IJIREEICE
ISSN (Online) 2321 – 2004
ISSN (Print) 2321 – 5526
International Journal of Innovative Research in Electrical, Electronics, Instrumentation and Control Engineering
Nitte Conference on Advances in Electrical Engineering NCAEE-2016
NMAM Institute of Technology, Nitte
Vol. 4, Special Issue 2, April 2016

ENHANCEMENT OF LOAD VOLTAGE REGULATION USING ELECTRIC SPRING

Benzeeta Ann D'Souza[1], **Dr. Nagesh Prabhu**[2]
PG Scholar, Micro Electronics and Control Systems, NMAMIT, NITTE, Udupi, India[1]
Professor, Department of E&E, NMAMIT, NITTE, Udupi, India[2]

Abstract: Power grid connected to an intermittent renewable energy source is associated with voltage and frequency fluctuations. This paper aims to use an Electric Spring (ES) in a smart way to enhance the load voltage regulation and increase the stability of the system. In the proposed model the Electric Spring is connected in series with the Non Critical Load forms a smart load. The critical load is connected in shunt with this smart load whose voltage to be maintained constant. Depending on the type of Critical Load, the phase angle between the current of Non Critical Load (Z_{nc}) and ES voltage is controlled to maintain constant bus voltage. The simulation results show the effectiveness of ES in enhancing the load voltage regulation.

Keywords: Electric Spring, smart load, load voltage regulation, stability.

I. INTRODUCTION

A number of non linear and unbalanced loads in power distribution network cause distortion in the grid voltage and current waveforms, or can cause voltage fluctuation. The critical loads are sensitive to voltage variations and there is a need for high quality power. Some special industries and hospitals which have many sensitive electrical power equipments require constant voltage and good power quality as any active power (P) and reactive power (Q) problems any lead to financial loss and equipment failure.

In order to minimize PQ problems, a new technique called Electric Spring (ES) is introduced which regulates the voltage across Critical Load (V_{nc}) inspite of the fluctuation caused in the line voltage [1] [2].The line voltage regulation is achieved by varying the voltage across non critical load. Electric Spring (ES) is connected in series with Non Critical Load (Z_{nc}) which is less sensitive to voltage fluctuations.

ES injects a controllable voltage to regulate the voltage across the sensitive Critical Loads. This paper is aimed at developing a simple yet accurate model for the ES.

The description of ES based on the Hooke's law, principle and operation of Electric Spring are described. The simulation results are presented for capacitive and inductive modes of operation of ES.

II. PRINCIPLE AND FUNCTIONALITY OF ELECTRIC SPRING

An ES is an electric device which is similar to a mechanical spring and can be used to i) store electric energy; ii) provide power support; and iii) damp power oscillations. When a mechanical spring is stretched or compressed, it exerts a force proportional to its change in displacement. Potential energy is stored in the mechanical spring when the length of the spring deviates from its natural length. The principle of the mechanical springs has been described by Robert Hooke [3]. The Hooke's law states that the force of an ideal mechanical spring is:

$$F = -kx \qquad (1)$$

where k-spring constant, F-force vector, x-displacement vector.
Corresponding to Equation 1, the basic physical relationship of the ES can be expressed as

$$q = \int i_c \, dt \qquad (2)$$

$$q = \begin{cases} C\,V_{es}, & \mathit{Inductive\ mode} \\ -C\,V_{es}, & \text{Capacitve mode} \end{cases} \qquad (3)$$

The dynamic reduction and boosting functions of an ES is shown in Equation 3. ES can be controlled by the charge stored in the capacitor. By using a current controlled source the charge control can be realized as represented in Equation 2. Therefore, an ES can be represented as a Current-Controlled Voltage Source.

