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Control Strategy for Distribution Static Compensator based on Instantaneous Reactive Power Theory for Power Quality Improvement in Distribution System

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Abstract: Nonlinear loads inject harmonics in the power system and distorts the load current waveform. These load current harmonics ultimately give rise to harmonics on the supply side and hence can affect the neighboring consumers. Custom power technology is employed to avert issues of power quality on the source side. Among numerous custom power tools, Distribution Static Compensator (D-STATCOM) is considered to be an effectual Shunt Active Power Filter to banish current harmonics, providing a good balance between cost and performance. A control strategy based on Instantaneous Reactive Power (IRP) theory for D-STATCOM is discussed in this paper. D-STATCOM is controlled to compensate for reactive power and to discard the objectionable harmonics injected in the distribution system by nonlinear load. Anti-harmonics current is inserted in the grid lines by the mentioned Shunt Active Power Filter, which nullify the harmonics introduced by the nonlinear load. To be used for the nullification of current harmonics, D-STATCOM is connected parallel with the load. Moreover, the power factor of the system is ameliorated along with a significant decrease in Total Harmonic Distortion (THD) in the source current. The model is simulated in MATLAB/SIMULINK in order to investigate the performance and efficiency of the propounded system. The simulation results reveal expeditious dynamic response and high precision of D-STATCOM in achieving the desired goals.

Keywords: Distribution Static Compensator (D-STATCOM), Power Quality, Instantaneous Reactive Power (IRP) Theory, Custom Power.

I. Introduction

The term power quality is more frequently utilized these days in the power industry and both the power providers as well as the cessation users are equally perturbed about it. The quality of power distributed to the end users is of great paramount and depends on all the three parameters i.e. voltage, current and frequency. Power quality is considered to be affected if there occurs a deviation in any of the above mentioned parameters of the distributed power i.e. frequency voltage or current, from the nominal values.

Reasons of these deviations may include the presence of a variety of loads in the electric power network or the happening of faults in the exposed network. Majority of the loads in our system have inductive nature such as industrial load, motors, fans etc. These loads draw reactive power with a lagging power factor and hence affect the source power factor by incrementing reactive burden on the source [1]. This will augment losses within the distribution network and essentially lessen active power flow capacity in the network. A poor power factor causes terrible voltage regulation with a rise in the load current since load current and power factor has an indirect relation. A load with poor power factor will draw higher current as compared to a load with good power factor, even if power rating of both loads is same. Consequently a low power factor implicatively insinuates more sizably voluminous machine size, more voltage drops, more sizably voluminous conductor size and low efficiency. common feeder. These voltage/current harmonics may affect the normal operation of the appliances and ultimately may result in the breakdown of the equipment [2].

Custom power device technology is utilized to rectify problems of power quality in the distribution network [3]. A Distribution Static compensator (D-STATCOM) is a member of custom power device family utilized for harmonics banishment, reactive power redress and load balancing in the distribution system [4]. Several control strategies are implemented to extract reference signals for D-STATCOM including Instantaneous Reactive Power (IRP) theory [5], Modified Power Balance Theory [6], Synchronous Reference Frame (SRF) theory [7] and neural network predicated technique [8]. Among all these mentioned techniques, IRP theory and SRF theory are widely employed [9]. This paper utilizes IRP theory as a control strategy for D-STATCOM in MATLAB/SIMULINK and results are analyzed.

II. System Configuration

A simplified system model is show in fig.1. The distribution feeder shown in the figure represent the secondary side of distribution transformer which supplied the load. Rs reflects resistance of the source and distribution line. Similarly, Ls reflects inductance of the source and the line. For elimination of current harmonics, D-STATCOM is connected parallel with the load wherein the harmonics are banished by injecting compensating current identical to harmonic-frequency components of current. Consequently, the source current will be sinusoidal with no harmonics at PCC.

