MULTI-LEVEL INVERTER STATCOM FOR HIGH-POWER APPLICATIONS USING FUZZY LOGIC CONTROLLER

R. SHYAM KUMAR, PG scholar
Vignana Bharathi Institute of Technology

M. PAVANI, M.Tech,
Assistant Professor
Vignana Bharathi Institute of Technology

Abstract- In this Paper, a simple static VAR compensating scheme using Cascaded Multi-level Inverter based STATCOM is proposed and finally concludes on the possible design and implementation of the Multi-level Inverter based STATCOM for High Power applications. This conceptual design addresses the Voltage stability of the STATCOM inverters during unbalance conditions, Maximum percentage of sag voltage that can be compensated, Maximum swell voltage that can be absorbed by the STATCOM. The dc-link voltages of the inverters are regulated at different levels to obtain multilevel operation. A fuzzy logic control scheme is proposed for the controlling operation of STATCOM. The simulation study is carried out in MATLAB/SIMULINK to predict the performance of the proposed scheme under balanced and unbalanced supply-voltage conditions. Further, stability behavior of the topology is investigated. The dynamic model is developed and transfer functions are derived. The system behavior is analyzed for various operating conditions.

***Index Terms*— DC-link voltage balance, multilevel inverter, power quality (PQ), static compensator (STATCOM).**

INTRODUCTION

The recent developments in the industrial power sector as well as domestic sectors calls for a huge power transfer from sources which are located at a very large distances like cross country transmission system or elsewhere. It also demands for the addressing on issues which involve power quality, system reliability and stability. The large penetration of renewable sources, which are in uncertain and highly variable by nature as effective means of power generation has arisen new challenges to existing power networks. Nonlinear loads such as single phase ac tractions systems make the network to operate under undesired conditions [i.e., distorted, uncontrolled reactive power (VAR)], restricting the maximum active power transfer and significant unbalance enforcement. The rapid development of power electronics industry on the other hand has opened up opportunities for improving the operation and management of power system networks via flexible ac transmission. New developments are evolved in a perpetual manner in order to enhance the power electronic devices and their configurations to solve the new challenges ahead in a effective manner. Devices such as STATCOM have already proved their reliability and robustness in overcoming the problems caused due to grid overloading. The STATCOM as a reactive power source to increase the voltage profile of a power system network is well addressed in various papers. As an additional enhancement this paper takes a new perspective on the application of STATCOM for high power applications. The drawbacks in a conventional STATCOM used for high power applications is that the Switching pulses of the Inverter is changed frequently, i.e., the STATCOM converter is operated in rectifier mode during Swell conditions in the grid, hence the reactive power is observed by the capacitor in the STATCOM. During sag condition the converter is operated in Inverter mode in ordered to enable the capacitor to discharge and hence allowing the capacitor to inject the reactive power into the grid, thus increasing the grid voltage profile. Hence this varying operation of the converter control causes a complexity in the whole control process of the converter itself.

Moreover the complexity extends to a new level during unbalanced voltage conditions; the symmetry of the grid voltage is lost when there is a phase unbalance in one of the phases. The control feedback signal tapped from the segregated phases of the grid starts to see swell of voltage in two of the phases and sag of voltage in one of the phase. Hence there will be a mixture of control signals which forces the converter to act in inverter mode for one of the phase and in inverter mode for two of the phases, hence causing miss-fire of the switches and leading to instability and collapse of the inverter

A new method is proposed in reference and which suggests in maintaining the control signals of the inverter as completely open loop thus maintaining only one mode of operation i.e., in inverter mode only, hence ensuring the stability of the inverter during all operation conditions. The capacitor of the STATCOM is replaced by a controlled stiff DC source. The voltage of the DC source is varied by the control signal. Thus the DC source voltage is increased when there is sag condition in the grid. During swell condition the DC source voltage is reduce to negative, hence switching off all the switching devices of the inverter.

In this paper, a static VAR compensation scheme is proposed for a cascaded two-level inverter-based multilevel inverter. The topology uses standard two-level inverters to achieve multilevel operation. The dc-link voltages of the inverters are regulated at asymmetrical levels to obtain four-level operation. To verify the efficacy of the proposed control strategy, the simulation study is carried out for balanced and unbalanced supply-voltage conditions. A laboratory prototype is also developed to validate the simulation results.

