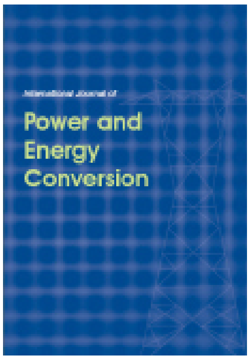

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Performance evaluation of DSTATCOM using retransformation of Clarke transformation technique for supply and load perturbations

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Abstract: This paper presents a novel simple controller for distribution static compensator (DSTATCOM) to achieve balanced source currents with power factor correction and harmonics mitigation in a three-wire distribution supply system under various supply and load conditions. The proposed algorithm rearranges the switching times for each device of the voltage source converter to compensate the reactive power demand by the nonlinear or unbalanced reactive loads. Simulation results demonstrate the optimised performance of the DSTATCOM after implementing proposed control algorithm. The proposed control algorithm applied to an improved power quality PWM AC to DC converter as reported in the literature is extended to the bidirectional converter operating in inversion mode. The PWM converter with proposed control algorithm operated as an inverter is made to work as DSTATCOM for perfect load compensation.

Keywords: distribution static compensator; DSTATCOM; harmonics mitigation; power factor correction; nonlinear load; point of common coupling.

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1 Introduction

Electric power quality term is related to access and maintain good quality of electric power at the different levels of AC electrical power system i.e, at transmission level, distribution level and utilisation level. At the utilisation level, tainting of electric power supply system in much severe with increased use of power electronics converters in domestic, commercial and industrial sector (Singh et al., 2015a). The tainting of electric power supply influences stability , reliability and quality of power system in term of fundamental components like voltage, current and frequency. From three decades, power quality has demanded special attention at levels of electrical distribution and utilisation system in electrical power system. Utilities must supply consumers with good quality power for satisfactory operation of equipment. Electric power quality has created a great challenge among manufactures and engineers. Manufactures must develop their electric equipment to be immune to such disturbance and engineers should develop custom power devices (CPDs) to mitigate the power quality problems in a distribution system. Some of the famous CPDs are unified power quality conditioners (UPQC), active power filters (APFs), dynamics voltage restorer (DVR) and distribution static compensator (DSTATCOM). All these CPDs depend on control techniques for their effective operation. For a low to medium voltage distribution system, DSTATCOM is considered to be most effective CPD in providing excellent performance in dealing with reactive power compensation, balancing of source currents and harmonics elimination from source currents. For the control of DSTATCOM, numerous control methods/algorithms have been reported in the literature. In Singh et al. (2015b), a three-phase DSTATCOM uses self tuning filter (STF) based instantaneous reactive power theory (IRPT) control algorithm for harmonics elimination, load balancing and reactive power compensation at the distorted PCC voltages under nonlinear loads. Use of hysteresis controller-based method (Jiang et al., 2010), enhanced phase-locked-loop method (Sharma and Singh, 2011), Icosϕ control technique (Mangaraj et al., 2020), sliding mode controller (SMC) together with a fuzzy logic controller (Sekhar et al., 2016) are reported in the literature. In Panda and Penthia (2017), authors used a superconducting magnetic energy storage (SMES) based shunt active power filter (SAPF) topology to compensate high power pulsating load demands in a power system. In Tripathi and Barnawal (2018), authors proposed control method that regulates DSTATCOM for nonlinear load using source quadrature current component forced to be zero so that only the active current component is drawn from the source and the harmonic can be eliminated. In Penthia et al. (2021), an adaptive control technique called Icosθ control algorithm along with a Kernel-based training method is proposed in a fuel cell-based DSTATCOM for harmonic compensation.

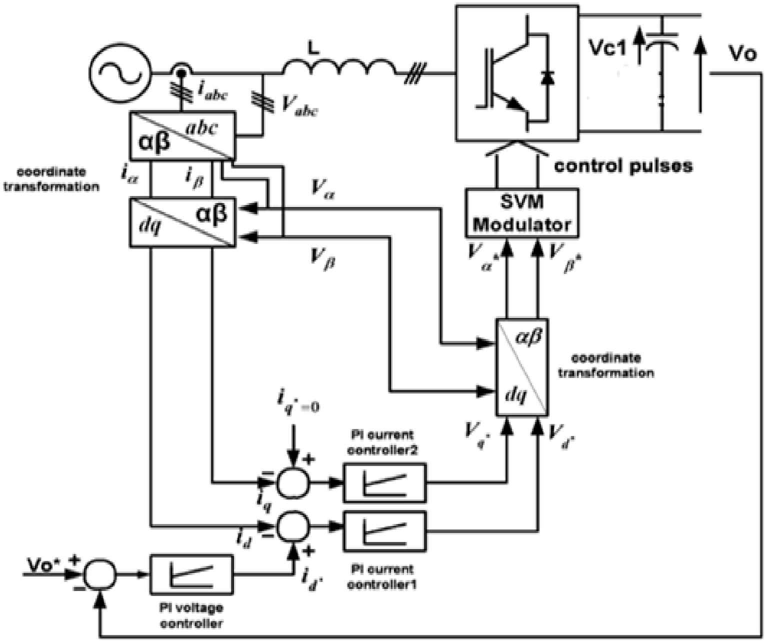
All the methods described above generate switching pulses for the DSTATCOM by generating reference or compensating signal from feedback signals, which may either be voltage or current signals. The reference signal can be named as load current or source current depending on the configuration of the control system.The algorithm proposed by the authors in the present work uses optimised switching sequences, this causes reduced switching transitions in SVPWM algorithm, hence reduced switching power losses and consequently increased converter efficiency.