D-STATCOM accommodates a three phase voltage source inverter (VSI) which can be realized by six IGBT switches

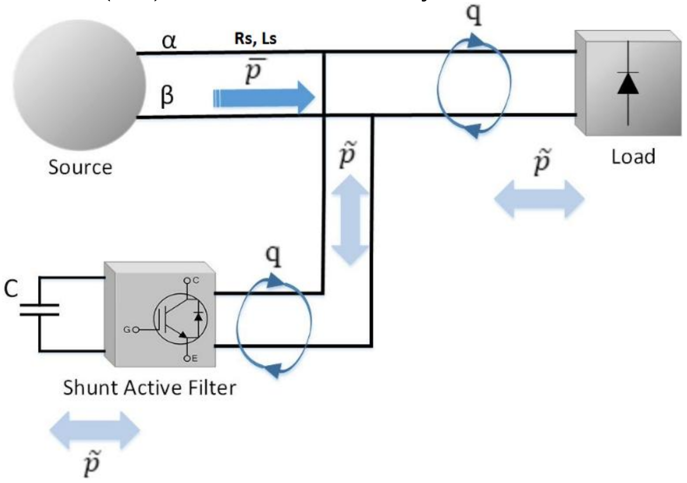


Figure 1: System Configuration

forming three legs [10]. A capacitor is applied at the DC side of voltage source inverter (VSI) whose purpose is to hold the voltage at a delegated degree to carry out switching of IGBTs. The DC capacitor being a voltage source plays a vital role satisfying reactive power demand of the load. DC capacitor voltage is kept constant by means of employing a PI controller. D-STATCOM is connected with the distribution line through interfacing inductance Lf to clear out excessive frequency additives of compensating current [11]. A complete system model is shown in fig. 2.

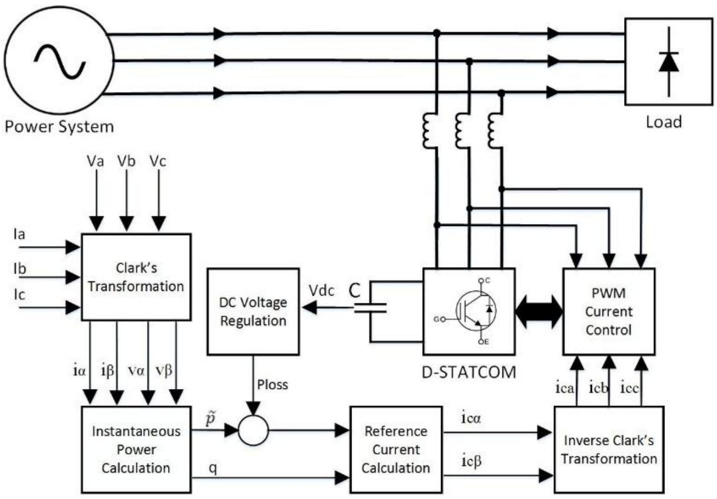
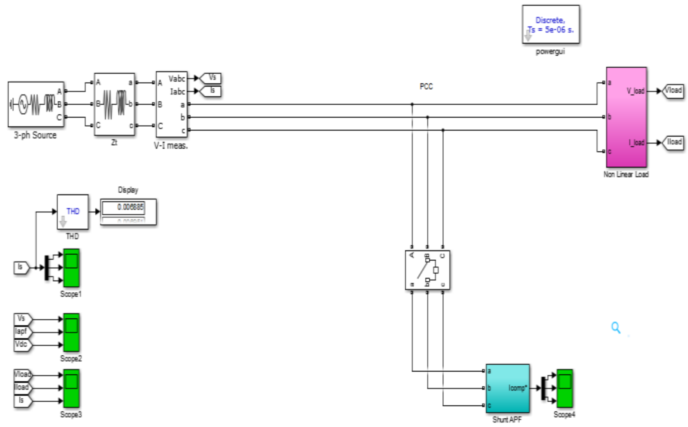


Figure 2: Complete System Model

The model is simulated for both linear and nonlinear load. Linear load is modelled using R-L load whereas nonlinear load is modelled by means of connecting three phase diode rectifier with the power lines. Reference current signals are extracted through instantaneous reactive power (IRP) theory and then pulse width modulation (PWM) technique is implemented using these reference current signals to trigger the IGBTs. Hysteresis based PWM current controller is used which is fed with the reference currents to sway the compensating current contemporary to observe these reference currents. A working model of D-STATCOM with instantaneous reactive power theory simulated in SIMULINK is manifested in fig. 3.