From the detailed simulation and experimentation by the authors, it is found that the dc-link voltages of two inverters collapse for certain operating conditions when there is a sudden change in reference current. In order to investigate the behavior of the converter, the complete dynamic model of the system is developed from the equivalent circuit. The model is linearized and transfer functions are derived. Using the transfer functions, system behavior is analyzed for different operating conditions.

In this paper, we are presenting the work carried out in designing the Fuzzy logic controller for switching operation of STATCOM, a member of FACTS family. A simple control strategy of STATCOM is adopted where the measurement of RMS current at the source terminal is needed. Then the performance of conventional PI controller and fuzzy logic controller (FLC) are investigated. Simulation results show that Total Harmonic Distortion (THD) in source current is drastically reduced fuzzy controller is included in the STATCOM control circuit. Simulation work has been done using MATLAB/SIMULINK software.

This paper is organized as follows: The proposed control scheme is presented in Section II. Stability analysis of the converter is discussed in Section III. Simulation and experimental results are presented in Sections IV and V, respectively.

II. MULTI-LEVEL INVERTER STATCOM

Fig. 1 shows the power system model considered in this paper. Fig. 2 shows the circuit topology of the cascaded two-level inverter-based multilevel STATCOM using standard two-level inverters. The inverters are connected on the low-voltage (LV) side of the transformer and the high-voltage (HV) side is connected to the grid. The dc-link voltages of the inverters are maintained constant and modulation indices are controlled to achieve the required objective. The proposed control scheme is derived from the ac side of the equivalent circuit which is shown in Fig. 3. In the figure, v'_a, v'_b and v'_c are the source voltages referred to LV side of the transformer, r_a, r_b and r_c are the resistances which represent the losses in the transformer and three inverters, L_a, L_b and L_c are leakage inductances of transformer windings, and e_{a1}, e_{b1}, e_{c1}, e_{a2}, e_{b2}, e_{c2} and e_{a3}, e_{b3}, e_{c3} are the output voltages of inverters 1, 2 and 3, respectively. r_1, r_2, r_3 are the leakage resistances of dc-link capacitors c_1, c_2 and c_3, respectively. Assuming $r_a = r_b = r_c = r$, $L_a = L_b = L_c = L$ and applying KVL on the ac side, the dynamic model can be derived using as

$$\begin{bmatrix} \frac{di'_a}{dt} \\ \frac{di'_b}{dt} \\ \frac{di'_c}{dt} \end{bmatrix} = \begin{bmatrix} \frac{-r}{L} & 0 & 0 \\ 0 & \frac{-r}{L} & 0 \\ 0 & 0 & \frac{-r}{L} \end{bmatrix} \begin{bmatrix} i'_a \\ i'_b \\ i'_c \end{bmatrix} + \frac{1}{L} \begin{bmatrix} v'_a - (e_{a1} - e_{a2}) \\ v'_b - (e_{b1} - e_{b2}) \\ v'_c - (e_{c1} - e_{c2}) \end{bmatrix} \quad (1)$$

Equation (1) represents the mathematical model of the cascaded two-level inverter-based multilevel STATCOM in the stationary reference frame. This model is transformed to the synchronously rotating reference frame [14]. The – axes reference voltage components of the converter and are controlled as

$$e^*_d = -x_1 + \omega L i'_q + v'_d \quad (2)$$

$$e^*_q = -x_2 + \omega L i'_d + v'_q \quad (3)$$

Where v'_d is the d-axis voltage component of the ac source and i'_d, i'_q are d, q- axes current components of the cascaded inverter, respectively. The synchronously rotating frame is aligned with source voltage vector so that the q-component of the source voltage v'_q is made zero. The control parameters and are controlled as follows:

$$x_1 = \left(k_{p1} + \frac{k_{i1}}{s}\right)(i^*_d - i'_d) \quad (4)$$

$$x_2 = \left(k_{p2} + \frac{k_{i2}}{s}\right)(i^*_q - i'_q) \quad (5)$$

The d-axis reference current i^*_d is obtained as

$$i^*_d = \left(k_{p3} + \frac{k_{i3}}{s}\right)[(v^*_{dc1} + v^*_{dc2}) - (v_{dc1} + v_{dc2})] \quad (6)$$

Where $v^*_{dc1}, v^*_{dc2}, v^*_{dc3}$ and $v_{dc1}, v_{dc2}, v_{dc3}$ are the reference and actual dc-link voltages of inverters-1 and 2, respectively. The q-axis reference current i_q^* is obtained either from an outer voltage regulation loop when the converter is used in transmission-line voltage support or from the load in case of load compensation.

