International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 1 Issue 8, October - 2012

Harmonic Immunity And Power Factor Correction By Instantaneous Power Control Of D-STATCOM

B.Veerraju
M.Tech Student (PE&ED)
MIST
Sathupally, Khammam Dist, India

M.Lokya
Assistant Professor in EEE Dept.
MIST
Sathupally, Khammam Dist, India

T.Vijay Muni
Assistant Professor in EEE Dept.
NRI Institute of Technology
Agiripalli, Krishna Dist, India.

Abstract

This paper presents the harmonic immunity and low power factor correction with instantaneous power control of S-DTATCOM. The proposed control strategy has been introduced in order to enhance some steady-state performances besides its functional elimination of power quality disturbances. Power factor and harmonic current of a controlled feeder section are two vital roles in steady-state power distribution system operation. If D-STATCOM is already installed in system we can achieve these additional control objectives which can help the system operators to improve the overall system performance. In this paper, a control scheme with constant power and sinusoidal current compensation [1,2] is exploited. In order to correct the power factor, a power factor control loop is required and therefore included in the control block. To verify its use, a 22-kV power distribution feeder with a three-phase rectifier load was tested. Results showed that integration of the proposed reactive power control loop can correct the power factor of the controlled feeder to be unity power factor.

1. Introduction

An increasing demand for high quality, reliable electrical power and increasing number of distorting loads may leads to an increased awareness of power quality both by customers and utilities. This type of power systems has a major function to serve distributed customer loads along a feeder line; therefore under competitive environment of electricity market service of electric energy transfer must not be interrupted and at the same time there must provide reliable, stable and high quality of electric power [2-3]. In order to reduce these problems we have to design carefully the power network planning.

Harmonic currents in distribution system can cause harmonic distortion, low power factor and additional losses as well as heating in the electrical equipment. It also can cause vibration and noise in machines and malfunction of the sensitive equipment.

The development of power electronics devices such as Flexible AC Transmission System(FACTS) and customs power devices have introduced and emerging branch of technology providing the power system with versatile new control capabilities [4].There are different ways to enhance power quality problems in transmission and distribution systems. Among these, the D-STATCOM is one of the most effective devices. A new PWM-based control scheme has been implemented to control the electronic valves in the D-STATCOM. The D-STATCOM has additional capability to sustain reactive current at low voltage, and can be developed as a voltage and frequency support by replacing capacitors with batteries as energy storage. [5.6].

From D-STATCOM literature, a majority of research works have been conducted in order to enhance electric power quality due to distribution voltage variations, e.g. voltage sags or swells. Apart from these voltage variations, the D-STATCOM is capable to enhance steady-state performances such as power factor and harmonic of a particular feeder portion. In this paper, a control scheme with constant power and sinusoidal current compensation [1] is exploited. In order to correct the power factor additionally, a power factor control loop is required and therefore included in the control block.

2. Description of D-STATCOM Operation

A D-STATCOM consists of a two-level VSC, a dc energy storage device, controller and a coupling transformer connected in shunt to the distribution network. Figure 2.1 shows the schematic diagram of D-STATCOM.

ISSN: 2278-0181
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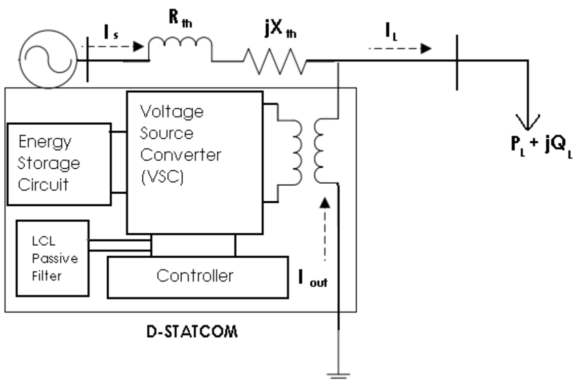