2 Proposed control algorithm

An improved power quality AC to DC converter reported in Sharma et al. (2016) has been considered as a basic converter for maintaing good power quality at source and laod side. In this work, space vector PWM modulation alogrithm has been used to address source side power quality (near unity input power factor and sinosidal source currents) under distrubed source conditions and load peturbation by retransformation of Clarke transformation technique. In this proposed contol algorithm, same converter can be used as an inverter under load and supply side perturbation by extending the control algorithm as proposed in Sharma et al. (2016) in inversion mode of operation. The inverter is connected across the load at the point of common coupling (PCC) and can be made to work as DSTATCOM for perfect load compension.

The basic conventional control algorithm of SVPWM for power factor correction converter as shown in Figure 1. The magnitude of V_α, V_β and I_α, I_β of Clarke Transformation affected with the change in the supply conditions which further results affects the rotating frame of reference (d-q) components, which are responsible for the formation of reference rotating space vector.

Figure 1 Conventional SVPWM control scheme for a converter



Three-phase voltages and fundamental line currents are given as,

$$
\begin{aligned}
&V_a = V_m \cos(\omega t). && i_a = \operatorname{Im}\cos(\omega t) \\
&V_b = V_m \cos\left(\omega t - \frac{2\pi}{3}\right) \quad \text{and} && i_b = \cos\left(\omega t - \frac{2\pi}{3} + \theta\right) \\
&V_c = V_m \cos\left(\omega t + \frac{2\pi}{3}\right) && i_c = \operatorname{Im}\cos\left(\omega t + \frac{2\pi}{3} + \theta\right)
\end{aligned}
\tag{1}
$$

Transformation from *A-B-C* coordinate system to the stationary α–β frame expressed in (2) to (4).

The reference vector '*Vref*' is obtained by mapping three phase output voltages through the Clarke transformation given by

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} =_N \begin{bmatrix} 1 & \frac{1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \text{ and } \begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} =_N \begin{bmatrix} 1 & \frac{1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \tag{2}$$

$$V_\alpha = \frac{2}{3}\left(Va - \frac{1}{2}Vb - \frac{1}{2}Vc\right) \text{ and } V_\beta = \frac{2}{3}\left(\frac{\sqrt{3}}{2}Vb - \frac{3}{2}Vc\right) \tag{3}$$

Similarly,

$$I_\alpha = \frac{2}{3}\left(Ia - \frac{1}{2}Ib - \frac{1}{2}Ic\right) \text{ and } I_\beta = \frac{2}{3}\left(\frac{\sqrt{3}}{2}Ib - \frac{3}{2}Ic\right) \tag{4}$$

The reference vector 'V_{ref}' rotates in six sectors for two-level three-phase rectifiers. The reference vector V_{ref} for a particular sector is synthesised using the two adjacent space vectors, U_a and U_b.

$$Vref = t_a U_a + t_b U_b + t_o U_0 \tag{5}$$

where U_a, U_b are the active vectors and U_0 is the zero vector, t_a, t_b and t_o are the respective duty ratios and sum of duty ratios is constant i.e, $ta + tb + to$ = constant value.

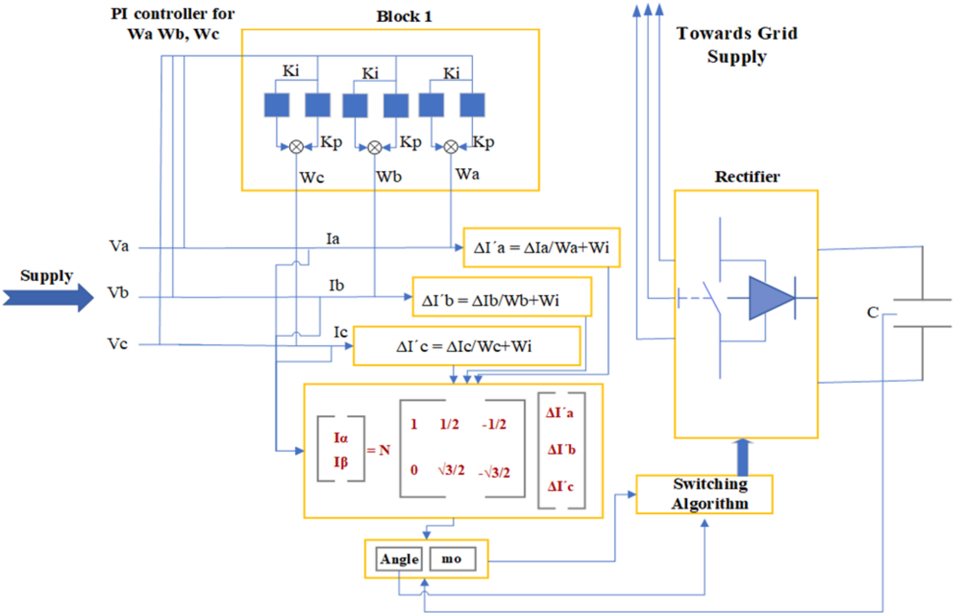
$$\begin{aligned} &t_a = T_s\left(2m\sin\left(\theta + \frac{\pi}{3}\right) - 1\right), t_b = T_s\left(1 - 2m\sin - \theta\right), \\ &t_0 = T_s\left(1 - 2m\sin\left(\theta + \frac{\pi}{3}\right) - \theta\right) \end{aligned} \tag{6}$$

$$ta + tb + t_0 = T_s/2, \tag{7}$$

Ts is the sampling time.

