Implementation of Shunt Compensating Device for the Mitigation of Harmonic Current in Non-Linear Distributed System

T.M. Thamizh Thentral, R. Jegatheesan, K. Vijayakumar, S. Senthilnathan, T.V. Abhinav Viswanaath

Abstract: ***With the extensive use of harmonic generating devices, the control of harmonic currents to maintain a high level of power quality is becoming increasingly important. An effective way to suppress harmonics is harmonic compensation by using passive filters, active power filters and custom power devices. In this paper one of the custom power device called Distribution static synchronous compensator (DSTATCOM) taken to improve the power quality in the distribution systems. This device provides reactive power compensation, load balancing and harmonic current compensation in ac distribution networks. By using this DSTATCOM harmonic current can also be compensated. The reference current is extracted with help of synchronous reference frame theory and control signal to the device is generated from the hysteresis current control method. Both the simulation and the experimental results were analyzed. Simulation results are obtained with a condition of*** **balanced sinusoidal voltage source and balanced load.**

Keywords: ***Total Harmonic Distortions, DSTATCOM, Hysteresis Current Controller, Synchronous Reference Frame Theory.***

I. INTRODUCTION

Power quality (PQ) has to be maintained within the standard limits to avoid the malfunctions in the equipments, to reduce the power losses and to avoid disturbances in the communication lines [1]. Power Quality is affected by transients, interruptions, swell (over voltage), sag (under voltage), harmonic distortion, voltage spikes and noise. In recent days, one of the major issues in power quality is the harmonic distortion viz. voltage and current harmonics. There are many solutions to compensate the current harmonics. At the start, passive filters are used to maintain the current harmonic within the specified standard limits. Having many advantages, due to the larger size and additional resonance problem the passive filters are replaced with active power filters. Along with the compensation in the voltage and current harmonic, active power filters used to regulate the terminal voltage, suppress the voltage flicker, improve the voltage imbalance, provides power factor correction and reactive power compensation [2]. Based on the connection between the source and the load active power filters are classified as series, shunt and hybrid. To maintain the Total Harmonic Distortion (THD) percentage in voltage, Series Active Power Filters are used. The same way shunt active power filters is providing better THD percentage in current [3]. The main drawback in the active power filter is the rating. When the voltage and current rating of the system increases the requirement of higher rating of active power filter also will increase that leads to the increment in the cost. This can be overcome by having the hybrid filters, which is the combination of both the active power filters and passive filters [4].

The enhancement in the power electronic technology leads to devices based on power electronics at various voltage levels in most of the industries and utility grid systems [5-6]. Nowadays FACTS devices are popularly used to achieve the better power quality. To control the operation parameters in steady state and transient state, FACTS devices are classified based on connection to the transmission line static synchronous compensator, Static Synchronous Series Compensator, Unified Power Quality Controller and Dynamic Voltage Restorer. The static synchronous compensator (STATCOM) is connected in shunt with the transmission lines. Within the capability of the converter the static synchronous compensator can adjust the required reactive power dynamically in the transmission lines. It can be operated in reactive power (Var) control mode and Automatic voltage control mode. Static Synchronous Series Compensator (SSSC) operated in series with the transmission line to inject the voltage for maintain the flow of power in line either directly or indirectly. Dynamic Voltage Restorer (DVR) injects a voltage component in series with the supply voltage. It is compensating voltage sags and swells on the load side. Unified Power Quality Controller (UPQC) is best suited for sensitive loads. It is a combination of series and shunt active power filters with common dc link capacitor. In this paper a voltage source inverter with dc link capacitor is used as a DSTATCOM. From load side, reference current is extracted with the help of Synchronous Reference Frame theory algorithm. The control signal to the DSTATCOM is generated from the hysteresis current control method. At the point of common coupling both the linear and non-linear is considered. A non-linear three phase bridge rectifier load is considered.

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II. DISTRIBUTION STATIC COMPENSATOR (DSTATCOM)

Static compensators are normally used in transmission system, when such compensators are used in distribution system it is called as a Distribution Static Compensator (DSTATCOM). It is a FACT controller it consists of many power electronics devices which are used for solving power quality problems faced by distribution system. Conventionally, static capacitors and passive filters are used to increase the power quality in the distribution system. However, few problems such as fixed compensation, system-parameter-dependent performance, and possible resonance with line reactance [1] are faced. To get over such discussed drawbacks, a distribution static compensator (DSTATCOM) has been advanced in the literatures [2]-[7]. It tries to mitigate both harmonic content and reactive component of load current to make the source currents sinusoidal, balanced and in phase with the source voltages.