Figure: 2.1 Schematic diagram of a DSTATCOM

2.1 Overview of D-STATCOM

The Distribution Static Compensator (DSTATCOM) is a voltage source inverter based static compensator that is used for the correction of line currents [7]. Connection (shunt) to the distribution network is via a standard power distribution transformer [8]. The DSTATCOM is capable of generating continuously variable inductive or capacitive shunt compensation at a level up its maximum MVA rating. The DSTATCOM continuously checks the line waveform with respect to a reference ac signal, and therefore, it can provide the correct amount of leading or lagging reactive current compensation to reduce the amount of voltage fluctuations. The major components of a DSTATCOM are shown in Fig.2.1 [9]. It consists of a dc capacitor, one or more inverter modules, an ac filter, a transformer to match the inverter output to the line voltage, and a PWM control strategy. In this DSTATCOM implementation, a voltage-source inverter converts a dc voltage into a three-phase ac current that is synchronized with, and connected to, the ac line through a small tie reactor and capacitor (ac filter).

$$I_{out} = I_L - I_S = I_L - ((V_{th} - V_L)/Z_{th}) \quad (1)$$

$$I_{out} < \gamma = I_L < (-\theta) - (V_{th}/Z_{th}) < (\delta-\beta) + V_L/Z_{th} < (-\beta) \quad (2)$$

I_{out} = *Output current*
I_S = *Source current*
I_L = *Load current*
V_{th} = *Thevenin voltage*
V_L = *Load voltage*
Z_{th} = *Impedance*

Referring to the equation (1), output current, I_{out} will correct the voltage sags by adjusting the voltage drop across the system impedance, (Z_{th} = $\boldsymbol{R+jX}$). It may be mentioning that the effectiveness of D-STATCOM in correcting voltage sags depends on:

a) The value of Impedance, Z_{th} = $\boldsymbol{R+jX}$
b) The fault level of the load bus

The main title (on the first page) should begin 1-3/8 inches (3.49 cm) from the top edge of the page, centered, and in Times 14-point, boldface type. Capitalize the first letter of nouns, pronouns, verbs, adjectives, and adverbs; do not capitalize articles, coordinate conjunctions, or prepositions (unless the title begins with such a word). Leave two 12-point blank lines after the title.

2.2 Voltage Source Converter

A voltage-source converter is a power electronic device, which can generate a sinusoidal voltage with any required magnitude, frequency and phase angle. Voltage source converters are widely used in adjustable-speed drives, but can also be used to mitigate voltage dips. The VSC is used to either completely replace the voltage or to inject the 'missing voltage'. The 'missing voltage' is the difference between the nominal voltage and the actual. The converter is normally based on some kind of energy storage, which will supply the converter with a DC voltage. The solid-state electronics in the converter is then switched to get the desired output voltage. Normally the VSC is not only used for voltage dip mitigation, but also for other power quality issues, e.g. flicker and harmonics.

A special gate unit and voltage divider across each IGBT maintain an even voltage distribution across the series connected IGBTs. The gate unit not only maintains proper voltage sharing within the valve during normal switching conditions but also during system disturbances and fault conditions. A reliable short circuit failure mode exists for individual IGBTs within each valve position.

Depending on the converter rating, series-connected IGBT valves are arranged in either a three-phase two-level or three level bridge. In three-level converters, IGBT valves may also be used in place of diodes for neutral point clamping. Each IGBT position is individually controlled and monitored via fiber optics and equipped with integrated anti parallel, free-wheeling diodes. Each IGBT has a rated voltage of 2.5 kV with rated currents up to 1500 A. Each VSC station is built up with modular valve housings which are constructed to shield electromagnetic interference (EMI). The valves are cooled with circulating water and water to air heat exchangers. PWM switching frequencies for the VSC typically range between 1-2

ISSN: 2278-0181
Vol. 1 Issue 8, October - 2012

kHz depending on the converter topology, system frequency and specific application.

2.3 Energy Storage Circuit

Energy storage circuit is connected in parallel with the DC capacitor. The circuit carries the input ripple current of the converter and it is the main reactive energy storage element. The DC capacitor could be the charged by the battery source or could be recharged by the converter itself.