DSTATCOM-A SHUNT ACTIVE POWER FILTER

Figure 3: System Configuration in SIMULINK

III. CONTROL ALGORITHM

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A. IRP Theory

Akagi was the first to instigate the conception of instantaneous reactive power theory [12]. This theory possess flexibility and can be utilized in both transient state as well as steady state. IRP theory or p-q theory transmute three phase quantities to α-β-0 stationary orthogonal coordinates and then computation of instantaneous power is realized on these axes [13],[14]. Zero sequence component may subsist in a three phase 4 wire distribution system because there exists a system ground. However zero sequence component cannot be realized in a three phase 3 wire system, ergo transformation is done to α-β frame. Figure 4 displays the block diagram representation of IRP theory.

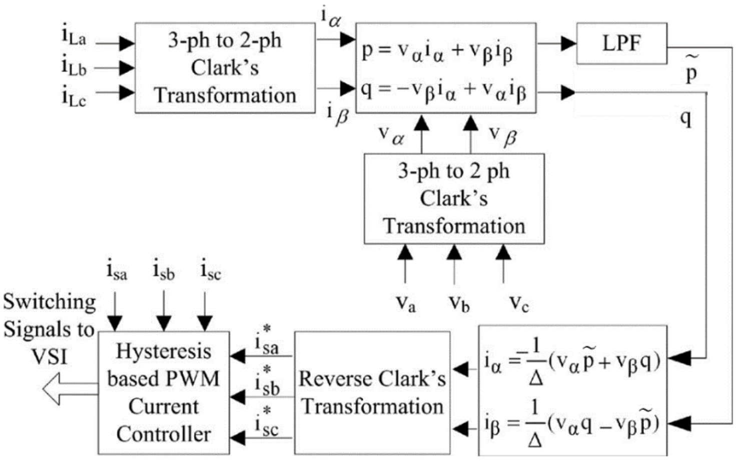

Figure 4: Block diagram representation of IRP theory

The system three phase instantaneous voltages are stated as

$$v_a = V_{max}\,Sin(\omega t)$$

$$v_b = V_{max}\,Sin(\omega t - 2\pi/3)$$

$$v_c = V_{max}\,Sin(\omega t + 2\pi/3)$$

Similarly, the instantaneous load currents can be stated as under

$$i_a = \sum i_{an}\ Sin\{n(\omega t) -\ \theta_{an}\}$$

$$i_b = \sum i_{bn}\ Sin\{n(\omega t - 2\pi/3) -\ \theta_{bn}\}$$

$$i_c = \sum i_{cn}\ Sin\{n(\omega t + 2\pi/3) -\ \theta_{cn}\}$$

The instantaneous currents and voltages are set on a, b and c axes whose amplitudes change with respect to time. These voltage and current quantities are transmuted to α-β frame from a-b-c axes using Clark's transformation as given below

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

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

Instantaneous three phase power on a-b-c axes is given by

$$p = v_a * i_a + v_b * i_b + v_c * i_c$$

Similarly, instantaneous powers can be translated onto α-β frame as follows

$$p =\ v_\alpha * i_\alpha + v_\beta * i_\beta$$

$$q =\ -v_\beta * i_\alpha + v_\alpha * i_\beta$$

Expressing in matrix form as

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

Both active and reactive powers can be splitted into two constituents

Active power: $p = \bar{p} + \tilde{p}$

Reactive power $q = \bar{q} + \tilde{q}$

$\bar{p}$ and $\bar{q}$ represents average (dc) components of real and imaginary powers whereas the swaying components are represent by $\tilde{p}$ and $\tilde{q}$ respectively. $\bar{p}$ corresponds to the actual active power flow from source towards load. $\bar{q}$ shows the fundamental component of reactive power that sway between the phases. No power transfer between source and load is implied by this component. $\tilde{p}$ is oscillating active power that flows due to the harmonic current. $\tilde{q}$ corresponds to the oscillating component of reactive power ascribable to current harmonics.