To generate the reference control signals for the DSTATCOM, various control schemes have been scrutinized such as instantaneous reactive power theory (p-q theory) [8], synchronous reference frame (SRF) theory [9][11], power balance theory [10], SVPWM [12]. A three-phase four-wire distribution system has been compensated satisfactorily under non-sinusoidal supply condition using p-q theory [13], adaptive neural networks[14] and Lyapunov-function-based-control.

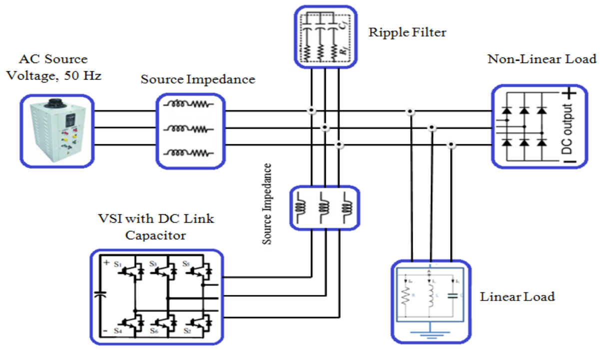

Figure 1: Block diagram of DSTATCOM

DSTATCOM is a device which is used in AC distribution systems where, harmonic current suppression, reactive power compensation and balancing of load are to be achieved. The important elementary units of a DSTATCOM is a voltage source converter (VSC) consisting of self-commutating semiconductor valves and a capacitor on the DC bus. The device is connected in shunt to power distribution network through an inductive coupling. In the outset, the DSTATCOM helps in correcting the power factor, compensating the harmonics and balancing the load.

A schematic diagram of a typical DSTATCOM setup connected to three phase AC supply is shown by Figure 1. It is connected to three phase loads which may be either a lagging power factor load, an unbalanced, non-linear load or a mix of these loads. In compensating current, the reduction of ripple is done by interfacing inductors (Lf) which are used at AC side of voltage source converter (VSC). At the PCC, a ripple filter is installed in parallel with load and compensator represented by a small capacitor (Cf) and a resistor (Rf) connected in series for filtering switching noise of high frequency present in the voltage at PCC. The harmonic/reactive currents (Icabc) are injected using DSTATCOM for cancelling the harmonic/reactive power components of load current so that the source current harmonics reduced also compensating the reactive power of load.

III. CONTROL STRATEGY

To generate the control or gating signals for the Voltage Source Inverter (VSI), various control schemes exist viz. Synchronous Reference Frame Technique (dq theory), Modified Power Balance Theory, NBP-based icosφ control strategy. The Neural Network based control is still in a stage of development and the NBP-based icosφ control strategy often accomplishes voltage regulation and power factor correction along with harmonic reduction and is used when size is one major constraint. A typical Instantaneous reactive power theory compensation setup is found to only account for sinusoidal balanced or unbalanced three phase power system which does not have zero sequence components. However, that can be modified to even account for non-sinusoidal system. In this work, Synchronous Reference Frame (SRF) theory is implemented due to it's simplicity, easy implementation in FPGA and DSPs, good accuracy and it eliminates the need for averaging by allowing instantaneous compensation of reactive power in addition to harmonic reduction.

As given in Figure: A, The DSTATCOM setup consists of a 3 phase voltage source, a non-linear balanced or unbalanced load which injects harmonics in the source current, a Voltage Source Inverter to which the gate or control pulses are given by Hysteresis Band Current Controller. The DC input to the inverter is given by a DC link capacitor whose voltage is stabilized by a PI controller. The 3 phase AC output of the inverter is attached at the Point of Common Coupling (PCC) along with a Ripple filter to filter out small distortions. Current and voltage sensors are placed at the appropriate places to sense source and load voltage and current.