2.4 Controller

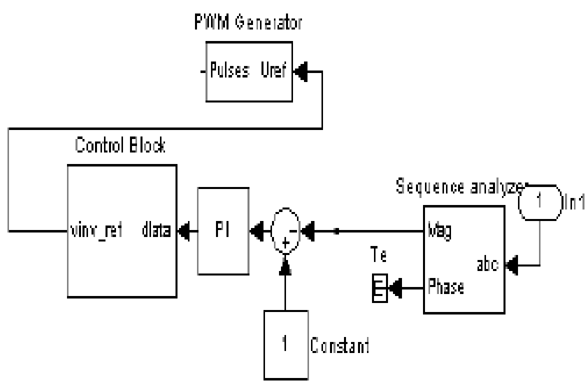

Figure: 2.2 Block diagram of Controller System

Figure 2.2 shows the block diagram of Controller sytem.The controller system is partially part of distribution system.

Proportional-integral controller (PI Controller) is a feedback controller, which drives the system to be controlled with a weighted sum of the error signal (difference between the output and desired set point) and the integral of that value.

In this case, PI controller will process the error signal to zero. The load r.m.s voltage is brought back to the reference voltage by comparing the reference voltage with the r.m.s voltages that had been measured at the load point. It also is used to control the flow of reactive power from the DC capacitor storage circuit.

PWM generator is the device that generates the Sinusoidal PWM waveform or signal. To operate PWM generator, the angle is summed with the phase angle of the balance supply voltages equally at 120 degrees. Therefore, it can produce the desired synchronizing signal that required. PWM generator also received the error signal angle from PI controller. The modulated signal is compared against a triangle signal in order to generate the switching signals for VSC valves.

3. Description of Instantaneous Power Theory

As the name implied, the instantaneous power theory [1] is based on a definition of instantaneous real and reactive powers in time domain. It is very useful not only in the steady-state but also in the transient state analysis for both three-phase systems with or without a neutral conductor. To illustrate the theory, let consider a set of instantaneous three phase quantity, for example *Va, Vb, Vc*. It starts with transforming a set of three-phase variables in the *abc* into αβ*0* coordinates. This transformation is so-called as the Clark transformation as described follows.

$$\begin{bmatrix} v_0 \\ v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & -\frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (2)$$

In three-phase, three-wire systems, there is no zero sequence components. If *Vo* and *Io* are both neglected, instantaneous voltage, **v**, and current phasors, **i**, can be defined from their corresponding instantaneous α and β components as
follows.

$$\mathbf{v} = v_\alpha + jv_b \quad (3)$$

$$\mathbf{i} = i_\alpha + ji_\beta \quad (4)$$

From (3) and (4), instantaneous complex powers, **s**, can be defined as the product of the instantaneous voltage phasor and the complex conjugate of the instantaneous current phasor given in (5).

$$\mathbf{s} = \mathbf{vi}^* = (v_\alpha + jv_\beta)(i_\alpha - ji_\beta) = p + jq \quad (5)$$

Where,

$p = v_\alpha i_\alpha + v_\beta i_\beta$ p is the instantaneous active power

$q = v_\beta i_\alpha - v_\alpha i_\beta$ is the instantaneous reactive power

The instantaneous complex power is useful. It can be applied for transient or steady-state analysis. The following equation is a compact form for the instantaneous real and reactive power definition and its inversion.

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \quad (6)$$

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} p \\ q \end{bmatrix} \quad (7)$$