DOI 10.17148/IJIREEICE/NCAEE.2016.41

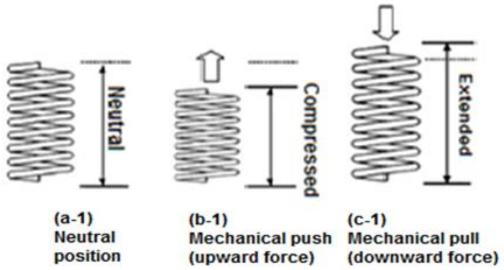

Figure 1: Functionality of a mechanical spring

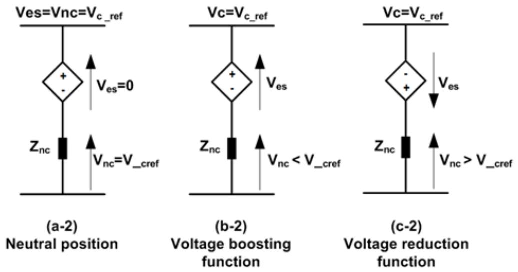

Figure 2: Functionality of an electric spring

Fig 1 and Fig 2 show functionality of the mechanical spring and an ES under three conditions. Here the dissipative electric load Z_{nc} is in series with ES. The neutral position of an ES is a reference voltage (e.g:220 V) at which the ES is designed to maintain. To maintain this voltage, the ES is in series with Z_{nc} across the ac mains which is considered as the neutral position. The charge control in equation 2 is a way through which an electric voltage is generated in both directions so as to reduce or boost the grid voltage in a power system to provide dynamic voltage support [4].

III. ELECTRIC SPRING – BASIC OPERATION

One of the approaches to control the disturbed voltage with the help of voltage compensator connected in series with the Non Critical Load is electric spring. These Non Critical Loads are not very sensitive to voltage fluctuations. Series voltage is injected by the voltage compensator which leads or lags the current flowing through it, thus regulates the PCC voltage where the Critical Loads are connected. As it regulates the voltage across Critical Load, ES also contributes to the control of frequency by changing the voltage and power consumed by the Non Critical Loads. Fig 3 shows the Non Critical Load (Z_{nc}) which is connected in series with the ES which forms a smart load. The System data is given in Table 1.

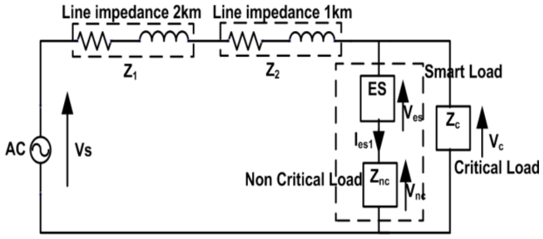

Figure 3 Smart load and Critical load in future smart grid

SYSTEM DATA		
Nominal Phase Voltage (V_i)	220 V_{ac}	
Critical Load Impedance (Z_C)	11Ω, 3.99mH	
Non Critical Load Impedance (Z_{NC})	7Ω, 5.99mH	
LINE IMPEDANCE (Z_1 and Z_2)		
DISTANCE	RESISTANCE	INDUCTANCE
1Km	0.1 Ω	1.22mH
2Km	0.1 Ω	2.4mH

Table 1 System Data

To control the reactive power, an ES injects a compensation voltage V_{es} in quadrature with the series current (I_{es1}) flowing through it. The series current (I_{es1}) leads the voltage V_{es} by 90° (Capacitive mode for voltage support) or lags the voltage V_{es} by 90°(Inductive mode for voltage reduction). Fig 4 shows the phasor diagrams for capacitive and inductive modes.

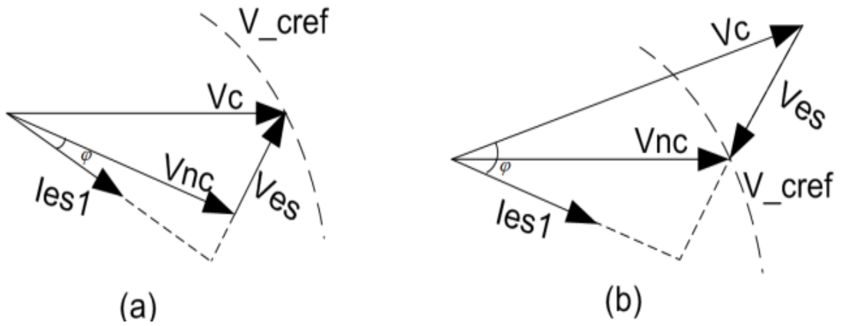

Figure 4 Phasor diagrams for (a) Capacitive mode (b) Inductive mode.

The Critical and Non Critical Loads are considered to be RL loads. As we regulate the input voltage V_s, the output voltage V_c fluctuates dynamically, and thus the ES will provide voltage support. Thus ES provides input voltage control [5].

