Dynamic Performance Analysis and Voltage Regulation of a Wind Energy Conversion System with STATCOM

C. Veeramani, G. Mohan

Abstract*: Aim of this paper is to present the model and control design of a conventional wind energy system by employing induction generator. The system is divided into three stages whereas stage one consists of induction generator engendered by horizontal axis wind turbine and bordered to function by a twofold overhead transmission line. Second stage is to interface a static synchronous compensator (STATCOM) with the induction generator's terminal in order to regulate its voltage level. The third stage deals with controlling the mechanical power unit by blade pitch-angle. The proposed system has been evaluated using MATLAB/SIMULINK software. The simulation result proves the efficiency of the closed loop system beneath various sorts of disturbances.

Index Terms: Induction generator, Static synchronous compensator (STATCOM), Wind turbine, PI controller.

I. INTRODUCTION

Most modern wind turbines have three blades, and operate facing the wind and it consist of tall towers reach for constant, strong airflow. The wind turns the blades which spin a shaft, which in turn connects to a generator and makes electricity. The blades are controlled so they always spin at the same rate. Big, efficient turbines can generate up to 3.6 megawatts each. One megawatt is enough to provide power to about 300 or more homes.

The above statement gives us the brief knowledge about the function of wind mills from which it is clear that wind is given as input to produce electricity which is an unstable input that can be subjected to several kind of disturbance. The unstable state of wind is the major problem. That is the speed of wind varies from time to time. Another major problem is the shadow of the large tower. These problems have been analyzed and several solutions were obtained. The speed of the wind is synchronized with the blade movement using blade pitch angle control [1], [2].

Detailed study is made on mathematical model of stand-alone wind energy conversion system that consist of battery energy storage [3] further, knowledge about the efficiency of induction generator is obtained by analyzing [4]. Induction generator grabs the advantage of higher reliability and lower cost comparing to the synchronous generator and the control equipments of induction generator is not complex like that of synchronous generator.

Manuscript Received Nov 10, 2013.

C.Veeramani, Department of Electrical & Electronics Engineering, Annamalai University, Chidambaram, TamilNadu, India.
Prof. G.Mohan, Department of Electrical & Electronics Engineering, Annamalai University, Chidambaram, TamilNadu, India.

In this paper induction generator is coupled with Static synchronous compensator (STATCOM) in order to compensate the synchronous function of synchronous generator. Horizontal axis wind turbine with induction generator coupled with Static synchronous compensator (STATCOM) is taken into account and dynamic modeling and control designs were showcased. Linear model is used to regulate the output in PI controllers and the system efficiency is tested by subjecting it to higher order disturbance.

II. WIND GENERATION SYSTEM CONFIGURATION

Figure 1 shows the overview of wind generation system, it consists of Horizontal Axis Wind Turbine (HAWT) followed by induction generator with STATCOM at its terminals for voltage regulation and it is then interfaced to utility grid through overhead transmission line.

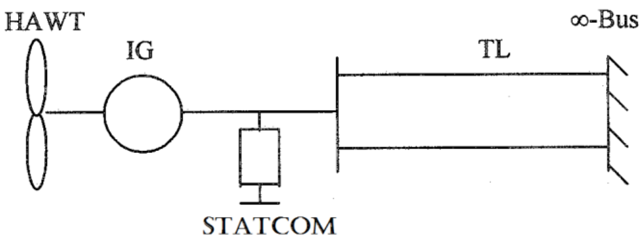

Fig. 1: Wind generator system

III. SYSTEM MODELING

A. Wind turbine model

The wind turbine is characterized by non-dimensional curves of the power co-efficient C_p is expressed as a function of tip speed ratio λ and blade pitch angle β. λ represents the ratio between the linear speed at the blade's tip and the wind's speed. λ can be represented as follows

$$\lambda = \Omega R / V_w \tag{1}$$

Where, R represents Wind Turbine's rotor radius, Ω represents Wind Turbine rotor's mechanical angular velocity and V_w is the velocity of the wind. Then, the power co-efficient C_p can be given as [2]

Published By:
Blue Eyes Intelligence Engineering
& Sciences Publication

$$C_p = (0.44 - 0.0167\beta)\sin\pi(\lambda - 3)/(15 - 0.3\beta) - 0.00184(\lambda - 3)\beta \quad (2)$$

T_m is the Wind Turbine's mechanical torque and it can be calculated by [1]

$$T_m = \frac{\frac{1}{2}\rho A R C_p V_w^2}{\lambda} \quad (3)$$

where, ρ represents the air density and A represents the area swept by the blades.