The alteration in the shape of circular trajectory, duty ratios of nearest three vectors change due to change in t_a, t_b, t_o. But the total sum of the duty ratios in the each sector will be constant (7). The change in duty ratio in each sector will be unsymmetrical which results in deterioration of quality of source currents. The conventional algotithm is unable to work under load or supply perturbation. From Sharma et al. (2016, 2017, 2018a, 2018b, 2018c, 2019), Sharma and Bhat (2021) and Sharma (2022), authors have proposed a current regulator for a three-phase neutral-point clamped rectifier to mainatian power quality at both sides of the rectifier for any supply or load perturbed conditions moreover at the same time support in presevation of least capacitor potential differnces. Control algorithms adapts itself according to any change in load or supply voltage. The controller generates refernce compensating signals from DC-bus teminals as well as from input supply to generate desired gate pulses to the converter for the correct working of the converter using Clarke retransformation technique. In this work, authors use modified SVPWM for inversion mode for the control of DSTATCOM. The proposed algorithm modifies Clarke Transformation parameters $V\alpha$, $V\beta$ and $I\alpha$, $I\beta$ against supply and load perturbation so as to generate required trajectory of the space reference vector to vary time ratio of devices of DSTACOM inverter. This results in injection of reactive power to the system as shown in Figure 2.

Figure 2 Schematic diagram of the proposed control algorithm (see online version for colours)



Block1 represents a pool of PI controllers. The main purpose of this block is to control gate pulses for the converter according to maintain power quality at the source side by controlling the duty ratio of the devices. In equation (8), $e(t)$ = error difference in the line voltages, K_p represents proportional controller gain which ranges from 0 to 0.2 and ki represents integral gain.

$$Wa, Wb, Wc \quad \alpha c(t)(control\ signal) = Kp * e(t) + ki\int_{0}^{t} e(t)\,dt \tag{8}$$

The controller gain ranges from 0.01 to 0.001. After the implementation of PI controllers, Clarke transformation given by (2) will be reframed as (9).

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

$$\begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} = N \begin{bmatrix} 1/Ix1 & \frac{1}{2}\Big/Ix2 & \frac{-1}{2}\Big/Ix3 \\ 0 & \frac{\sqrt{3}}{2}\Big/Ix2 & -\frac{\sqrt{3}}{2}\Big/Ix3 \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \tag{9}$$

where $n_{(\alpha,\beta)}$ is the new coefficient value for $V\alpha$, $V\beta$ and N is the new coefficient value for $I\alpha$, $I\beta$.

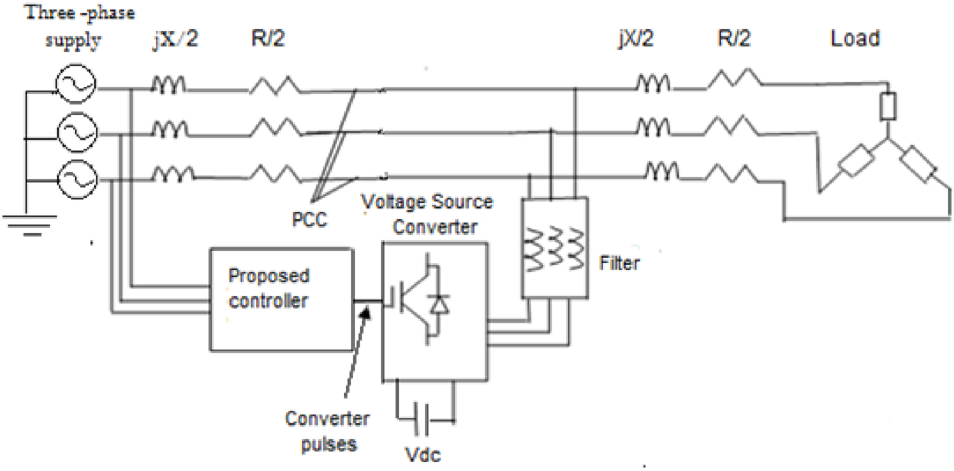
$x1, Ix2, Ix3 =$ *new transformed values.*

Under disturbed supply conditions or nonlinear or unbalanced loads, if the switching state of the voltage-source converter (VSC) is controlled somehow depending upon the required magnitudes of t_a, t_b, t_o, then improved power quality at the source side of the electrical system can be achieved. The reactive power generated by the converter is fed to the electrical network.