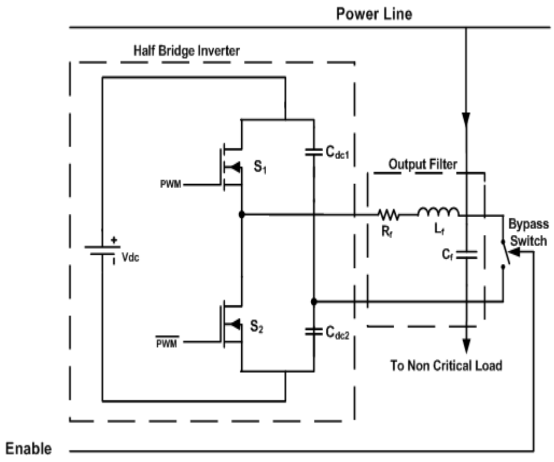

Figure 5 Circuit diagram of a single phase half bridge inverter.

Switching frequency	20kHz
Topology of an inverter	Single Phase Half Bridge Inverter
DC Bus Capacitance	C_{dc1}=1000µF C_{dc2}=1000µF
DC Bus Voltage (V_{dc})	400V_{dc}
Output Low Pass Filter	
Measured Resistance (R_f)	0.5Ω
Measured inductance (L_f)	1.92mH
Measured Capacitance (C_f)	13.2µF
Switching Scheme	Sinusoidal PWM

Table 2 ES data.

A. PWM Generation

Sinusoidal Pulse Width Modulation (SPWM) consists of a relational operator to compare the reference signal (V_r) and carrier signal (V_c) and generate a bipolar switching signal. V_r is a sine wave having frequency 50Hz. V_c is a triangular carrier wave having a frequency 20Khz.

B. Half Bridge Inverter with filter

Fig 5 shows the schematic of Half Bridge Inverter with filter. It consists of two semiconductor switches S_1 and S_2. MOSFET switches are used. S_1 is ON during the positive half cycle of the output voltage, which makes $V_a = + V_{dc}/2$ and S_2 is ON during the negative half cycle which makes $V_a = - V_{dc}/2$.

The both switches must operate alternatively otherwise there may be a chance of short circuiting.

The output of the PWM half bridge inverter is given to RLC filter so as to get a sinusoidal voltage waveform. The selection of inductance and capacitance values of a filter is based on capacitor voltage and current ripple.

The filter adds a base load to the inverter, which increases the inverter losses. The operations of the filter rely on the DC bus voltage, inductance and capacitance values and switching frequency.

IV. POWER CIRCUIT OF AN ELECTRIC SPRING

Power circuit of an ES is shown in Fig 6. The injected voltage by the ES is represented as V_{es}. R_f, L_f and C_f are the resistance, inductance and capacitance of the output filter at the inverter terminal [6].

Maintaining active power balance on the DC and AC side of the DC –AC converter neglecting looses in an inverter, results in:

$$P_{dc} = \frac{1}{2}(C_{dc1} + C_{dc2})\frac{d(V_{dc})^2}{dt}$$

$$= (C_{dc1} + C_{dc2})V_{dc}\frac{d(V_{dc})}{dt} = I_{in}{}^2 R_f \qquad (4)$$

On the AC side applying KCL:

$$I_{es1} + I_{in} = C_f\frac{dV_{es}}{dt} \qquad (5)$$

Applying KVL on the output side of the inverter:

$$V_a - V_{es} = L_f\frac{dI_{in}}{dt} + R_f I_{in} \qquad (6)$$

and

$$V_C = R_{NC}\, I_{es1} + V_{es} \qquad (7)$$

From Fig 5 and Fig 6 the terminal voltage at the Half-bridge module can be written as:

$$V_a(t) = \left(\frac{V_{dc}}{2}\right) PWM - \left(\frac{V_{dc}}{2}\right)\overline{PWM} \qquad (8)$$

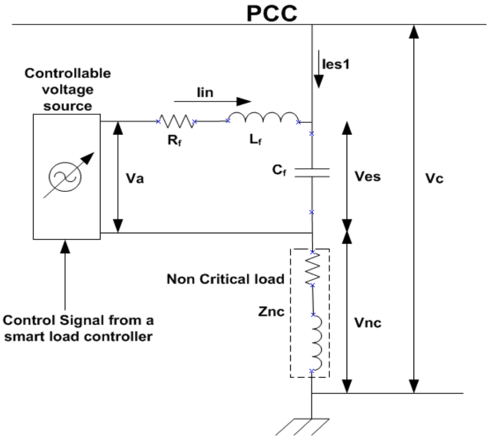

Figure 6 Power circuit model of Smart Load and ES.