SRF TECHNIQUE (DQ THEORY)

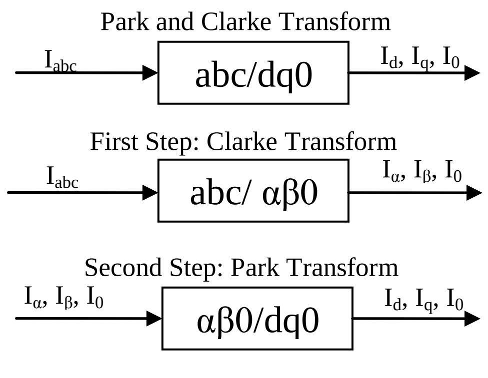

Figure 2: dq-theory

The measured load voltage in abc fixed reference frame is fed to abc-dq0 block. Inside the abc-dq0 block, there exist a 2 step conversion.

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Firstly, the abc components in fixed reference frame is converted to αβ0 components in rotating reference frame. This transformation is known as Clarke Transformation. After this step, the αβ0 components in rotating reference frame are converted to dq0 components in rotating reference frame. After obtaining the q axis and zero sequence components are unaltered whereas the d axis current I_d is given to a low pass filter to filter out the fundamental component and have the harmonic component alone.

The Clarke and Park transform are mathematically done as follows.

Clarke Transformation:

$$I_\alpha = \frac{2}{3} I_a - \frac{1}{3}(I_b - I_c) \qquad --- (1)$$

$$I_\beta = \frac{2}{\sqrt{3}}(I_b - I_c) \qquad --- (2)$$

Park Transformation:

$$I_d = I_\alpha * \cos\theta + I_\beta * \sin\theta \qquad --- (3)$$

$$I_q = I_\beta * \cos\theta - I_\alpha * \sin\theta \qquad --- (4)$$

Where, θ is the angle through which the frame is rotated. The Zero Sequence component does not experience any change.

The harmonic component is inverted and the power loss calculated by the PI controller is also accounted. Now, the dq0 components are converted back to abc components using Inverse Park and Inverse Clarke in sequence. The inverted compensating current is given as a reference to the Hysteresis Band Current Controller (HBCC).

Hysteresis Band Current Controller (HBCC)

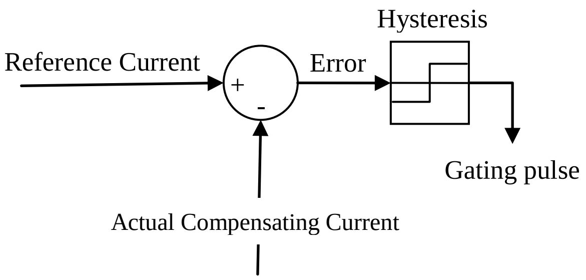

Figure 3: Hysteresis Band Current Controller (Inside FPGA)

The inverted compensating current is provided to the HBCC by SRF Technique as discussed above. The HBCC takes this reference current and also the actual compensating current and calculates the error which actuates the hysteresis band. The Hysteresis band consists of an upper and a lower limit beyond which if a current goes, the switching signal is given to the power electronic switches in Voltage Source Inverter (VSI) to account for the change.

The HBCC is one of the simple technique for PWM. It does not require any system parameter information and it is fast. It has a inherent-peak current limiting capability. The Switching frequency is inversely proportional to the bandwidth. So, greater switching frequency and hence, a greater resolution can be achieved by varying the bandwidth. But, this is limited as the losses in switching also needs to be taken into account.

The logic for switching of IGBTs is contrived as follows:

Considering I_c as the compensating current, I_r as the reference current and HBW as the Hysteresis Bandwidth,

If Ic< (Ir- HBW) upper switch is in OFF condition and lower switch is in ON condition

for leg ‘a’(SA=l).

If Ic> (Ir + HBW) upper switch is in ON condition and lower switch is in OFF condition

for leg ‘a’(SA=O).

PI CONTROLLER

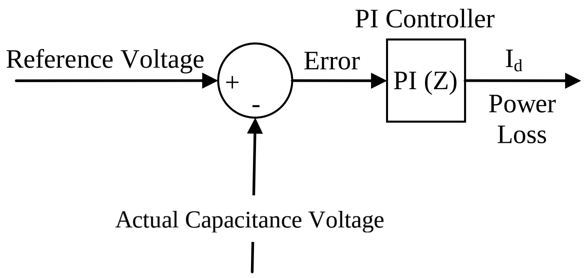

Figure 4: PI Controller

PI controller is used to stabilize the voltage of the DC link capacitor in the Voltage Source Inverter (VSI). In addition to stabilizing the voltage fluctuations in the capacitor due to the power semiconductor switching devices, it also calculates the power loss.