3 Performance evaluation

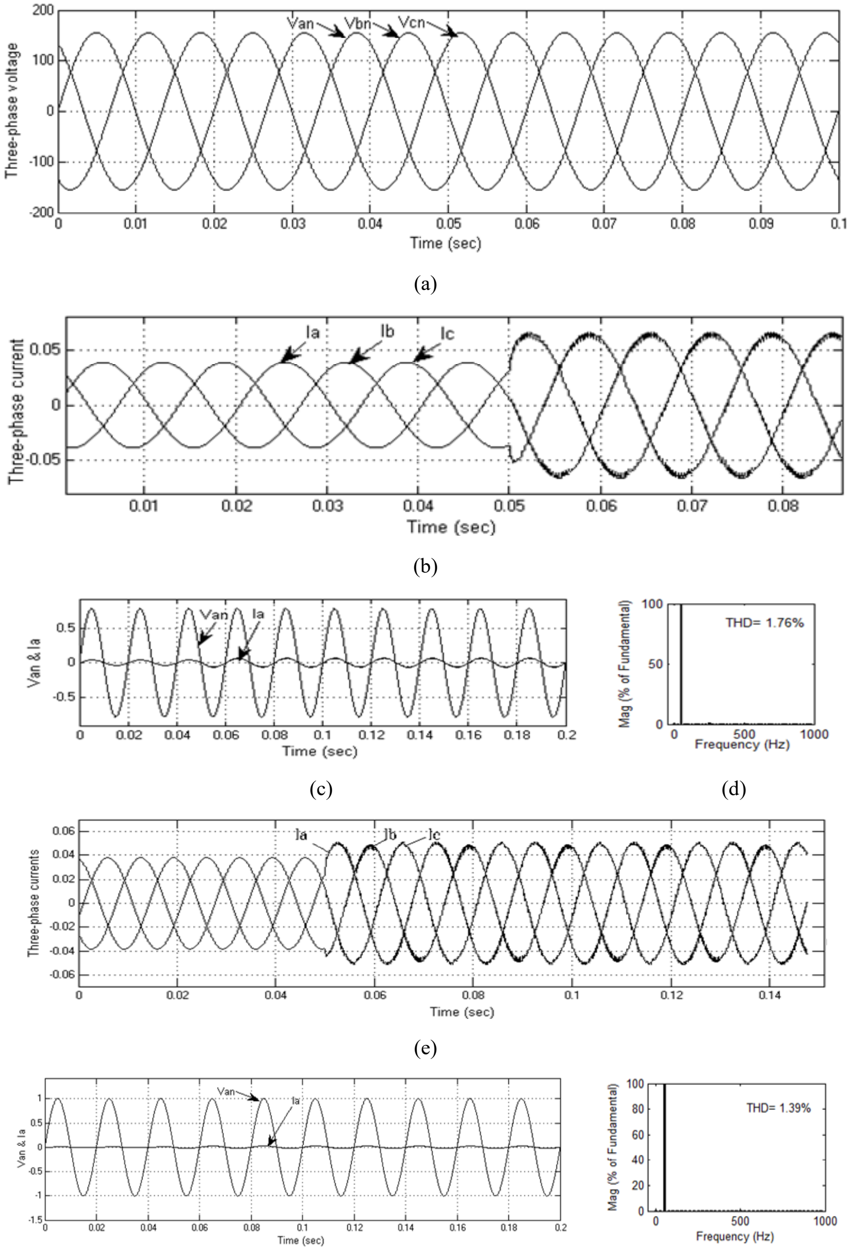
CPDs are static power electronics converters connected to an AC distribution system for providing highly reliable and good quality power to consumers (Bakshi and Bakshi, 2018). DSTATCOM is power electronics VSC connected across the load and acts as source of relative power. The proposed novel control algorithm for the control of DSTATCOM is to maintain power quality parameters well within the permitted limits as defined by IEEE 519 standards under any load and supply conditions.

Figure 3 Three-phase, three wire distribution system with DSTATCOM



The proposed algorithm cancels the effect at the source side of the electrical system caused by balanced/unbalanced or any type of loads in a way such that source currents are almost balanced in magnitude and sinusoidal in nature. The proposed controller also cancels the effect of poor power factor caused by load perturbation by maintaining most unity power factor at the source. Moreover, the proposed controller also eliminates the effect of harmonic current caused due to nonlinear loads in such a way that source currents are sinusoidal waveforms.

Figure 4 Performance evaluation for balanced supply with star resistive load in inversion mode



(a)

(b)

(c) (d)

(e)

(f) (g)

Notes: (a) Three-phase balanced supply voltages (b) Balanced source currents Ia, Ib, Ic with conventional SVPWM control algorithm (c) Van and Ia with unity power factor with conventional SVPWM control algorithm (d) Harmonic spectrum of source current (e) Balanced source currents Ia, Ib, Ic with proposed modified SVPWM control algorithm (f) Van and Ia with unity power factor with proposed modified SVPWM control algorithm (g) Harmonic spectrum of source current.

The performance of DSTATCOM based on modified proposed SVPWM is evaluated using MATLAB/Simulink and SimPowerSystems software. The system parameters for simulation are Source voltage: 110 V volts, System frequency = 50 Hz, Sampling frequency, fs = 5 kHz, Line Thevenin equivalent resistance Rth = 1.2 ohm, Line Thevenin equivalent reactance Xth = 0.6735 mH. Loads = balanced / unbalanced star resistive load/inductive /nonlinear load. The DSTATCOM parameters V_{dc} = 50 V, Capacitance C_{dc} = 0.6 e-6 F, Filter reactance L_f = 0.5 mH.