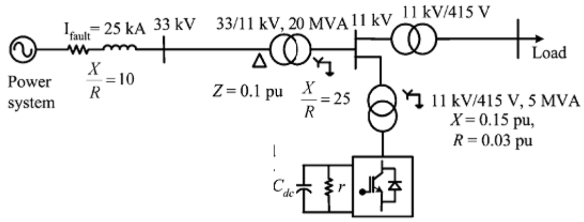


Fig. 1. Power system and the STATCOM model.

A .Implementation strategy

The control block diagram is shown in Fig. 4. The unit signals $\cos \omega t$ and $\sin \omega t$ are generated from the phase-locked loop (PLL) using three-phase supply voltages [14]. The converter currents are transformed to the synchronous rotating reference frame using the unit signals. The switching frequency ripple in the converter current components is eliminated using a low-pass filter (LPF). From $(v_{dc1}^* + v_{dc2}^*)$ and i_q^*loops, the controller generates d–q axes reference voltages, $e_d^*$and e_q^* for the cascaded inverter. With these reference voltages, the inverter supplies the desired reactive current and draws required active

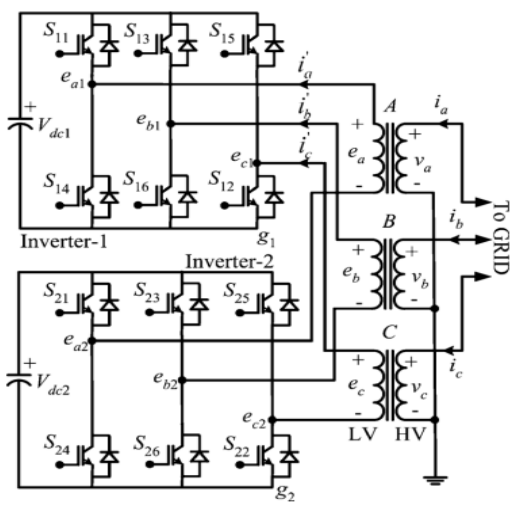


Fig.2. Cascaded two-level inverter-based multilevel STATCOM.

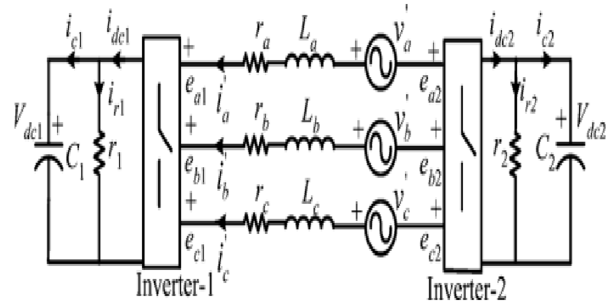


Fig. 3. Equivalent circuit of the cascaded two-level inverter-based multilevel STATCOM

current to regulate total dc-link voltage $(v_{dc1}^* + v_{dc2}^*)$. However, this will not ensure that individual dc-link voltages are controlled at their respective reference values. Hence, additional control is required to regulate individual dc-link voltages of the inverters.

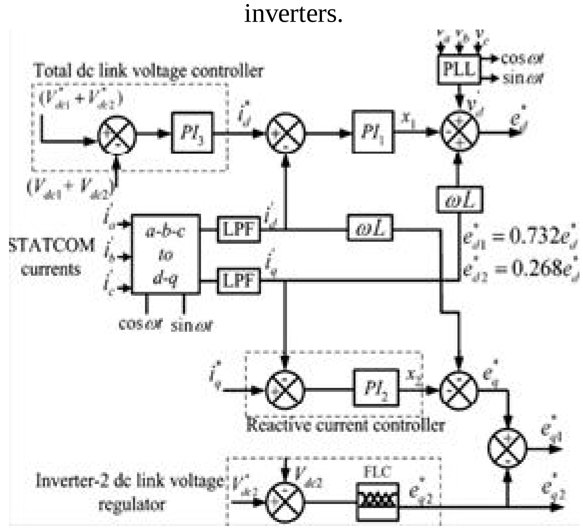


Fig. 4. Control block diagram

B . DC link balance controller:

The resulting voltage of the cascaded converter can be given as $e_I \angle \delta$, where $e_I = \sqrt{e_d^2 + e_q^2}$ and $\delta = \tan^{-1}\left(\frac{e_q}{e_d}\right)$. The active power transfer between thesource and inverter depends on δ and is usually small in the inverters supplying VAR to the grid [1]. Hence, δ can be assumed to be proportional toe_q.Therefore, the q-axis reference voltage component of inverter-2$e_{q2}^*$is derived from the fuzzy logic controller to control the dc-link voltage of inverter-2