B. Model of induction generator

The wind turbine drives an induction generator whose flux linkage model can be described in d- and q-axis synchronous reference frame as [5]:

$$p\varphi_{ds} = \omega_b(V_{ds} + R_s i_{ds} + \varphi_{qs}) \quad (4)$$

and

$$p\varphi_{qs} = \omega_b(V_{qs} + R_s i_{qs} - \varphi_{ds}) \quad (5)$$

$$p\varphi_{dr} = \omega_b(V_{dr} - R_r i_{dr}) + (\omega_b - \omega_m)\varphi_{qr} \quad (6)$$

$$p\varphi_{qr} = \omega_b(V_{qr} - R_r i_{qr}) - (\omega_b - \omega_m)\varphi_{qr} \quad (7)$$

In the above equations, all the rotor variables are referred to the stator side. The expression for the electromagnetic torque in per unit can be written as:

$$T_e = (\varphi_{ds}\, i_{qs} - \varphi_{qs}\, i_{ds}) \quad (8)$$

The wind turbine and induction generator rotors are represented as a lumped one mass. So, the dynamic equation of motion can be written as:

$$p\omega_m = (\omega_b\ / 2H) * (T_m - T_m) \quad (9)$$

where H is the equivalent inertia constant of both wind turbine and induction generator rotors.

C. STATCOM model

The STATCOM is a Flexible AC transmission system (FACTS) controller based on voltage sourced converter (VSC). A VSC generate a synchronous voltage of fundamental frequency, controllable magnitude and phase angle. If a VSC is shunt-connected to a system via a coupling transformer then the resulting STATCOM can inject or absorb reactive power to or from the bus to which it is connected and thus regulate the bus voltage magnitude [6], [7]. This STATCOM model is known as Power Injection Model (PIM) or Voltage Source Model (VSM). Steady state modeling of STATCOM within the Newton-Raphson method in rectangular co-ordinates is carried out as follows:

The Thevenin equivalent circuit representing the fundamental frequency operation of the switched-mode voltage sourced converter and its transformer is expressed in Norton equivalent form shown in figure 2.

$$V_{STC} = V_k + Z_{SC} I_{STC} \quad (10)$$

$$I_{STC} = I_N - Y_{SC} V_k \quad (11)$$

where,

$$I_N = Y_{SC} V_{STC} \quad (12)$$

In these expressions, V_K represents bus K voltage and V_{STC} represents the voltage source inverter. I_N is the Norton's current while I_{STC} is the inverter's current.

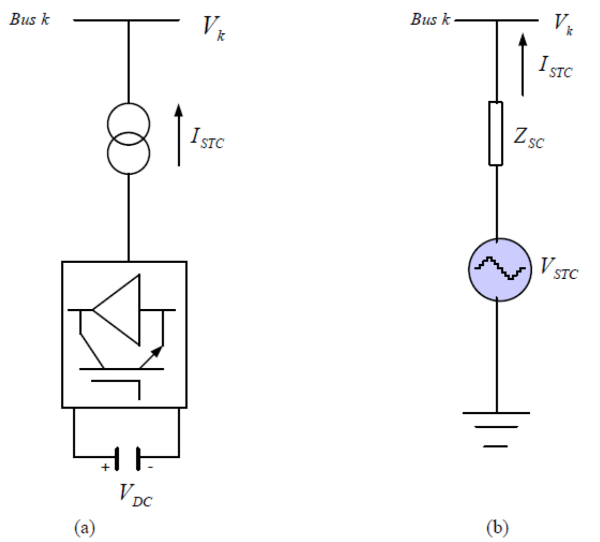

Fig. 2: Thevenin Equivalent Circuit Diagram of STATCOM: (a) STATCOM Schematic Diagram; (b) STATCOM Equivalent Circuit

The STATCOM voltage injection V_{STC} bound constraints is as follows:

$$V_{STC\,min} \le V_{STC} \le V_{STC\,max} \quad (13)$$

Where V_{STCmin} and V_{STCmax} are STATCOM's minimum and maximum voltages.