For current harmonics abstraction and reactive power redress, $\tilde{p}$, $\bar{q}$ and $\tilde{q}$ should be used for the determination of reference current for gating VSI. Accordingly, the reference compensating current signals in α-β frame can be written as

$$\begin{bmatrix} i^*_{s\alpha} \\ i^*_{s\beta} \end{bmatrix} = \frac{1}{\Delta} \begin{bmatrix} v_\alpha & v_\beta \\ v_\beta & -v_\alpha \end{bmatrix} \begin{bmatrix} -\tilde{p} \\ -q \end{bmatrix}$$

Where

$$\Delta =\ v_\alpha^2 +\ v_\beta^2$$

These reference compensating currents can be retransformed to a-b-c coordinates utilizing inverse Clarke's transformation.

$$\begin{bmatrix} i_{sa}^* \\ i_{sb}^* \\ i_{sc}^* \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_{s\alpha}^* \\ i_{s\beta}^* \end{bmatrix}$$

B. PI Controller

The AC source satisfies the active power requirement of the load as well as some losses e.g. switching losses in DSTATCOM [15]. If switching losses are not provided by the source, it would be provided by the dc capacitor itself and its voltage would drop down perpetually. Consequently, the reference current for triggering VSI contains two components, one is for emolument of reactive power and harmonics and others is for emolument of these losses. PI controller is used for voltage regulation as its main feature is to diminish steady state error. PD controller improves the speed and transient response of the system. PD or PID is not used because they may cause system instability.

The switching loss component is computed by comparing a set value of dc bus voltage $V_{dc\ ref}$ with observed dc voltage V_{dc}

$$v_{diff\,(x)} = v_{dc\ ref\,(x)} - v_{dc\,(x)}$$

The above difference gives the error signal which gets processed by PI controller as shown in fig. 5.

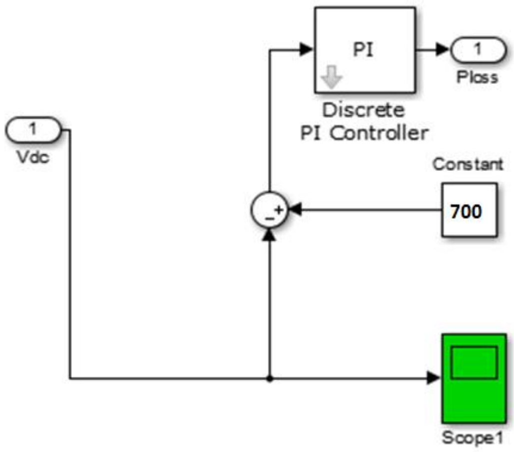

Figure 5: Voltage error signal processing by PI controller

At the xth sampling moment, PI controller gives output $I_{p(x)}$ as

$$I_{p(x)} = I_{p(x-1)} + K_p\left(v_{diff\,(x)} - v_{diff\,(x-1)}\right) + K_i v_{diff\,(x)}$$

Where

K_p = Proportional gain

K_i = Integral gain

PI controller outputs the loss component P_{loss} which is added with $\overline{p}$ i.e. the real power drawn by the load, so that the source furnish this component along with the real power of the load.

C. Hysteresis Current Controller

The reference compensating current signals obtained by means of IRP theory are now utilized for triggering the VSI. Sundry current controllers are available for controlling D-STATCOM such as PI controller, Hysteresis current controller [16], Predictive current controller [17], Sliding mode controller [18], Delta modulation controller [19] etc. Hysteresis current control provides the best balance as it can be facilely implemented with enhanced current controllability and fast response. Hysteresis current controller is elucidated in fig 6 with the help of a block diagram.. $\boldsymbol{i_f^*(t)}$ is the reference line current of D-STATCOM whereas $\boldsymbol{i_f(t)}$ is the real-time line current. Triggering pattern of VSI is decided by Hysteresis current controller upon comparing both of these currents.