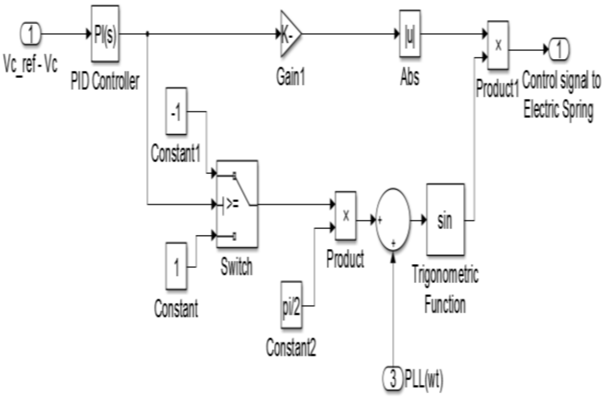

Figure 7 Electric Spring Controller.

V. DESIGN OF CONTROLLER FOR AN ELECTRIC SPRING

Fig 7 shows a block diagram of the ES controller modeled in MATLAB/SIMULINK. The phase angle between the injected voltage (V_{es}) and series current (I_{es1}) is 90° leading or lagging depending on the sign of the error between the reference value and measured value. The phase angle of I_{es1} is determined using a single-phase phase locked loop (PLL). The PI compensator output determines the magnitude of the modulation index (m) which drives the difference between reference PCC voltage (V_{c_ref}) and measured PCC voltage (V_c) to zero. A scaling factor K is used to limit the PI controller output within ±1 .The PI controller is a continuous controller to act and help in track the phase of I_{es1}.

VI. SIMULATION RESULTS

As shown in Fig 7, the voltage error is fed to the continuous PI controller. A gain factor is used to limit the value to ±1.Thus the magnitude of the signal is controlled for the sinusoidal PWM generation. Along with magnitude, the phase of the control signal is also fed to the sinusoidal PWM generator, which generates gating pulses to trigger MOSFET's. The PWM voltage output of the half bridge inverter is filtered using RLC low pass filter so as to get a sinusoidal voltage. Phase of the control signal ensures that the ES injected voltage (V_{es}) is either leading or lagging the ES current (I_{es1}) by 90°. Matlab simulation is done and the results are as shown.

When the electric spring is in neutral position, ie when $V_c = V_{c\_ref}$ ES is not activated. Thus Z_{nc} and Z_c are connected in parallel across the grid. The voltages V_c and V_{nc} remain constant.

When $V_c < V_{c\_ref}$ it results in under voltage. In order make $V_c = V_{c\_ref}$ the ES operates such as to boost V_c, thus operating in capacitive mode. Fig 8 shows where ES operates in capacitive mode i.e I_{es1} leads V_{es} by 90°. The ES is activated at t=0.15sec.

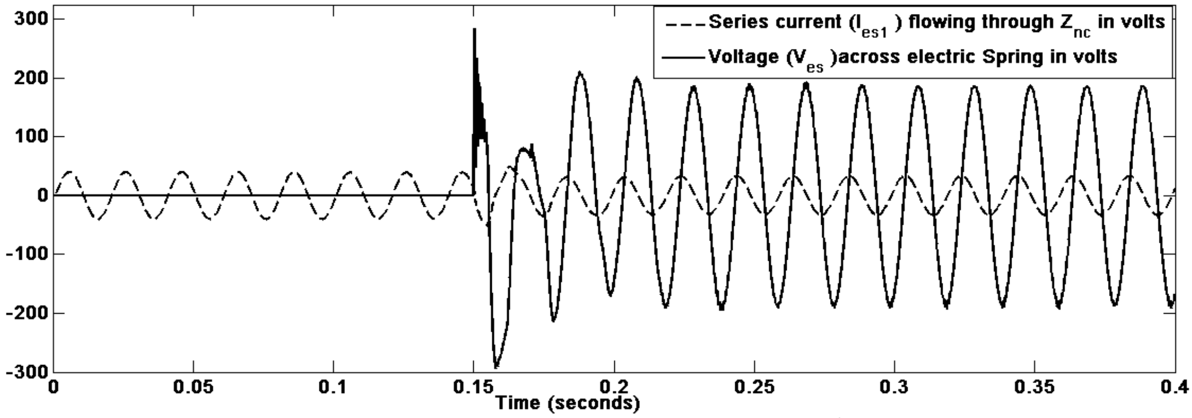

Figure 8 Capacitive mode Ies_1 leads Ves by 90°.