The current expression in (8) is transformed into a power expression by the VSC and power injected into bus k as shown in equations (11) and (12) respectively.

$$S_{STC} = V_{STC} I^*_{STC} \quad (14)$$

$$S_{STC} = V^2_{STC} Y^*_{SC} - V_{STC} Y^*_{SC} V^*_k \quad (15)$$

$$S_k = V_k I^*_{STC} \quad (16)$$

$$S_k = V_{STC} Y^*_{SC} V^*_k - V^2_k Y^*_{SC} \quad (17)$$

IV. OUTPUT CONTROLLER DESIGN

Published By:
Blue Eyes Intelligence Engineering
& Sciences Publication

Two paths are available for control of the wind turbine. STATCOM control at the terminal of the induction generator allows for regulation the terminal voltage to a set point. The second path is control of the blade pitch angle, which effects the mechanical input power to the generator. To limit the mechanical stress in the wind turbine torsional system, a rate limit +/-10 deg/s should be put on the blade pitch actuator, which controls the mechanical power. The electrical power and voltage regulations are achieved through PI controllers. The controllers' design is based on the linearized model. Two integrators are applied on the error signals (Pref - Pg) and (Vref - Vs). These two integrators are augmented with the state space linearized model to give the following augmented model:

$$pz = \phi z + \Gamma u + Ed \tag{18}$$

Based on the augmented model, a state feedback controller, which takes the following form:

$$u = -K_s z \tag{19}$$

can be designed using modern control design techniques. In this paper, the pole-assignment technique was used. By selecting the desired closed loop poles, Ks can be obtained using the MATLAB software.

The output feedback controller gains can be derived from the state feedback gains using Pseudo-inverse matrix form. The output vector y can be written as follows:

$$y = Cz \tag{20}$$

If CtC is invertible, the state vector z can be obtained as a function of output vector y as follows:

$$z = [C^t C]^{-1}, Cy = pinv(C)y \tag{21}$$

By defining the output feedback control law as

$$u = -K_o y \tag{22}$$

and using (14) and (16), Ko can be derived from Ks as follows:

$$K_o = K_s pinv(C) \tag{23}$$

Fig. 3 shows the block diagram representation of state and output controllers.

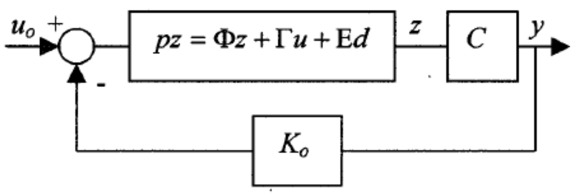

Fig. 3: Output feedback controllers

V. RESULTS AND DISCUSSIONS

Pitch angle control systems of the wind turbine were simulated using MATLAB/SIMULINK tool to test the control strategy and evaluate the performance of the system.

A wind farm consisting of 1.5-MW wind turbines is connected to a 25-kV distribution system exports power to a 120-kV grid through a 25-km 25-kV feeder [8], [9]. Wind turbine uses induction generator. The stator winding is connected directly to the 60 Hz grid and the rotor is driven by a variable-pitch wind turbine. The Simulink model of the system is shown in figure 4.

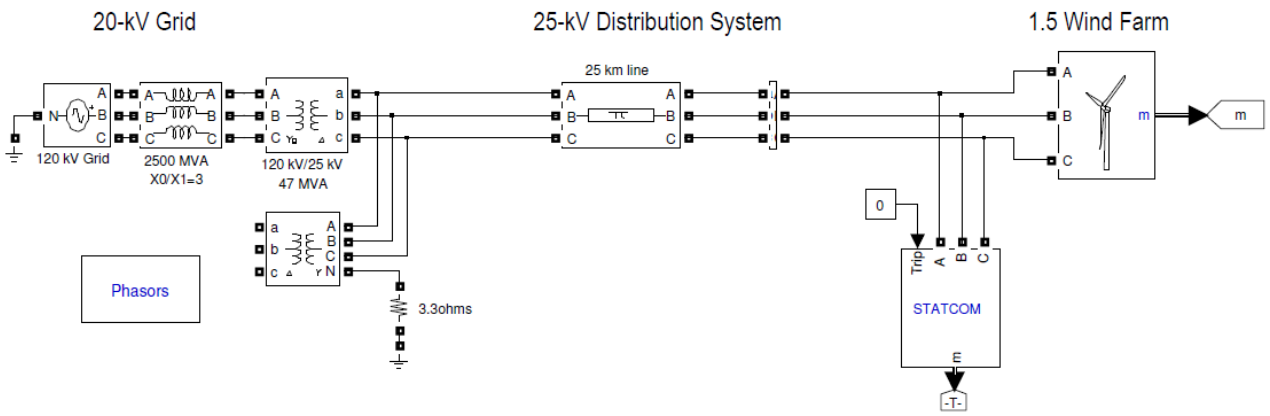

Fig. 4: Simulink model of Wind Energy Conversion System

The pitch angle is controlled by output PI controller with gain Kp = 5 and Ki = 25, in order to limit the generator output power at its nominal value for winds exceeding the nominal speed (9 m/s). In order to generate power the generator speed must be slightly above the synchronous speed. Speed varies approximately between 1 pu at no load and 1.005 pu at full load. Each wind turbine has a protection system monitoring voltage, current and machine speed.