The q-axis reference voltage component of inverter-1 $e_{q1}^*$is obtained as

$$e_{q1}^* = e_q^* - e_{q2}^* \quad (7)$$

The dc-link voltage of inverter-2 is controlled at 0.366 times the dc-link voltage of inverter-1 [9]. It results in four-level operation in the output voltage and improves the harmonic spectrum. Expressing dc-link voltages of inverter-1 and inverter-2 in terms of total dc-link voltage, V_{dc} as

$$V_{dc1} = 0.732 V_{dc} \quad (8)$$

$$V_{dc2} = 0.268 V_{dc} \quad (9)$$

Since the dc-link voltages of the two inverters are regulated, the reference d-axis voltage component e_d^* is divided in between the two inverters in proportion to their respective dc-link voltage as

$$e_{d1}^* = 0.732 e_d^* \quad (10)$$
$$e_{d2}^* = 0.268 e_d^* \quad (11)$$

For a given power, if $V_{dc2} < v_{dc2}^*$, $\delta_2 = \left(\tan^{-1}\left(\frac{e_{q2}^*}{e_{d2}^*}\right)\right)$ increases and $\delta_1 = \left(\tan^{-1}\left(\frac{e_{q1}^*}{e_{d1}^*}\right)\right)$ decreases. Therefore, power transfer to inverter-2 increases, while it decreases for inverter-1. The power transfer to inverter-2 is directly controlled, while for inverter-1, it is controlled indirectly. Therefore, during disturbances, the dc-link voltage of inverter-2 is restored to its reference quickly compared to that of inverter-1. Using e_{d1}^* and e_{q1}^*, the reference voltages are generated in stationary reference frame for inverter-1 and using e_{d2}^* and e_{q2}^* for inverter-2. The reference voltages generated for inverter-2 are in phase opposition to that of inverter-1. From the reference voltages, gate signals aregenerated using the sinusoidal pulse-width modulation (PWM) technique. Since the two inverters' reference voltages are in phase opposition, the predominant harmonic appears at double the switching frequency.

C. UNBALANCED CONDITIONS:

Network voltages are unbalanced due to asymmetric faults or unbalanced loads. As a result, negative-sequence voltage appears in the supply voltage. This causes a double supply frequency component in the dc-link voltage of the inverter. This double frequency component injects the third harmonic component in the ac side. Moreover, due to negative-sequence voltage, large negative-sequence current flows through the inverter which may cause the STATCOM to trip. Therefore, during unbalance, the inverter voltages are controlled in such a way that either negative-sequence current flowing into the inverter is eliminated or reduces the unbalance in the grid voltage. In the latter case, STATCOM needs to supply large currents since the interfacing impedance is small. This may lead to tripping of the converter.

The negative-sequence reference voltage components of the inverter e_{dn}^* and e_{qn}^* are controlled similar to positive-sequence components in the negative synchronous rotating frame as

$$e_{dn}^* = -x_3 + (-\omega L) i'_{qn} + v'_{dn} \quad (12)$$

$$e_{qn}^* = -x_4 - (-\omega L) i'_{dn} + v'_{qn} \quad (13)$$

Where, v'_{dn}, v'_{qn} are - axes negative-sequence voltage components of the supply i'_{dn} and i'_{qn} are d-q axes negative-sequence current components of the inverter, respectively. The control parameters and are controlled as follows:

$$x_3 = \left(k_{p5} + \frac{k_{i5}}{s}\right)(i_{dn}^* - i'_{dn}) \quad (14)$$

$$x_4 = \left(k_{p6} + \frac{k_{i6}}{s}\right)(i_{qn}^* - i'_{qn}) \quad (15)$$

The reference values for negative-sequence current components i_{dn}^* and i_{qn}^* are set at zero to block negative-sequence current from flowing through the inverter.