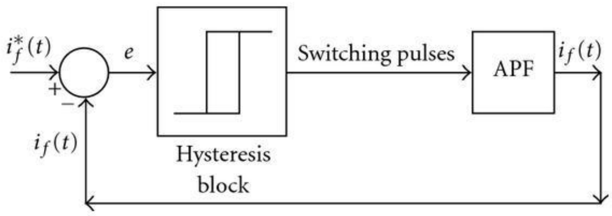

Figure 6: Block diagram of hysteresis based current controller

IV. SIMULATION RESULTS

The efficacy of D-STATCOM with the implementation of IRP theory for current harmonics abstraction, reactive power redress, load balancing, and power factor improvement is analyzed by simulating the model in SIMULINK. The efficiency of D-STATCOM for both unbalanced linear and nonlinear loads is promised by the simulation results. Difference parameters are investigated by exhibiting their waveforms afore and after emolument.

A. Current Harmonics Elimination

The load and source current prior to and after application of compensation is manifested in fig. 7 below.

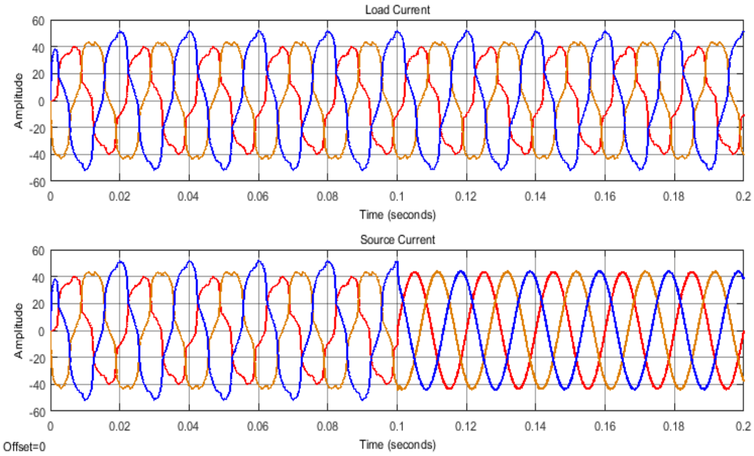

Figure 7: Pre/Post compensation Load and Source current

The deformation of load current waveform is caused by the presence of nonlinear load. It can be seen that before inserting D-STATCOM in the circuit, source current is affected by the harmonics introduced by nonlinear load, but the source becomes sinusoidal after connecting D-STATCOM at 0.1 sec since the compensating current after 0.1 sec is provided by the D-STATCOM. Figure 8 shows the three separate phases of source current.

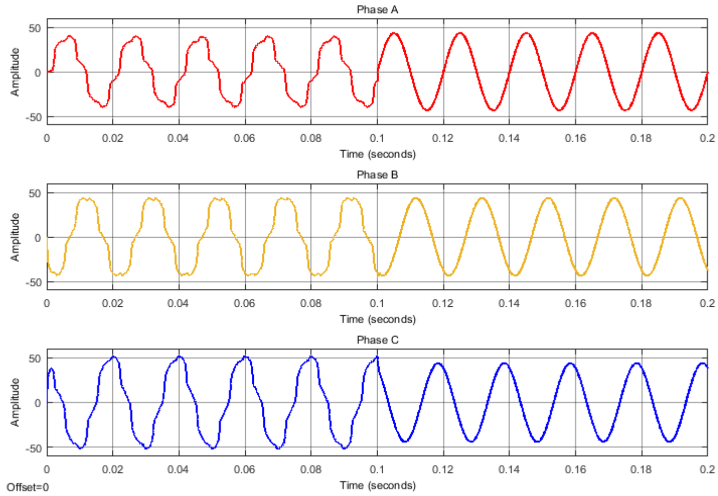

Figure 8: Three phase source current

The source current is outstandingly improved by reducing THD from 20% to 0.78%.