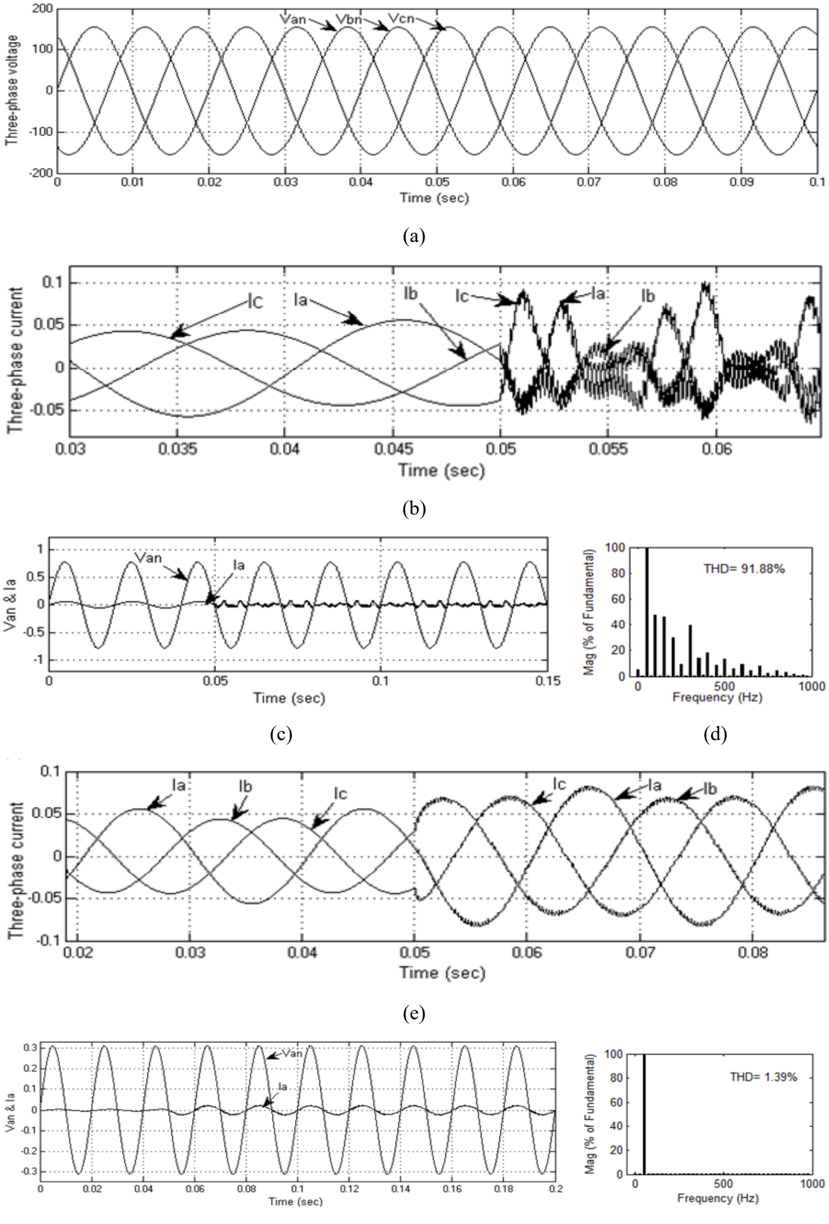
The proposed control algorithm is tested for conventional SVPWM for a balanced supply in all phases having magnitude of peak input voltage 155.6 V as shown in Figure 4(a). After *t* = 0.05 sec, the waveforms reveal that with the induction of conventional as well as proposed control algorithm, source currents are almost balanced and having sinusoidal waveforms as shown in Figures 4(b) and 4(e) with almost unity power factor as shown in Figures 4(c) and 4(f). Moreover results also show THD = 1.67% and THD = 1.39% as shown in Figures 4(d) and 4(g). Although with balanced source and resistive three-phase load, there is no role of DSTATCOM due to the absence of any power quality issue. The purpose here is only to show the working of improved power quality AC to DC converter in inverstion mode as DSTATCOM which works both for conventional SVPWM technique as well as proposed control algorithm.

The controller is tested against conventional SVPWM under balanced supply voltages, i.e., peak input voltage 155.6 V with unbalanced star resistive load magnitude R_a = 5 ohm and R_b = R_c = 10 ohm. After t = 0.05 sec, results display that with conventional algorithm source currents are non-sinusoidal as shown in Figure 5(b) with poor power factor and high THD = 271.9% as shown in Figure 5(c) and Figure 5(d) respectively. But with proposed algorithm source currents are almost equal in magnitude and have sinusoidal waveforms as shown in Figure 5(e), having almost unity power factor shown in Figure 5(f) with low THD = 1.39% as shown in Figure 5(g).

The controller is tested under unbalanced supply voltages and unbalanced resistive load. Sag of 52% in phase A is introduced.The peak input voltage 80V in phase A, peak input voltage 155.6 V in phase B, peak input voltage 155.6 V in phase C with unbalanced star resistive load magnitude R_a = 5 ohm and R_b = R_c = 10 ohm as in Figure 6(a). After t = 0.05 sec, Figure 6(b) results display non-sinusoidal source currents having poor power factor and high THD = 91.88 % as shown in Figure 6(c) and Figure 6(d) respectively under the influence of conventional algorithm. With proposed algotithm, the source currents are almost sinusoidal waveforms in Figure 6(e), having almost unity power factor shown in Figure 6(f) with THD = 3.80% at the PCC.

The controller is tested under balanced supply voltages conditions peak input voltage 155.6 V in all phases B, with RL load connected phase A, i.e. R_{AL} = 5 ohm and X_{AL} = 15 mH in a star resistive load. R_b = R_c = 10 ohm as in Figure 7(a). After t = 0.05 sec, results display non-sinusoidal source currents as shown in Figure 7(b). Figure 7(c) exhibits poor power factor and a high THD = 129.50% as in Figuer 7(d) under the influence of conventional algorithm. After t = 0.05, with proposed algotithm, as shown in Figure 7(e), source currents are almost sinusoidal aveforms and also at the same time have unity power factor shown in Figure 6(f) with low THD = 2.19%, which is well within the acceptable limits.

Figure 5 Performance evaluation for balanced supply with unbalanced star resistive load in inversion mode



(a)

(b)