IV. RESULTS AND DISCUSSIONS

A Simulink model of DSTATCOM is depicted in Figure 5. Even if the non-linear load is connected to sinusoidal voltage source, it can be seen as a source of non-sinusoidal voltage. This model provides analysis between source and load waveform based on voltage and current parameters before and after compensation techniques are applied. A voltage source of magnitude 415V, 50Hz is connected to series of interconnected blocks mainly consisting of SRF block, hysteresis current control block, linear/non-linear load and DSTATCOM. The hysteresis current control generates firing pulses which are passed to inverter. The voltage measurement block measures all the current and voltage parameter thereby allowing FFT analysis. The waveform obtained by running the matlab program without switching on the filter. The current waveform is non-sinusoidal. The load taken is a balanced three phase bridge rectifier which may be linear or non-linear. It can be observed from Figures 7.a and 7.b that the load current ripple gets minimized due to the action of ripple filter giving rise to a pure DC load current.

From Figure 5, it can be observed that till 0.25s, the circuit operates in open loop and the presence of harmonics can be clearly observed in source current. When the filter circuit is included by closing the switch at 0.25s, after the transience, the harmonic content gets removed which results in a pure sinusoidal source current. Figures 6 and 9 give the load current and load voltage at PCC before and after compensation where a very slight change in frequency can be observed.

Figure 8 shows the voltage level of DC link capacitor which is used to supply the inverter.

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It can be observed that the variation in DC link voltage due to the power electronic switches is stabilized by the PI controller after a short lag. During simulation, the harmonic content before and after compensation is analyzed through an FFT window which is depicted in Figures 14 and 15. It can be found that harmonic content is reduced from 25.97% to 1.35% while maintaining the percentage of fundamental frequency.