B. Reactive Power Compensation

The real and imaginary powers required by load are displayed in figure 9. Due to existence of current harmonics, both powers are oscillating. The instantaneous power supplied by the source is shown in fig. 10. After connecting the shunt active filter at 0.1 sec, the source only satisfies the active power requirement of load along with switching losses. Whereas the reactive power as well as oscillating active power is supplied by the D-STATCOM.

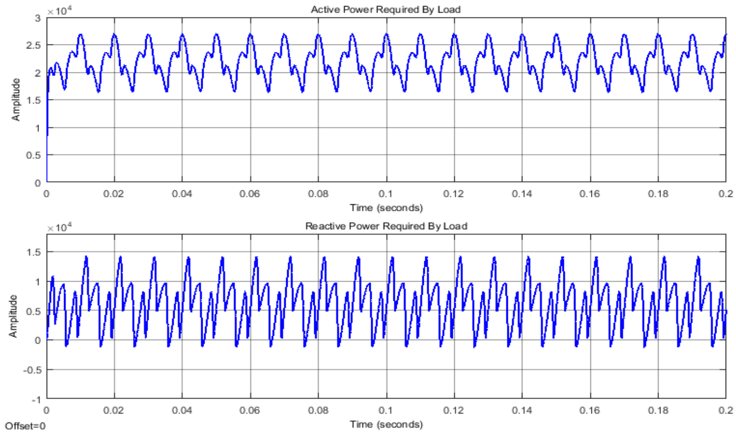

Figure 9: Active and Reactive power drawn by load

The reactive power compensation capability of D-STATCOM is clearly demonstrated in fig. 10.

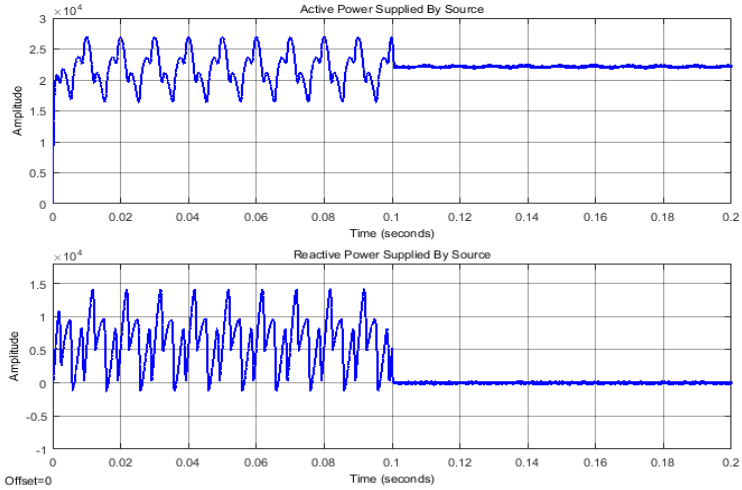

Figure 10: Active and Reactive power supplied by source

C. Power Factor Improvement

After inserting D-STATCOM in the circuit at 0.1 second, it furnishes the reactive power to the load. Therefore, the source is relieved from reactive power burden thereby improving source power factor to unity.

Figure 11 displays the waveforms for Red phase of source current and source voltage. Before compensation, the presence of inductive load determine the source power factor to be 0.8 lagging. However after inserting D-STATCOM at 0.1 second, the source power factor becomes unity as is obvious from the figure below, although the load power factor remains the same.

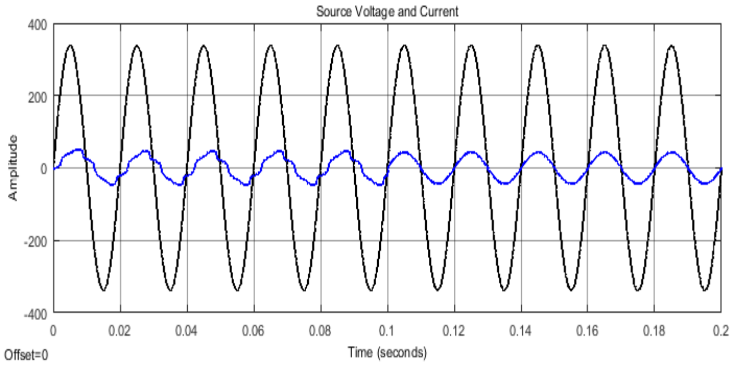

Figure 11: Power factor improved by compensation

D. Load Balancing

Load balancing achieved by compensation is shown in fig. 12. Unbalanced current flows in all the three phases due to unbalanced load before compensation. After compensation, the current in all phases become equal.