Fig 9 shows ES operating in capacitive mode when $V_c < V_{c\_ref}$, for $V_{c\_ref} = 216V$. At t=0 sec disturbance is created and the reactive power is Q= 487Var. At t= 0.1sec the disturbance is further increased (line voltage is reduced) and the reactive power will be Q = 1100Var. At t= 0.15 sec electric spring is activated. The controller varies the modulation index is varied line voltage is increased and maintained at a value equal to V_{c_ref}.

The measured RMS voltage across Critical Load when $V_c < V_{c\_ref}$ is shown in Fig 9. It is observed that, at t = 0.15sec when ES is activated, it injects a voltage (V_{es}) such as to boost V_c to the reference value ($V_{\_ref}$ = 216V). As the ES tries to boost V_c ,V_{nc} reduces.

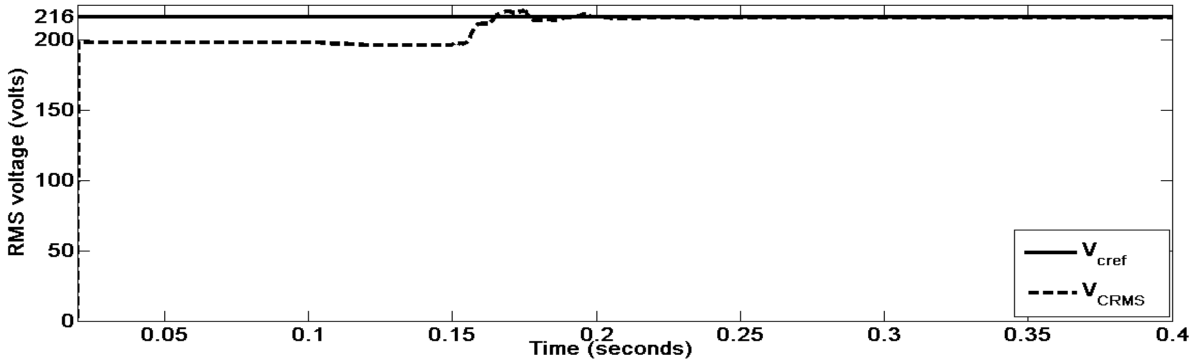

Figure 9 RMS voltage across critical load when $V_c < V_{c\_ref}$.

When $V_c > V_{c\_ref}$ it results in over voltage. In order make V_c=V_{c_ref} ES operates such as to reduce V_c, thus operating in inductive mode. Fig 10 shows ES operating in inductive mode i.e I_{es1} lags V_{es} by 90°. The ES is activated at t=0.15sec.

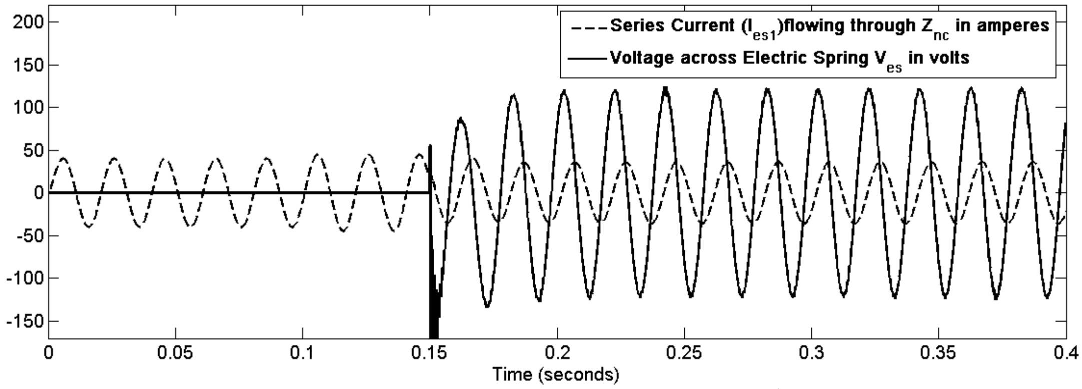

Figure 10 Inductive mode Ies_1 lags Ves by 90°.

When $V_c > V_{c\_ref}$ the ES operates such as to reduce V_c as shown in Fig 11 for V_{c_ref} = 216V. At t=0 sec disturbance is created, the reactive power is Q= 487Var and grid voltage is 220Vrms. At t= 0.1sec the grid voltage increases to 245Vrms. At t= 0.15 sec electric spring is activated. The controller varies the modulation index and the line voltage is decreased and maintained at a value equal to V_{c_ref}. . The measured RMS voltage across critical load when $V_c > V_{c\_ref}$ is shown in Fig 11.When ES is activated at t=0.15sec, it injects a quadrature voltage and tries to reduce the voltage across Z_c, thus reducing the voltage across Z_{nc}.