This control strategy is done by using the fuzzy logic controller (FLC). The control scheme consists of a Fuzzy controller, a limiter, and a three phase sine wave generator for the generation of the internal structure of the control circuit. The control scheme consists of a Fuzzy controller, a limiter, and a three phase sine wave generator for the generation of reference currents and switching signals. The peak value of the reference current is estimated by regulating the DC link voltage. The actual capacitor voltage is compared with a set reference value. The error signal is then processed through a Fuzzy controller, which contributes to the zero steady error in tracking the reference current signal. A fuzzy controller converts a linguistic control strategy into an automatic control strategy, and fuzzy rules are constructed either by expert experience or with a knowledge database. Firstly, the input Error 'E' and the change in Error '4E' have been placed with the angular velocity to be used as the input variables of the fuzzy logic controller. Then the output variable of the fuzzy logic controller is presented by the control Current Imax to convert these numerical variables into linguistic variable.

Rule Base: The elements of this rule base table are determined based on the theory that in the transient state, large errors need coarse control, which requires coarse input/output variables, while in the steady state, small errors need fine control, which requires fine input/output variables. Based on this, the elements of the rule base is highly impressive in all respects. It makes fuzzy logic an effective tool for the conception and design of intelligent systems. The fuzzy logic toolbox is easy to master and convenient to use. And last, but not least important, it provides a reader friendly and up-to-date introduction to methodology of fuzzy logic and its wide ranging application Fuzzy inference is a method that interprets the values in the input vector and, based on user defined rules, assigns values to the output vector. Using the GUI editors and viewers in the Fuzzy Logic Toolbox, we can build the rules set, define the membership functions, and analyze the behavior of a fuzzy inference system (FIS).

Table 1

Simulation system parameters

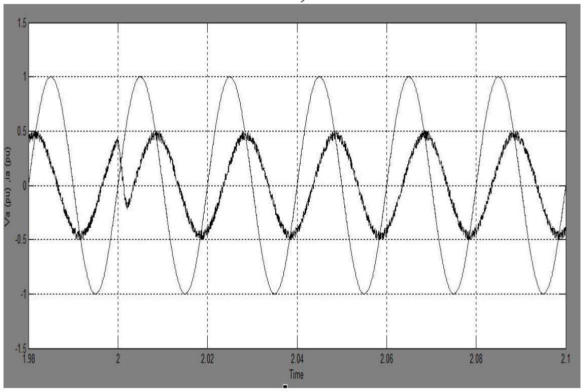
Rated power	5 MVA
Transformer voltage rating	11kV/400
AC supply frequency, f	50 Hz
Inverter-1 dc link voltage, V_{dc1}	659 V
Inverter-2 dc link voltage, V_{dc2}	241 V
Transformer leakage reactance, X_l	15%
Transformer resistance, R	3%
DC link capacitances, C_1, C_2	50 mF
Switching frequency	1200 Hz

IV. SIMULATION RESULTS

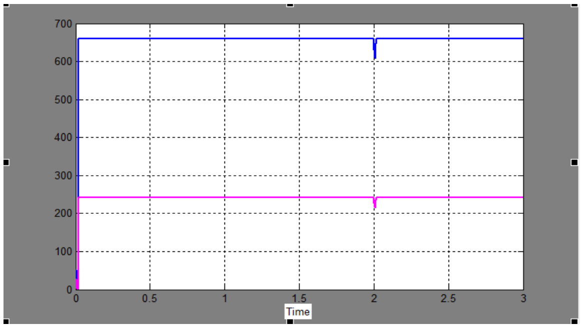
The system configuration shown in Fig. 1 is considered for simulation. The simulation study is carried out using MATLAB/ SIMULINK. The system parameters are given.

A. Reactive Power Control

In this case, reactive power is directly injected into the grid by setting the reference reactive current i_q^*component at a particular value. Initially,i_q^* is set at 0.5 p.u. At t=2.0 s,i_q^* is changed to -0.5 p.u.fig. 5(a) shows the source voltage and inverter current of A phase.



(a) Source voltage and current



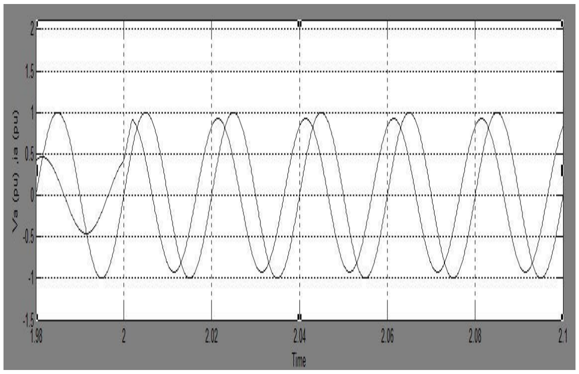
(b) DC-link voltages of two inverters.