$$p = \bar{p} + \tilde{p} \quad (8)$$

$$q = \bar{q} + \tilde{q} \quad (9)$$

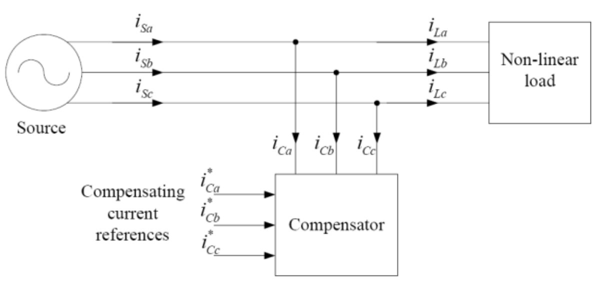

Figure 3.1 Concept of Shunt current compensation

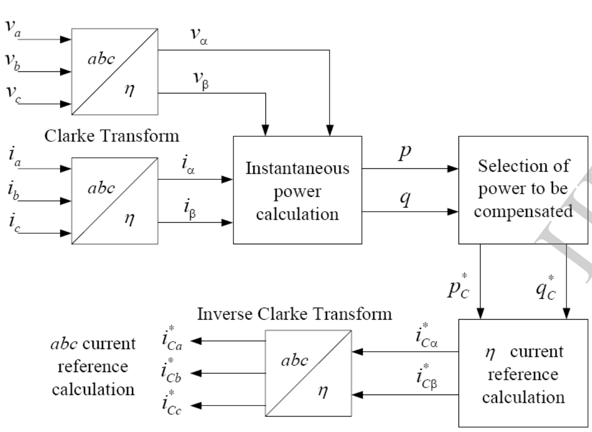

Figure 3.2 Control block of shunt current compensation based on the instantaneous power theory

4. Proposed Control Strategy for D-STATCOM

In general, power compensation by D-STACOM can have various functions such as elimination of power oscillation, improvement of power factor, elimination of harmonic current, etc. Under a balanced three-phase supply condition, some criteria must be met to optimize the overall system compensation. The research conducted by aimed to compensate the source current become purely sinusoidal and deliver the minimum average real power to the load. Although under non-linear loading it can guarantee only one optimal criterion, in this paper multiple objectives for shunt power compensation are proposed. In addition, power factor correction of a protected load can be included in the control scheme by zeroing reactive power supplied by the source.

As mentioned previously, the compensator must supply the oscillating power components to the load. In order to compensate the oscillating power flow by means of PWM converters, the DC voltage across the DC link capacitor must be large enough and kept constant at that value to stabilize the compensation. Therefore, DC link voltage regulator must be added to the control loop. To separate the oscillating real power components a low-pass filter is used. Together with the switching and ohmic losses of the PWM converter, the instantaneous real power reference is formed. Similarly, the instantaneous reactive power reference can be set as zero to achieve unity power factor. In practice, the reference signals for generating the switching pattern to drive IGBT gates are current waveforms, modified to equate the compensating current in αβ coordinates as expressed. Therefore, the αβ current is transformed back to the *abc* coordinate for switching pattern generation as described. With this power factor correction, the reactive power regulator is also added to the loop as shown in Fig. 4. The overview of the proposed control scheme can be depicted as shown in Fig. 5.

$$\begin{bmatrix} i_{C\alpha}^* \\ i_{C\beta}^* \end{bmatrix} = \frac{1}{v_\alpha^2 + v_\beta^2} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} -\tilde{p} + \bar{p}_{loss} \\ -q \end{bmatrix} \quad (10)$$

$$\begin{bmatrix} i_{Ca}^* \\ i_{Cb}^* \\ i_{Cc}^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{C\alpha}^* \\ i_{C\beta}^* \end{bmatrix} \quad (11)$$

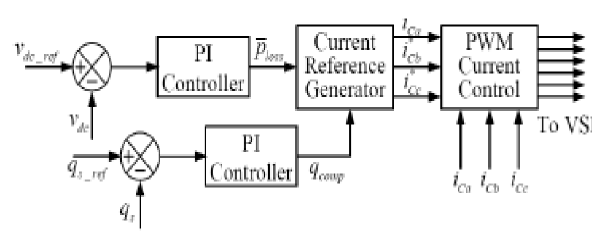

Figure 4.1 Proposed control scheme with reactive power regulation

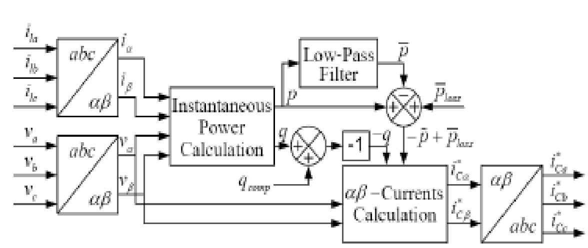

Figure 4.2 Overall proposed control scheme

5. Simulation Results

In order to verify the correction of power factor and compensate the harmonic current, a 22- kV power distribution feeder with three-phase rectifier loading was employed.