Reactive power absorbed by the Induction generator is partly compensated by capacitor banks connected at each wind turbine low voltage bus (400 kvar). The rest of reactive power required to maintain the 25 kV voltage at distribution system close to 1 pu is provided by a 3-Mvar STATCOM with a 3% droop setting.

Initially, wind speed is set at 8 m/s, then starting at t = 2s for wind turbine, wind speed is rammed to 11 m/s in 3 seconds. The gust duration time is 3 seconds. After the gust, the wind velocity was held constant at a new value superimposed i.e., 11 m/s. The figure 5 shows the waveform of Response of Generator Output Power for a gust change in wind speed. The figure 6 shows the waveform of Response of Generator Terminal Voltage for a gust change in wind speed. The figure 7 shows the waveform of Response of Rotor speed for a gust change in wind speed. The figure 8 shows the waveform of Response of Pitch Angle for a gust change in wind speed

From the figures, the closed loop response with STATCOM has a good damping and the maximum terminal voltage and electrical power excursions are significantly smaller and limited to about 0.45% for voltage and 1.25% for power. The rotor speed deviation is very small and is equal to 0.25 rad/s.

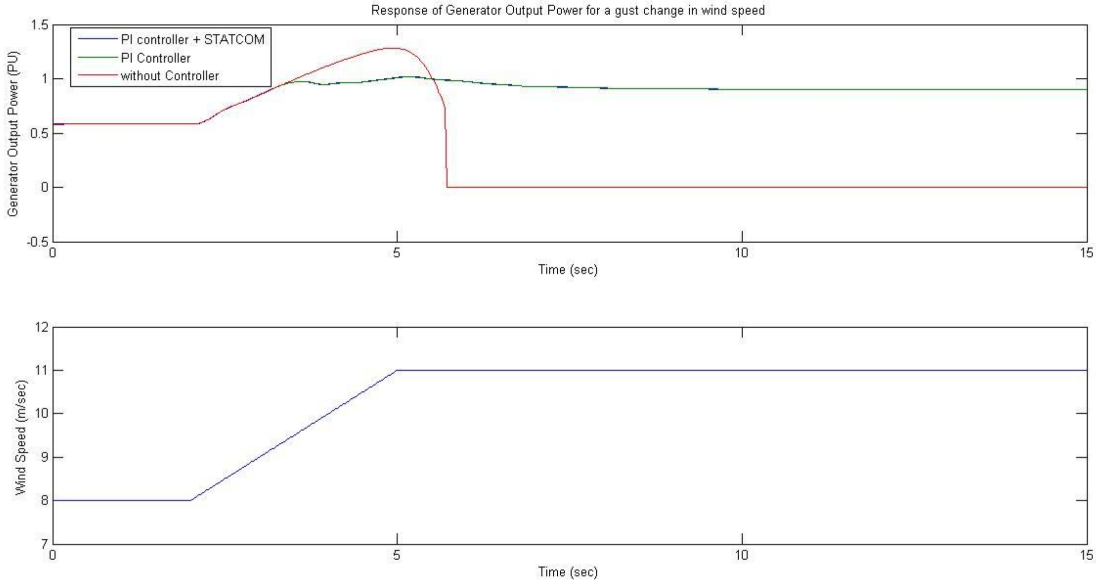

Fig. 5: Response of Generator Output Power for a gust change in wind speed

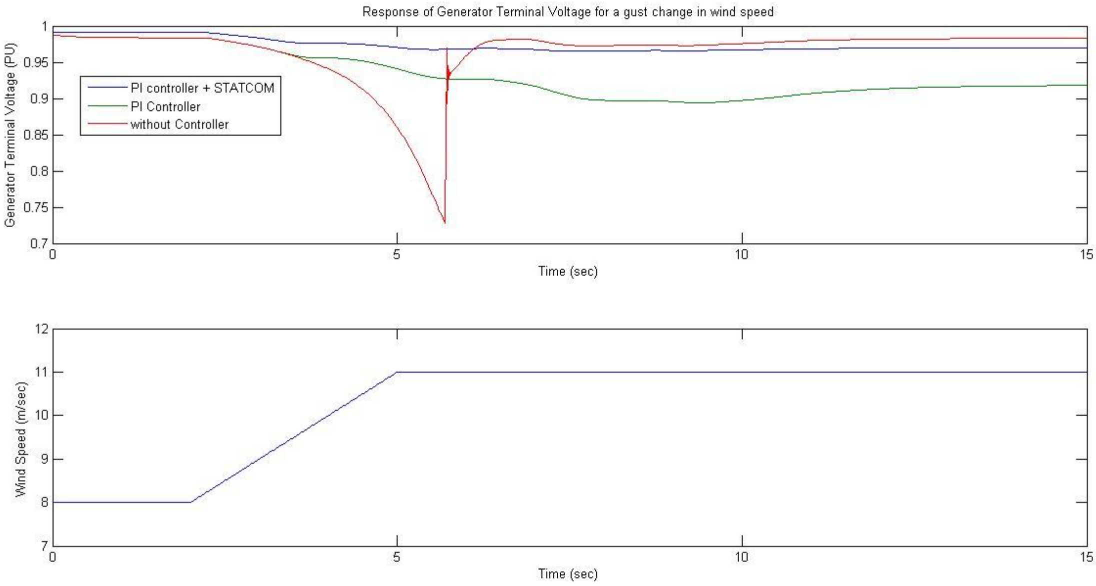

Fig. 6: Response of Generator Terminal Voltage for a gust change in wind speed