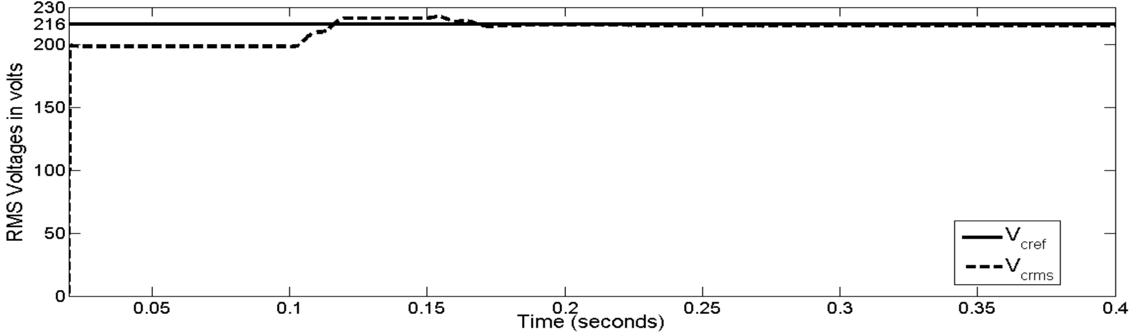

Figure 11 RMS voltage across Z_c when $V_c > V_{c\_ref}$.

VII. CONCLUSION

The use of ES is a noval way of regulating the voltage across critical loads. This paper describes the simulation results of an ES to form a smart load unit. The voltage across Critical Load is maintained constant by activating ES and injecting a voltage in series with the Non Critical Load. The performance of the ES is found to be satisfactory in enhancing the load voltage regulation.

ACKNOWLEDGEMENT

Authors express their gratitude for the support received from NMAMIT, Nitte and VTU Belagavi in carrying out the research work.

REFERENCES

[1]. C. K. Lee, N. R. Chaudhuri, B. Chaudhuri and S.Y.R. Hui, "Droop control of distributed electric springs for stabilizing future power grid", IEEE Transactions on Smart Grid, Vol 4,pp. 1558-1556, September 2013.

[2]. D. Westermann and A. John, "Demand matching wind power generation with wide area measurement and demand-side management", IEEE Transactions on Energy Conversion, vol. 22, pp. 145-149, March 2007.

[3]. Hooke's law - Britannica Encyclopedia [Online] Available: http://www.britannica.com/EBchecked/topic/271336/Hookes-law.

[4]. S. Y. R. Hui, C. K. Lee, andF.Wu, "Electric springs – A new smart grid technology," IEEE Trans. Smart Grid, vol. 3, no. 3, pp.1552–1561,Sep. 2012.

[5]. Jayantika Soni, Krishnanand K R, S K Panda, " Load-side Demand Management in Buildings using Controlled Electric Springs" 978-1-4799-4032-5/14/$31.00,2014 IEEE.

[6]. N.R. Chaudhuri, C.K. Lee, B. Chaudhuri, and S.Y.R. Hui, "Dynamic Model of Electric Spring, " IEEE Transactions on Smart Grid, vol.5, no.5, pp. 2450-2458, 2014.

BIOGRAPHIES

Benzeeta Ann D'Souza received her B.E degree in Electrical and Electronics Engineering from St. Joseph Engineering College, Vamajoor , Karnataka, India. Currently she is pursuing her M.Tech. in Micro Electronics and Control System at NMAM Institute of Technology, Karnataka, India. Her areas of interest include Power electronics, Power systems and Control systems.

Nagesh Prabhu received the Dipl. Elect. Eng. Degree from Karnataka Polytechnic, Mangalore, India in 1986, M.Tech. degree in power and energy systems from Karnataka Regional Engineering College, Surathkal, India (presently N.I.T. Karnataka) in 1995, and the Ph.D. degree from the Indian Institute of Science, Bangalore in 2005. Currently, he is Professor and Head of Electrical and Electronics Engineering at NMAM Institute of Technology, Nitte, India. He has served in the academic field since 1986. His research interests are in the area of power system dynamics and control, HVDC and FACTS, and custom power controllers. Dr. Prabhu is a life member of the Indian Society for Technical Education and Indian Society of Lighting Engineers.

DOI 10.17148/IJIREEICE/NCAEE.2016.41