.1, pp. 33-39, 1998.
4. Singh, Bhim, Murthy, S.S., Gupta Sushma : Transient analysis of self-*excited induction generator with electronic load controller(ELC)* supplying static and dynamic loads. In: IEEE Transaction on Industry Applications, Vol. 41 (2005), No.5, pp. 1194-1204, September 2005.
5. Chang, T.F.: *Capacitance requirements of Self-Excited Induction Generator*. In: IEEE Transaction on Energy Conversion, Vol. 8 (1993), No. 2, pp. 304-310, June 1993.
6. Malik, N.H., Mazi, A.A.: *Capacitance requirements for isolated self excited induction generators*. In: IEEE

Transaction on Energy Conversion, Vol. EC-2 (1987), No. 1, pp. 62-68, March 1987.
7. Sridhar, L., Singh, B., Jha, C. S.: *Transient performance of the self regulated short shunt Self excited induction generator*. In: IEEE Transaction on Energy Conversion, Vol. 10 (1995), No. 2, June 1995.
8. Wang, Li., Jian- Yi Su.: *Dynamic Performances of an Isolated Self Excited Induction Generator Under various loading conditions.* In: IEEE Transaction on Energy Conversion, Vol. 14 (1999), No. 1, March 1999.
9. Senjyu, T., Sueyoshi, N., Uezato, K., Fujita, H., Funabashi, T.: *Transient Stability Analysis of Induction Generator Using Torque-Time Characteristic.* In: The Proceedings of 5th International Conference on Power Electronics and Drive Systems, Vol.1 (2003), November 2003, pp. 760-765.
10. Ahshan R., Iqbal M.T.: *Voltage controller of self-excited induction generator*. In: The Open Renewable Energy Journal, Vol. 2(2009), pp. 84-90, 2009.
11. Bonert, R., Hoops, G.: *Stand alone induction generator with terminal impedance controller and no turbine controls.* In: IEEE/PES summer meeting, Long Beach, California, 9-14 July, 1989, pp.28-31.
12. Lopes, L. A.C., Almeida, R. G.: *Wind driven self-excited induction generator with voltage and frequency regulated by reduced-rating voltage source inverter*. In: IEEE Transactions on Energy Conversion, Vol.21 (2006), No.2, pp. 297-304, June 2006
13. Sekhar, T.C., Muni, B. P.: *Analysis of self excited induction generator by spiral vector theory*. In: The 30th Annual conference of the IEEE Industrial Electronics Society, IECON-04, Busan, Korea, Nov. 2-6, 2004, pp. 319-323.
14. Bodson, M., Kiselychnyk, Ol. : *Nonlinear dynamic model and stability analysis of self-excited induction generators.* In: American Control Conference 2011, San Francisco, USA, June 29-July01, 2011, pp.4574-4579.
15. Singh, B., .Murthy, S.S., Gupta, S.: *Analysis and Design of electronic load controller for self -excited induction generators.* In: IEEE Transactions on Energy Conversion, Vol.21 (2006), No.1, pp.285-93, 2006.
16. Singh, B., .Murthy, S.S., Kulkarni, A., Sivarajan, R., Gupta, S.: *Field experience on a novel pico-hydel system using self-excited induction generator and electronic load controller*. In: The 5th International Conference of Power Electronics and Drive System 2003, Vol. 2, Issue -17-20, November 2003, pp. 842 – 847.
17. Subramanian K., Ray K.K., Prasad Hari K., Gopal Nand, Gupta Nirupama, Pragyajha, Sinha Meenakshi: *State of art of electronic load controller of self-excited asynchronous generator used in mimi/micro hydro power generatio.* In: The Proceedings of International conference on Control, Communication and Power Engineering, Vol. (2010), pp. 21-25.
18. Farret, F.A., Palle, B., Simoes, M.G.: *State Space Modeling of Parallel Self-Excited Induction Generators for Wind Farm Simulation*. In: IEEE Transaction on Industry Applications, Vol. 41 (2005), No. 4, July/August 2005.
19. Kishore, A., Kumar, G. S.: *A generalized state-Space modeling of three phase self-excited induction generator for dynamic characteristics and analysis.* In: 1st International conference. on Industrial Electronics and Applications, May 24-26, 2006, pp. 1-6.
20. Radosavljević Jordan, Klimenta, Dardan, Jevtić, Miroljub.: *Steady-State Analysis of Parallel-Operated Self-Excited Induction Generators Supplying an Unbalanced Load*. In: Journal of Electrical Engineering, Vol.63(2012), No.4, pp.213–223, September 2012.