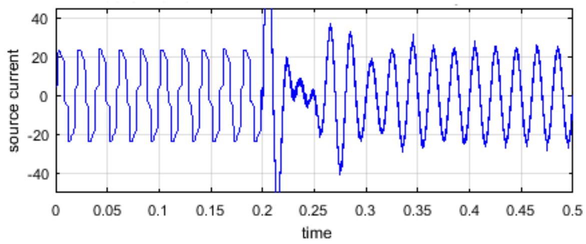

Figure 5: Source side current waveform for before and after compensation

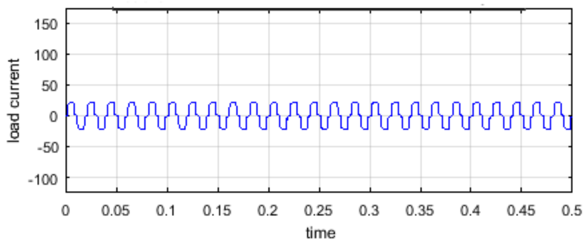

Figure 6: Load Current at PCC

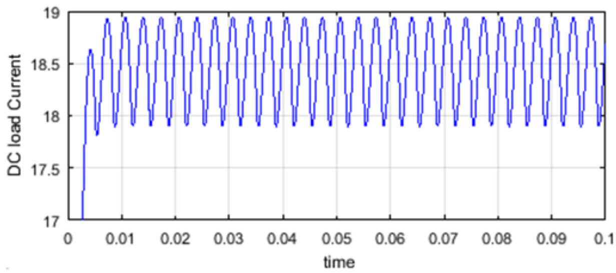

Figure 7: a Load side current waveform

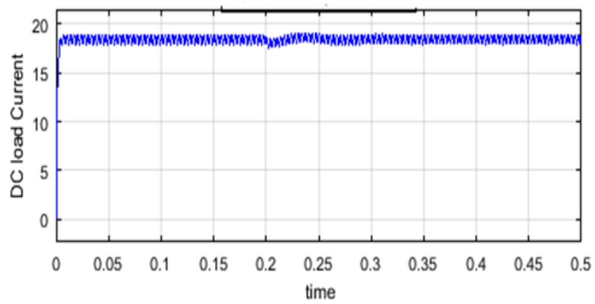

Figure 7: b Load side current waveform

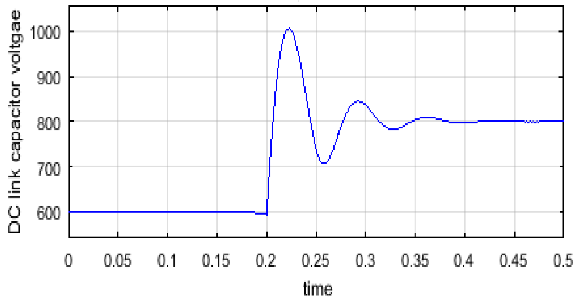

Figure 8: DC link capacitor voltage

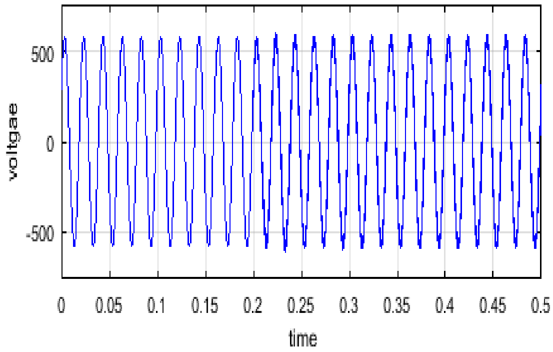

Figure 9: Voltage at PCC

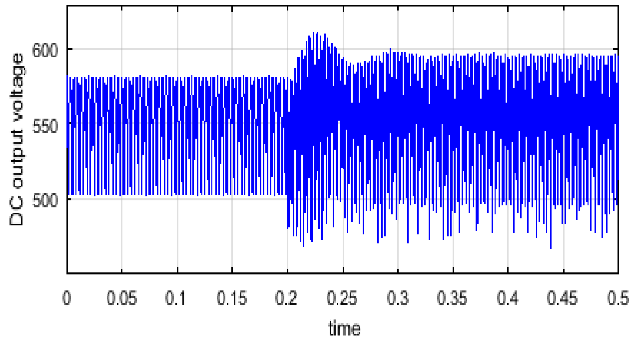

Figure 10: DC output voltage

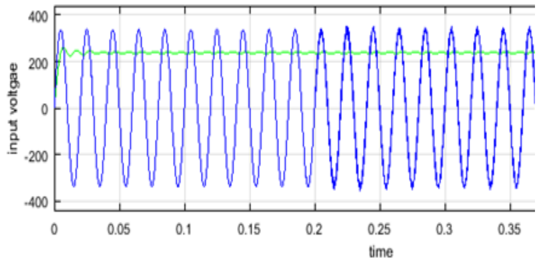

Figure 11: Input phase voltage and rms value

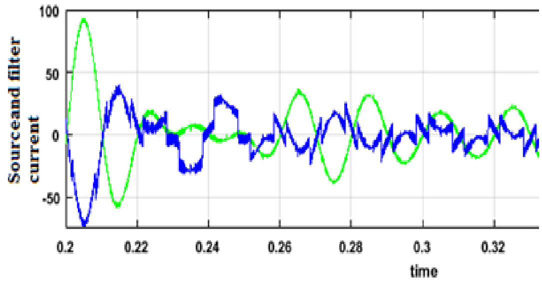

Figure 12: Source and filter current after compensation

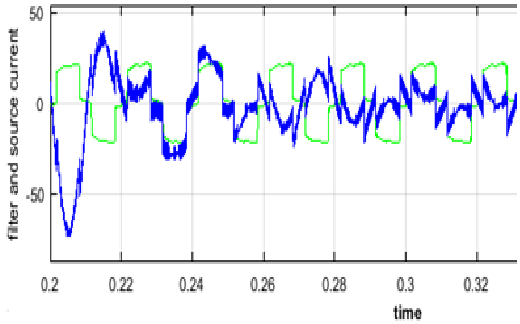

Figure 13: Source and filter current before compensation

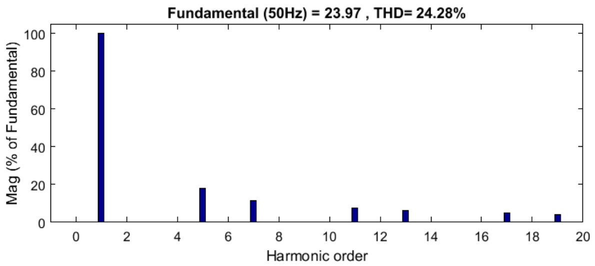

Figure 14: FFT Analysis before compensation

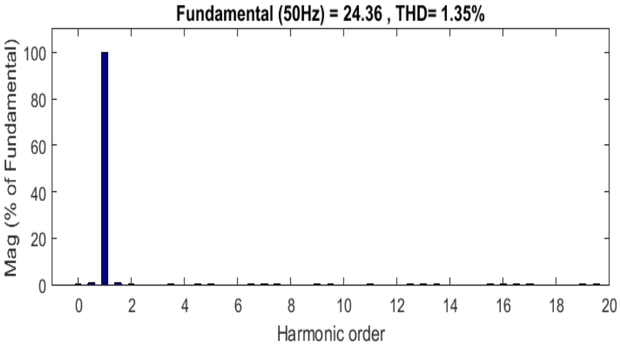

Figure 15: FFT Analysis after compensation

It can be seen from Figure 10 that the DC output voltage has been slightly boosted after compensation circuit is connected which may be reduced by using a freewheeling mechanism.