The test was divided into two cases. The first case was used the control scheme introduced by [1]. Whereas, the second case was the proposed control scheme given in this paper. Both test cases were assigned to be operated with the same instruction. The test system was started from zero initial conditions with only the rectifier load. At t = 0.2 s, the DSTATCOM was connected to the system via the point of coupling connection. At t = 0.5 s, the *RL* load was switched on to increase the system loading.

5.1 Case – I

With the control strategy proposed by [1], the system response without D-STACOM in the time interval 0 – 0.2 s was shown in Fig. 7. At t = 0.2 – 0.5s, the D-STATCOM was connected to compensate the non-linear load as responses. It can be seen that the source current was shaped to be nearly sinusoidal. However, due to the PWM operation of the D-STATCOM, higher-order harmonic components were inevitably experienced. At $t \geq 0.5$ s when the *RL* load switched, the source current was lagged the voltage at the point of coupling connection by 21.6 degree corresponding to 0.9298 power factor lagging.

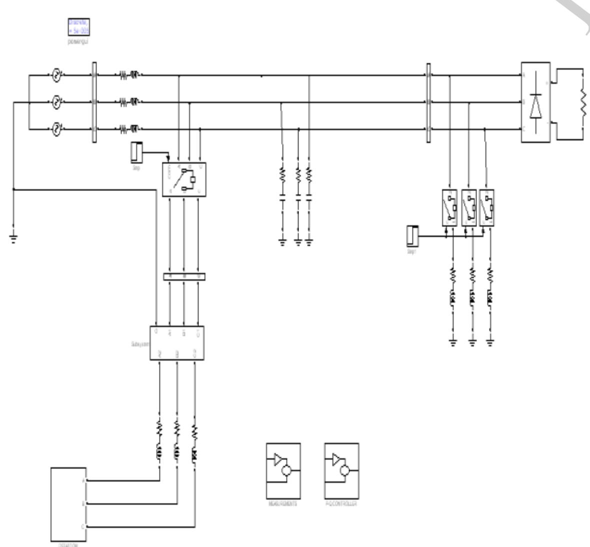

Figure 5.1 Simulation circuit with control scheme

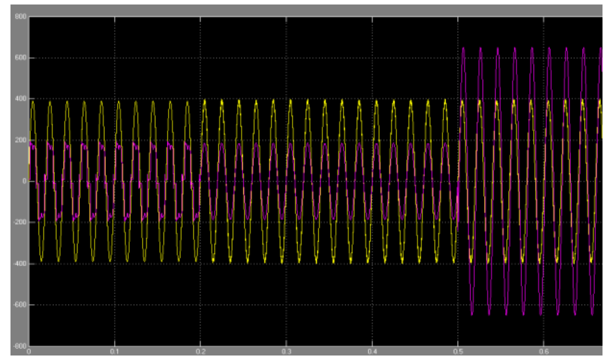

Figure 5.2 Source voltage and current

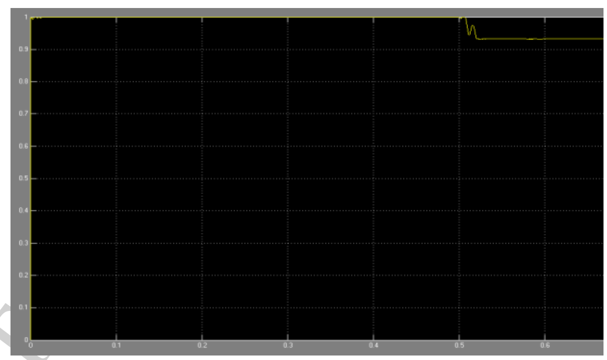

Figure 5.3 Power factor

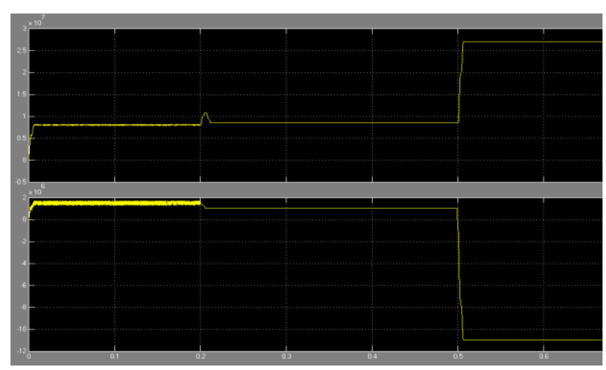

Figure 5.4 Three phase active and reactive power

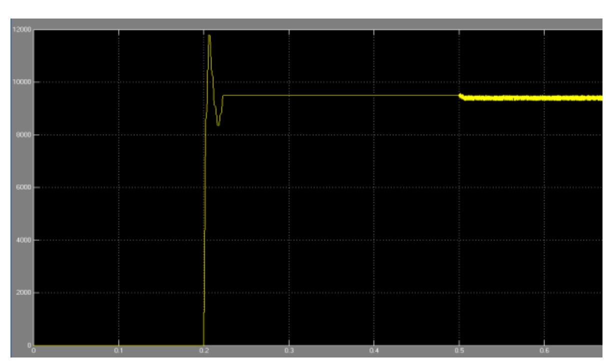

Figure 5.5 DC Voltage

5.2 Case - II

With the control strategy proposed in this paper, the system response without D-STACOM in the time interval 0 – 0.2 s was shown in Fig. 10. At t = 0.2 – 0.5s, the D-STATCOM was connected to compensate the non-linear load as responses. It can be seen that the source current was shaped to be nearly sinusoidal. However, due to the PWM operation of the D-STATCOM, higher-order harmonic components were inevitably experienced. At $t \geq 0.5$ s when the *RL* load switched, the source current that was previously lagged the voltage at the point of coupling connection in case 1 was resumed to in-phase with the voltage waveform. This described the success of power factor correction by the reactive power control scheme made in this paper.