Fig .5 REACTIVE POWER CONTROL

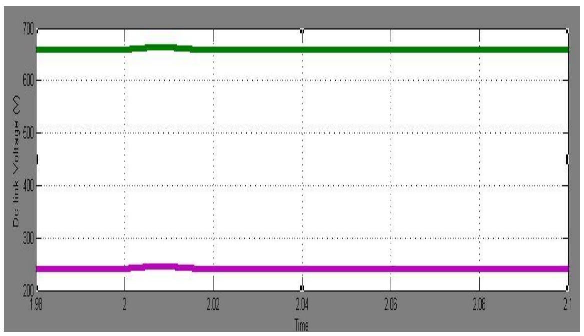
From the fig.5(b).it can be seen that the dc-link voltages of the inverters are regulated at their respective reference values when the STATCOM mode is changed from capacitive to inductive. Moreover, the dc-link voltage of inverter 2 attains its reference value faster compared to that of inverter 1

B. Load Compensation

In this case, the STATCOM compensates the reactive power of the load. Initially, STATCOM is supplying a current of 0.5 p.u. At t=2.0 s, the load current is increased so that STATCOM supplies its rated current of 1 p.u. Fig. 6(a) shows source voltage and converter current, while Fig. 6(b) shows the dc-link voltages of two inverters. The dc-link voltages are maintained at their respective reference values when the operating conditions are changed.

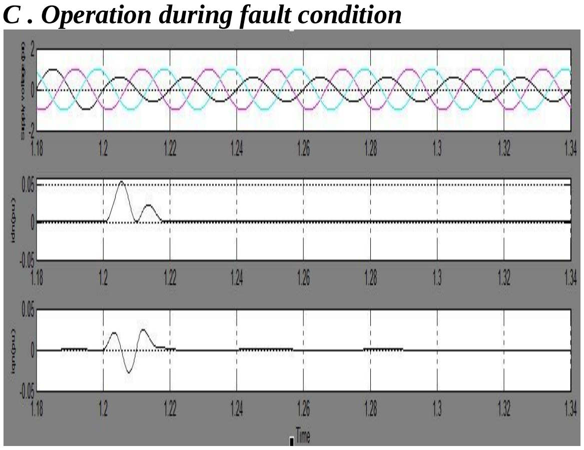


(a) Source voltage and current



(b) DC-link voltages of two inverters.
FIG.6. LOAD COMPENSATION

C . Operation during fault condition



Operation During Fault.

(A) Grid Voltages on the LV Side Of The Transformer.
(B) D-Axis Negative-Sequence Current Component i'_{dn}.
(C) Q Axis Negative-Sequence Current Component i'_{qn}.

FIG .7.OPERATION DURING FAULT

In this case, a single-phase-to-ground fault is created at t=1.2 s, on the phase of the HV side of the 33/11-kV transformer. The fault is cleared after 200 ms.Fig. 7(a)shows voltages across the LV side of the 33/11-kV transformer. Fig. 7(b) and (c) shows the d-q axes components of negative-sequence current of the converter. These currents are regulated at zero during the fault condition.

VI. CONCLUSION

DC-link voltage balance is one of the major issues in cascaded inverter-based STATCOMs. In this paper, a simple VAR compensating scheme is proposed for a cascaded two-level inverter-based multilevel inverter. The scheme ensures regulation of dc-link voltages of inverters at asymmetrical levels and reactive power compensation. By using fuzzy controller accuracy increases, performance increases. The performance of the scheme is validated by simulation and experimentations under balanced and unbalanced voltage conditions. Further, the cause for instability when there is a change in reference current is investigated and system behavior is analyzed for various operating conditions.

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R Shyam Kumar, received the Bachelor’s degree in Electrical & Electronics Engineering from Geethanjali College of Engineering & Technology, Hyderabad. He is pursuing his Master’s Degree in Power Electronics & Electrical Drives from Vignana Bharathi Institute of Technology, Hyderabad, expected to receive in 2016. His current research interests include FACTS devices, power quality improvement, power electronics and drives.

M. Pavani, **M.Tech.,** received the Bachelor’s degrees in Electrical and Electronics Engineering and Master’s degree in Power electronics and electrical drives from Jawaharlal Nehru Technological University, Hyderabad. She is currently working as Assistant Professor in Department of Electrical and Electronics Engineering, Vignana Bharathi institute of technology, since 2015. Her areas of interest are power electronics & electrical drives.