Figures 16 and 17 shows the magnitude of current and the percentage harmonic content for odd and even order harmonics before and after compensation is listed. It can be seen that, except for very few odd harmonics, the magnitude of current remains the same and harmonics percentage is greatly reduced in case of lower order. Higher order harmonics, even if present, can be easily filtered out.

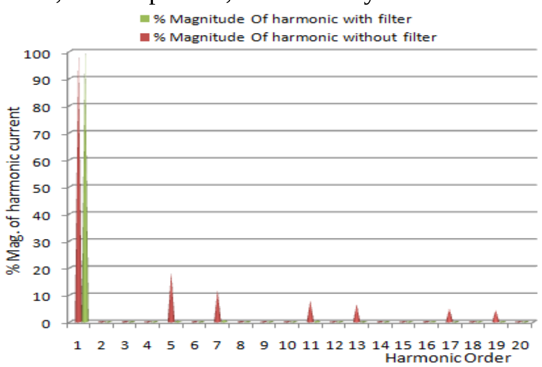

Figure 16: THD% vs harmonic order

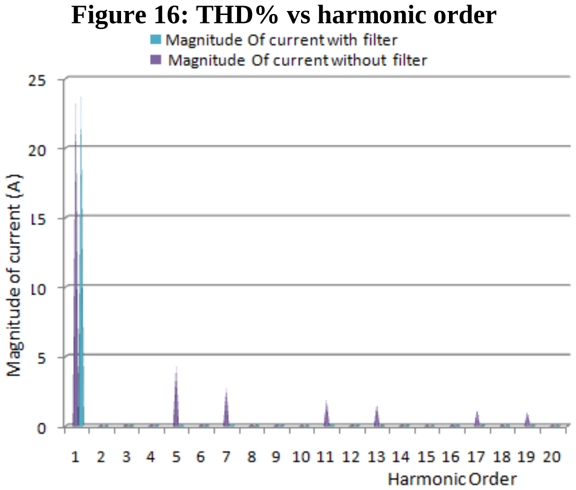

Figure 17: Magnitude of source current vs harmonic order

The hardware setup of the DSTATCOM is shown in Figure 18. The working model results are analyzed through a Digital Storage Oscilloscope and are projected in Figures 19.a to 19.e; it can be seen as almost matching with the waveforms obtained through simulation. Figure 19.a depicts the source current and load current after shunt compensation provided by the custom power device. Figure 19.b explains the supply current and shunt compensation current before and after the injection of compensating element to the system. Figure 19.c projects the transition waveform of supply side current before and after the inclusion of filter current. Figures 19.d and 19.e clearly show that the power factor is improved when shunt device provides the compensation.