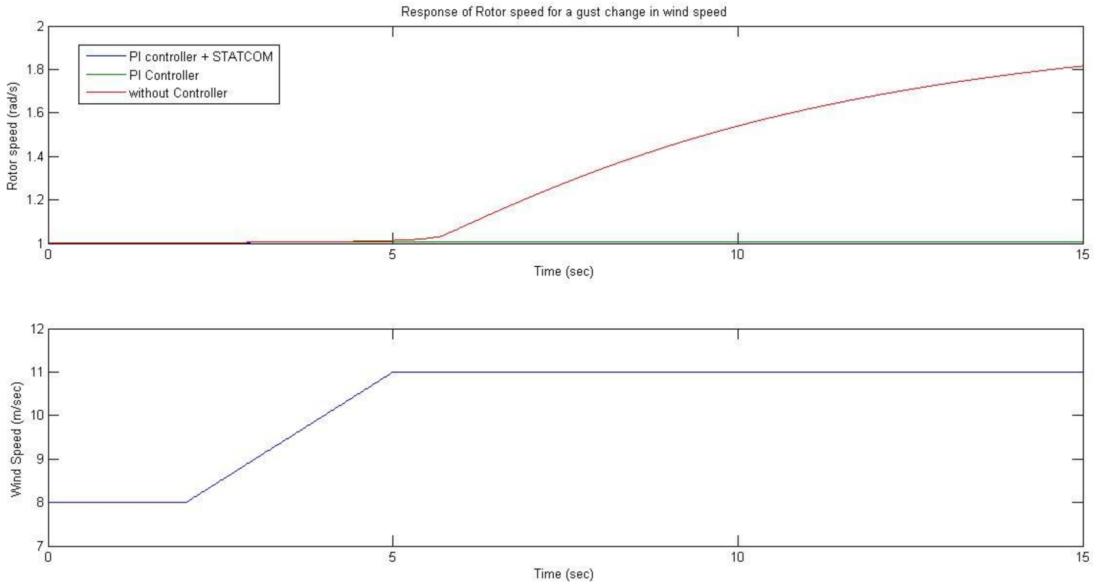

Fig. 7: Response of Rotor speed for a gust change in wind speed

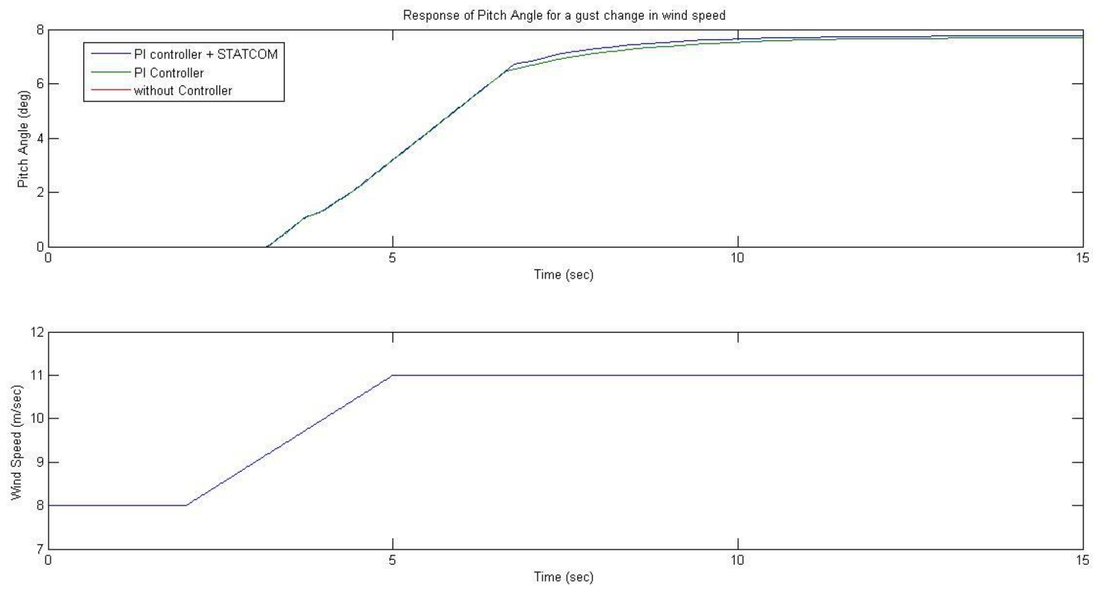

Fig. 8: Response of Pitch Angle for a gust change in wind speed.

VI. CONCLUSION

In this paper modeling and control design for a wind turbine induction generator unit has been analyzed. STATCOM has been used to achieve required voltage regulation. Output PI controllers were designed and implemented in the nonlinear simulation model. A good damping performance has been achieved for the closed loop system during severe wind gusts. The simulation result proves the performance of the system with STATCOM is high even during sever wind gusts.

ACKNOWLEDGMENT

The authors wish to thank the authorities of Annamalai University, Chidambaram, Tamil Nadu, India for the facilities provided to prepare this paper.

REFERENCES

1. O. Wasynczuk, D. T. Man, and J. P. Sullivan, "Dynamic behavior of a class of wind turbine generators during random wind fluctuations," IEEE Trans. on PAS, vol. 100, no. 6, pp. 2837–2845, June 1981.
2. J. R.Winkelman and S. H. Javid, "Control design and performance analysis of a 6 MW wind turbine generator," IEEE Trans. on PAS, vol. 102, no. 5, pp. 1340–1347, May 1983.
3. B. S. Borowy and Z. M. Salameh, "Dynamic response of a stand-alone wind energy conversion system with battery energy storage to a wind gust," IEEE Trans. on EC, vol. 12, no. 1, pp. 73–78, Mar. 1997.