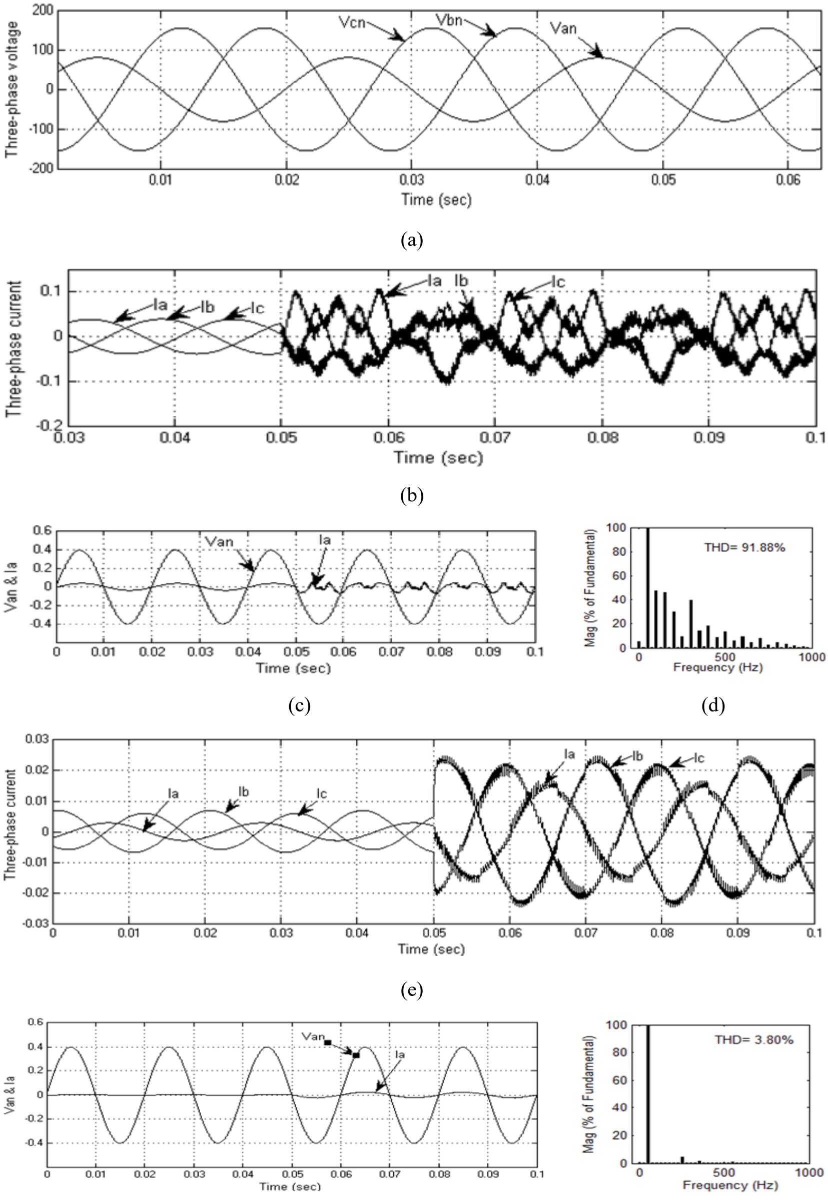
(c) (d)

(e)

(f) (g)

Notes: (a) Three-phase balanced supply voltage with unbalanced star resistive load (b) Non-sinusoidal source currents Ia, Ib, Ic with conventional SVPWM control algorithm (c) Van and Ia with poor power factor with conventional SVPWM control algorithm (d) Harmonic spectrum of source current (e) Balanced source currents Ia, Ib, Ic with proposed modified SVPWM control algorithm (f) Van and Ia with unity power factor with proposed modified SVPWM control algorithm (g) Harmonic spectrum of source current.

Figure 6 Performance evaluation for unbalanced supply with unbalanced star resistive load in inversion mode



(a)

(b)

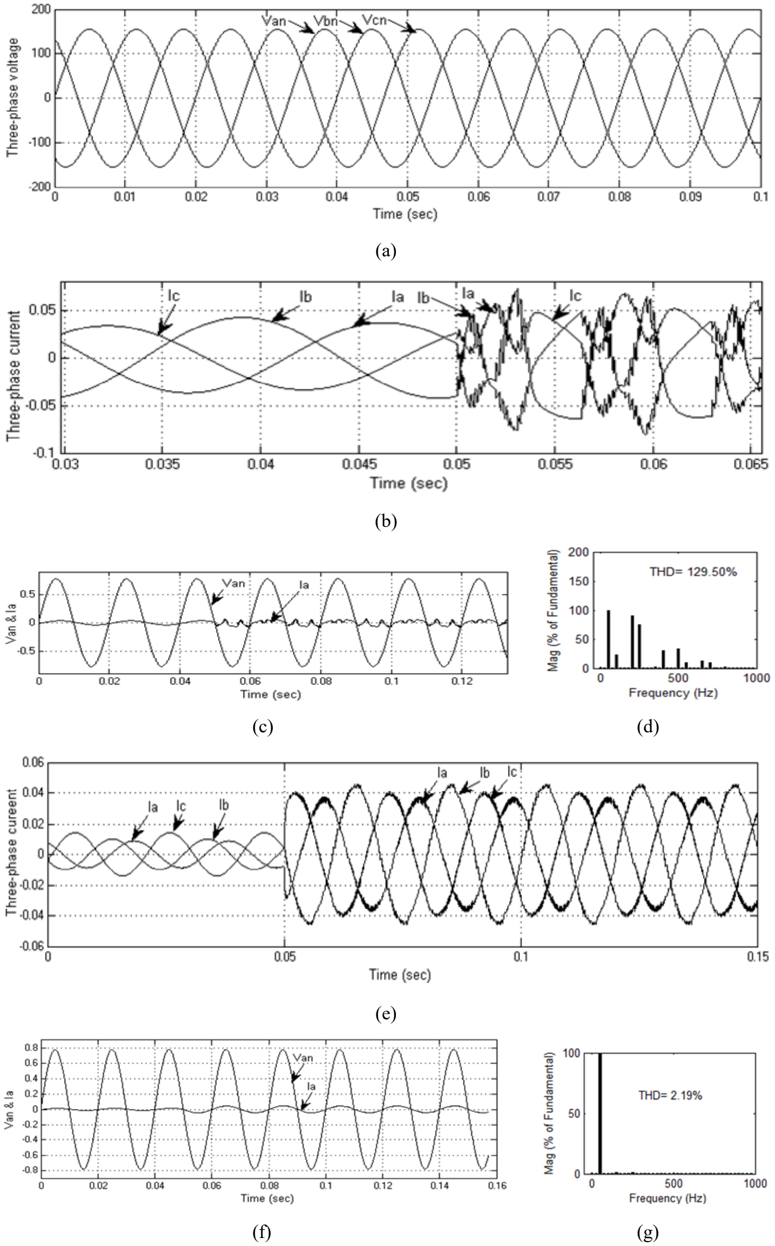
(c) (d)

(e)

(f) (g)

Notes: (a) Three-phase unbalanced supply voltage with unbalanced star resistive load (b) Non-sinusoidal source currents Ia, Ib, Ic with conventional SVPWM control algorithm (c) Van and Ia with poor power factor with conventional SVPWM control algorithm (d) Harmonic spectrum of source current (e) Balanced source currents Ia, Ib, Ic with proposed modified SVPWM control algorithm (f) Van and Ia with unity power factor with proposed modified SVPWM control algorithm (g) Harmonic spectrum of source current.