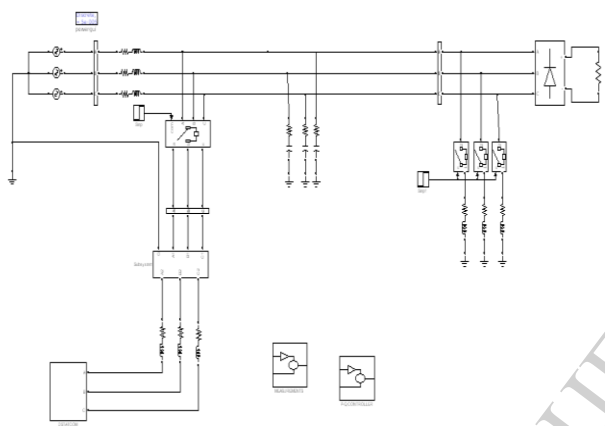

Figure 5.6 Simulation circuit with control scheme

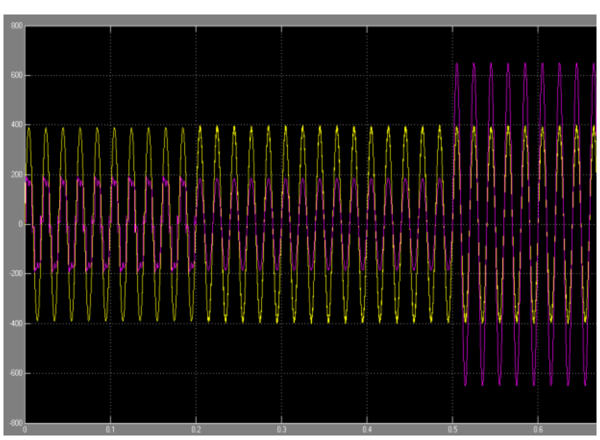

Figure 5.7 Source voltage and current

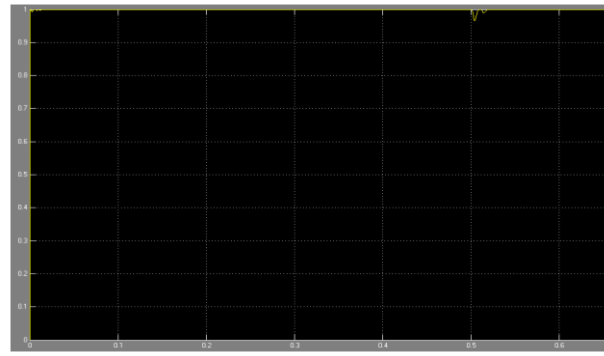

Figure 5.8 Power factor

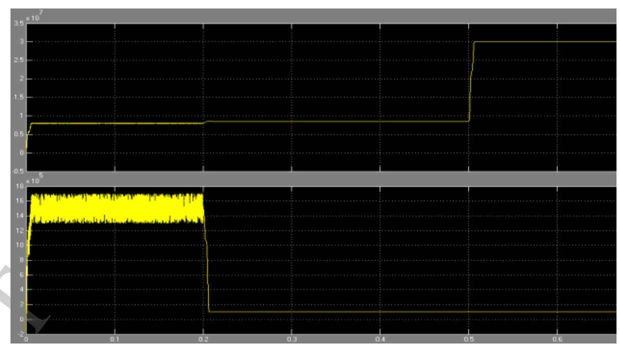

Figure 5.9 Three phase active and reactive power

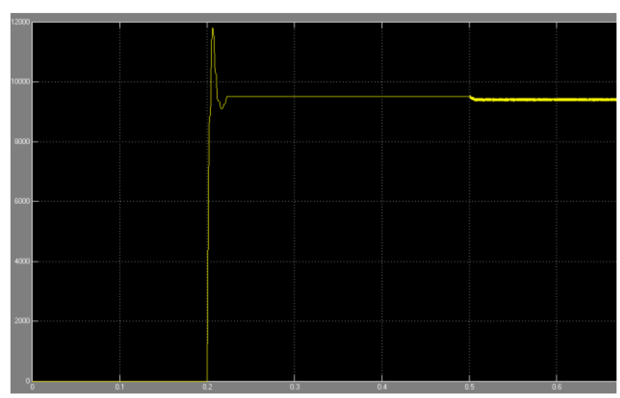

Figure 5.10 DC Voltage

6. Conclusion

This paper presents a modified control scheme to compensate a distribution feeder loading with non-linear loads. The compensation consists of three main objectives that are i) regulation of real powers delivering to loads, ii) regulation of DC link voltage to ensure PWM converter operation, and iii) correction of power factor. Modification of the control scheme made in this paper is to add the reactive power regulation into the control loop. With zero reactive power reference, unity power factor can be achieved. As a result, the modified control scheme can regulate DC link voltage and real power delivery at specified level while reactive power drawn from the load was cancelled by that injected from D-STATCOM.

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Author Profiles

B.Veerraju received Bachelor's Degree in Electrical & Electronics Engineering from Mother Teresa Institute of Science & Technology, Sathupally, India in 2007.

He presently peruses his M.Tech in Power Electronics & Electric Drives in Mother Teresa Institute of Science & Technology(MIST), Sathupally.

His areas of interest include Network Analysis, Control Systems and Power Electronics.

Mr.M.Loyka was born in 1984. He graduated from KAKATIYA UNIVERSITY, in the year 2005. He is presently working as Assistant Professor in the Department of Electrical and Electronics Engineering at Mother Teresa Institute of Science and Technology, Andhra Pradesh, India. He received M.Tech degree from Jawaharlal Nehru Technological University in the year 2011.

T.Vijay Muni was born in 1986 in India. He received the Bachelor's Degree in Electrical & Electronics Engineering from MIST, Sathupally, India in 2007. He received the Master's Degree in Power & Industrial Drives from NCET, Vijayawada, India in 2010.

He worked as Assistant Professor in SSIET, Nuzvid, India from 2007 to 2010. He presently is working as Assistant Professor in Department of Electrical & Electronics Engineering, NRI Institute of Technology, Agiripalli, India. He published four International Journals and two national conferences.

His research interests include FACTS, Power Electronics, Distribution System and Power System Analysis.