4. F. P. de Mello, J.W. Feltes, L. N. Hannett, and J. C. White, "Application of induction generators in power system," IEEE Trans. on PAS, vol. 101, no. 9, pp. 3385–3393, 1982.
5. I. Boldea and S. A. Nasar, Electric Machine Dynamics. NewYork, NY: Macmillan Publishing Company, 1986
6. Hingorani N.G. and Gyugyi, L. (2000), "Understanding FACTS", The Institute of Electrical and Electronics Engineers, New York.

7. Sen, K.K., (1999), "STATCOM-static synchronous compensator theory, modelling and applications", IEEE PES Winter Meeting 2, pp.1177-1183.
8. Krause, P.C., O. Wasynczuk, and S.D. Sudhoff, Analysis of Electric Machinery, IEEE Press, 2002.
9. Mohan, N., T.M. Undeland, and W.P. Robbins, Power Electronics: Converters, Applications, and Design, John Wiley & Sons, Inc., New York, 1995, Section8.4.1.

AUTHOR PROFILE

C. Veeramani received his B.E degree from Faculty of Engineering and Technology, Annamalai University, Chidambaram, Tamil Nadu, India in 2005 and M.E degrees from Faculty of Engineering and Technology, Annamalai University, Annamalai Nagar, Chidambaram, India in 2007. He is currently working towards the Ph.D. degree, Department of Electrical Engineering, Faculty of Engineering and Technology, Annamalai University, Chidambaram, Tamil Nadu, India. His research interest includes power system operation and control.

G. Mohan Professor, Department of Electrical Engineering, Faculty of Engineering and Technology, Annamalai University, Chidambaram, Tamil Nadu, India. His research interest includes power system operation and control.