Figure 7 Performance evaluation under balanced supply conditions having RL load connected in phase A in a star resistive load in inversion mode



(a)

(b)

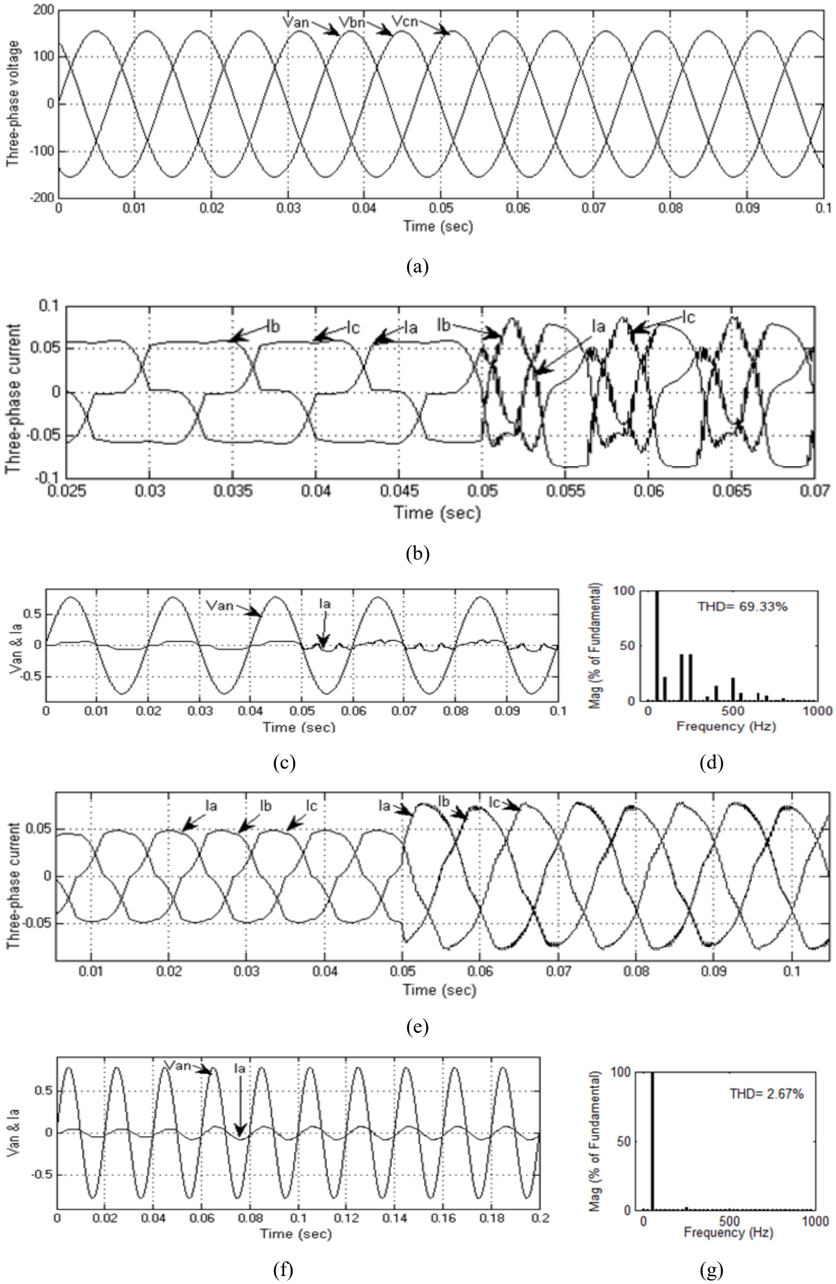
(c) (d)

(e)

(f) (g)