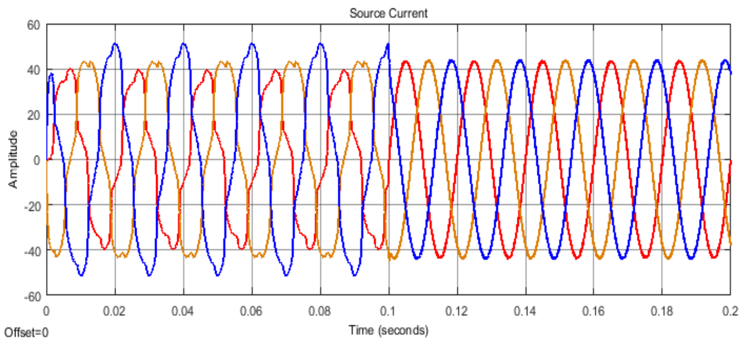

Figure 12: Load balancing achieved by compensation

E. Compensating Current

Fig. 13 illustrates that the compensating current provide by the D-STATCOM before 0.1 second is zero. After connecting it at 0.1 second, it provides the required compensating current for power factor improvement.

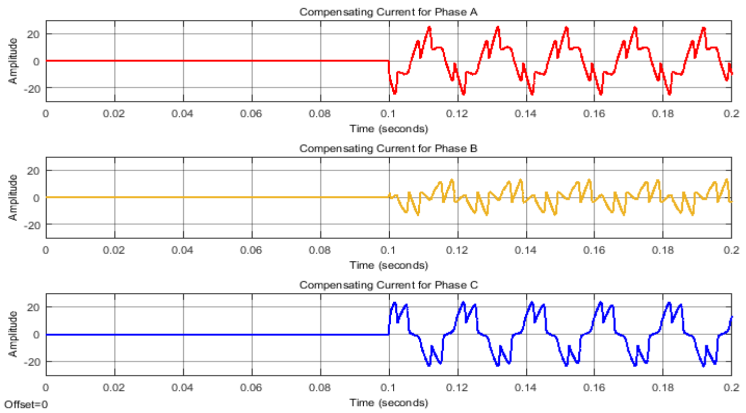

Figure 13: Compensating current provided by D-STATCOM

F. DC Bus Voltage

PI controller has proved its efficacy by maintaining the DC bus voltage at 700 V for proper switching of VSI as shown in fig. 14.

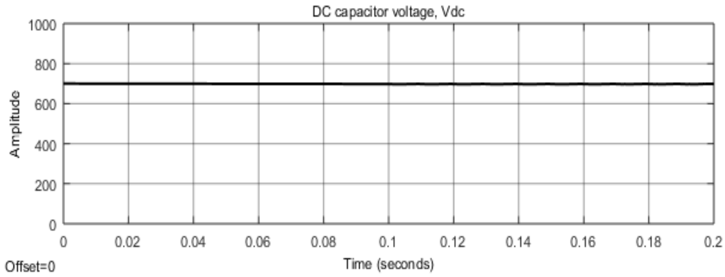

Figure 14: DC link voltage of D-STATCOM

CONCLUSION

The performance of D-STATCOM has been studied in this paper with implementation of IRP theory for generating reference current signals. Simulation results has proved the performance to be cop-acetic for reactive power emolument, current harmonics elimination, power factor amelioration and load balancing. As compared to other reactive power controlling contrivances, D-STATCOM has quite expeditious replication for reactive power compensation. The source current was improved remarkably by diminishing its THD down to a level of 0.78% to meet IEEE 519 standard for harmonics under non-ideal voltage conditions. Similarly, the regulation of DC bus voltage at a level specified by the reference value is swimmingly achieved for better performance of the shunt active filter.

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