Figure 18: Hardware implementation of DSTACOM

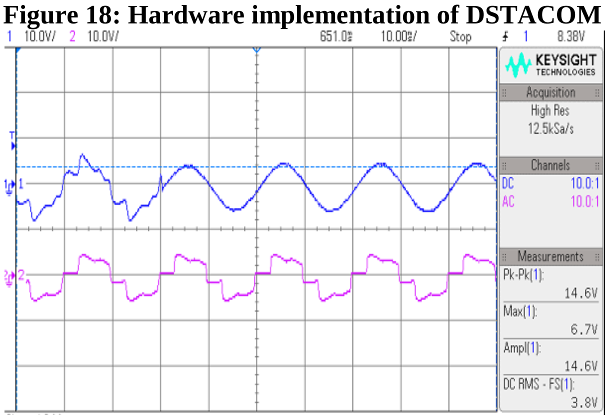

Figure19: a Source current and Load current waveforms after compensation

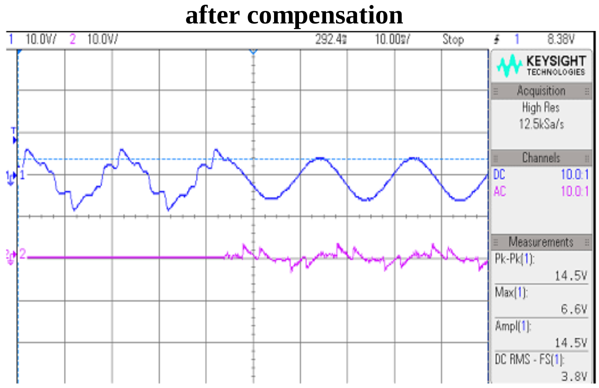

Figure 19: b Source Current and Filter Current

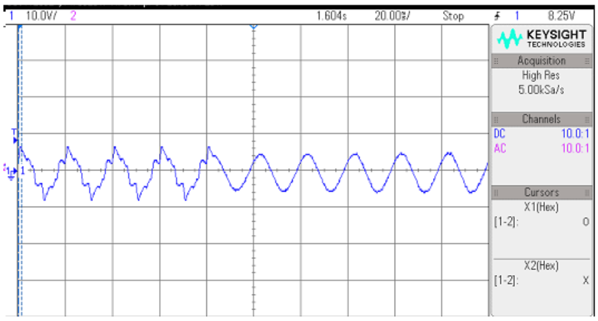

Figure 19: c Transient Current waveform

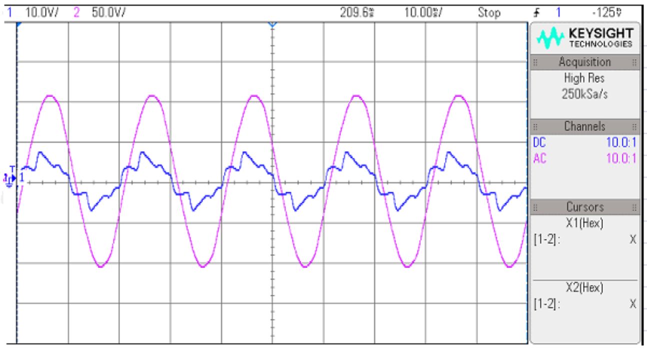

Figure 19: d Source voltage and Source current before compensation

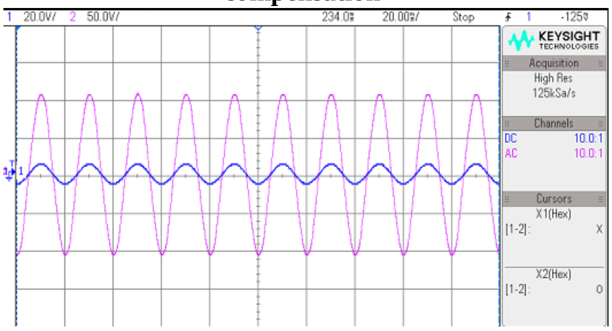

Figure 19: e Source voltage and Source current after compensation

V. CONCLUSION

The harmonic currents control is highly important to maintain a high level of power quality due to the substantial use harmonic producing solid state devices. Passive filters, active power filters and custom power devices are the correct way to suppress harmonics.

This paper gives the solution to improve the power quality in the distribution systems by using one of the custom power device called Distribution static synchronous compensator (DSTATCOM). The reference current for shunt compensation is extracted with help of synchronous reference frame theory and control signal to the device is generated from the hysteresis current control method. This device provides reactive power compensation, load balancing and harmonic current compensation in ac distribution networks. This implemented DSTATCOM improves the shape of the harmonic current. Both the simulation and the experimental results were analyzed. Simulation as well as hardware results are obtained with a condition of balanced sinusoidal voltage source and balanced load and it shows that the current is compensated and the pure sinusoidal result is obtained with thw use of DSTATCOM.

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