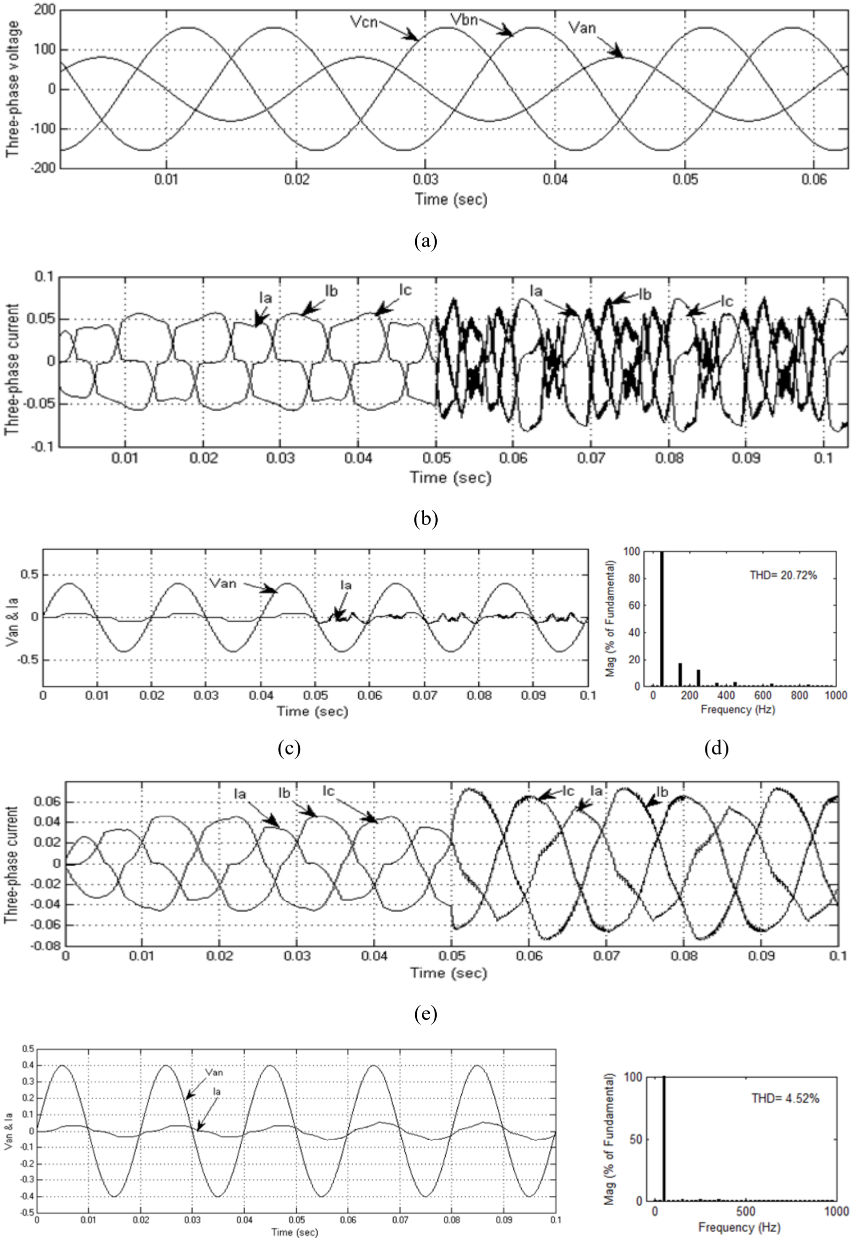
Note: (a) Three-phase balanced supply voltage with RL load connected in phase A in a star resistive load star resistive load (b) Non-sinusoidal source currents Ia, Ib, Ic with conventional SVPWM control algorithm (c) Van and Ia with poor power factor with conventional SVPWM control algorithm (d) Harmonic spectrum of source current (e) balanced source currents Ia, Ib, Ic with proposed modified SVPWM control algorithm (f) Van and Ia with unity power factor with proposed modified SVPWM control algorithm (g) Harmonic spectrum of source current.

Figure 8 Performance evaluation for balanced supply with nonlinear load in inversion mode



Notes: (a) Three-phase balanced supply voltage with nonlinear load (b) Non-sinusoidal source currents Ia, Ib, Ic with conventional SVPWM control algorithm (c) Van and Ia with poor power factor with conventional SVPWM control algorithm (d) Harmonic spectrum of source current (e) Balanced source currents Ia, Ib, Ic with proposed modified SVPWM control algorithm (f) Van and Ia with unity power factor with proposed modified SVPWM control algorithm (g) Harmonic spectrum of source current.

Figure 9 Performance evaluation for unbalanced supply with nonlinear load in inversion mode



(a) (b) (c) (d) (e) (f) (g)

Notes: (a) Three-phase unbalanced supply voltage with nonlinear load (b) Non-sinusoidal source currents Ia, Ib, Ic with conventional SVPWM control algorithm (c) Van and Ia with poor power factor with conventional SVPWM control algorithm (d) Harmonic spectrum of source current (e) Balanced source currents Ia, Ib, Ic with proposed modified SVPWM control algorithm (f) Van and Ia with unity power factor with proposed modified SVPWM control algorithm (g) Harmonic spectrum of source current.

The controller is tested under balanced supply voltages connected with a nonlinear load i.e, three phase universal bridge having RL load, magnitude R_L = 10 ohm and X_L = 20 mH. The three-phase supply peak input voltages in all is 155.6 V as shown in Figure 8(a). At t = 0.05 sec, results after implementation of conventional SVPWM algorithms, display non-sinusoidal source currents having poor unity power factor and high THD = 69.33% as shown in Figure 8(b), Figure 8(c) and Figure 8(d) respectively. But with proposed algorithm, source currents are almost sinusoidal waveforms with unity power factor with low THD = 2.67% as shown in Figure 8(e), Figure 8(f) and Figure 8(g) respectively which is well within the permitted limits as defined by IEEE std. 519.

The controller is tested under balanced supply voltages connected with a nonlinear load, i.e., three phase universal bridge having RL load, magnitude R_L = 10 ohm and X_L = 20 mH. The three-phase supply peak input voltages in phase B and peak input voltages phase C = 155.6 V, but in phase A peak input voltages = 80 V as shown in Figure 9(a). After the implementation of conventional SVPWM algorithms at t = 0.05 sec, results display non-sinusoidal source currents having poor unity power factor and high THD = 20.72% as shown in Figure 9(b), Figure 9(c) and Figure 9(d) respectively. But With proposed algorithm, source currents are almost sinusoidal waveforms with unity power factor with low THD = 4.52% as shown in Figure 9(e), Figure 9(f) and Figure 9(g) respectively which is well within the permitted limits.

4 Conclusions

In this work, a novel controller for DSTATCOM is presented. The results display satisfied working of the DSTATCOM under supply and load perturbation conditions. The proposed algorithm cancels the effect due to supply and load perturbation conditions at the source side of the electrical system. The control algorithm maintains source current magnitude almost balanced and at the same time maintains almost unity power factor. Moreover the proposed controller helps to maintain source currents to be sinusoidal waveforms. Thus the proposed control algorithm addresses both current related power quality problems by way of load compensation with DSTATCOM and voltage related power quality problems (source voltage unbalance) by providing compensation and producing nearly balanced three-phase source current even with unbalanced source voltages. Frequency perturbation is not considered in this proposed algorithm, work related to frequency perturbation can be considered future by modifying the proposed algorithm.

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