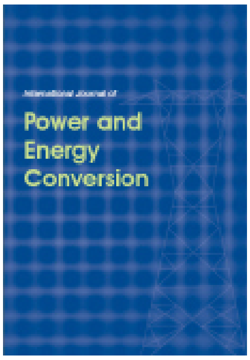

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Power quality enhancement in the presence of impulsive noise through novel control

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Abstract: With the emerging smart grid environment, information flow between generation, transmission and distribution centres increases. The huge information flow sometimes creates noise in the form of voltage signals that affects many working areas of the grid, one of which is power quality. Hence, a need arises for a power quality enhancement algorithm that is robust against the noise. Maximum Versoria criteria (MVC)-based control has found many applications in signal processing due to its advantage to reject impulsive noise. In this work, an attempt has been made to deploy MVC to enhance the quality of power flow at the distribution side by targeting issues like harmonics in the current, unbalance in load, voltage management at the point of common coupling (PCC), and reactive power requirement of the load with its ability to work in the impulsive noise. The performance of the algorithm is examined in MATLAB/Simulink as well as in a real-time environment to validate its performance for industrial applications. The algorithm has shown its advantage of less complexity and enhanced performance due to its ability to robustness against noises.

Keywords: distribution static synchronous compensator; DSTATCOM; harmonics filtering; maximum Versoria criteria; MVC; reactive power compensation.

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This paper is a revised and expanded version of a paper entitled 'Maximum Versoria criteria based adaptive filter algorithm for power quality intensification' presented at 2020 IEEE 9th Power India International Conference (PIICON), Sonepat, India, 28 February–1 March 2020.

1 Introduction

Power electronics-based converters become an inevitable part of the power industry today. Much electrical equipment uses power electronic devices for control applications. The use of power electronic converter-based equipment/products in households and industrial applications makes life easier but has a downside to polluting the electric power supply. Nonlinear loads like converters, electric arc furnaces, computers, variable speed drives, and many more have the effect of injecting harmonics in the electric current. The harmonics in electric current degrade the voltage profile at the point of common coupling (PCC) which leads to affect the performance of sophisticated loads like computers, hospital loads, etc. To ensure a good power supply, the maximum distortion range allowed to be produced by the utility and customer is defined in IEEE Std. (1992) and IEC.

Several solutions have been proposed to mollify the effect of poor power quality problems. The researchers are continuously focusing on power quality problems and mitigations. Singh et al. (2015) has addresses the problems caused by distorted power supply and proposed the mitigation techniques for the same. Ghosh and Ledwich (2009) have discussed the use of custom power devices and their high performance for power quality mitigation. Flexible AC controlled (FACTS) devices are commonly used for poor power quality mitigation (Hingorani and Gyugyi, 2000).

Active power filters (APF) is one of the FACTS devices commonly known to correct the power quality (El-Habrouk et al., 2000). The performance of APF dominantly driven by the control algorithms used for the formation of reference current signal that decides the amount of compensation needed to solve a particular PQ problem. As a result, researchers have tried to improve the performance of the APF by targeting the control algorithms (Arthy and Marimuthu, 2017). Synchronous reference frame (SRF) theory is one of the basic and popular control algorithm used for APF, the algorithm uses *d-q* reference frame to calculate the reactive current and generate a reference signal such that the reactive component of power supplied by APF. The conversion of reference frames requires the information of angle for synchronisation that is achieved by using phase locked loop (PLL), which introduces a delay in the reference current generation process.

The delay time is unwanted so other methods have been proposed, like *P-Q* theory, etc. But these algorithms have issues like not being able to operate during unbalance conditions, not being able to adapt to sudden changes in loads, or non-operative during unbalanced faulty conditions.

With the emergence of adaptive techniques, adaptive control algorithms have been proposed for reference current generation for power quality enhancement. The algorithms overcome the delay introduced by PLL for the calculation of the phase angle by introducing the unit templates, derived from the profile of PCC voltage. The generation of reference current depends on the adaptive theory that has been used as a control algorithm. Along with the adaptive techniques, computationally intelligent methods have also found applications in control algorithms for power quality enhancement. Kumar and Mahajan (2009) have discussed the role of computational intelligent control algorithms for APF in distribution static synchronous compensator (DSTATCOM). Jayachandran and Sachithanandam (2015) have implemented a control algorithm based on the learning rule of the neural network. Many more neural network training-based techniques have been used to control the DSTATCOM (Singh et al., 2005). The limitation of computationally intelligent techniques is the pre-processing training of the neurons. The algorithm works according to the training of the neurons, but the behaviour of the network in case of unbalance, fault, and transient are hard to predict.

One recent adaptive control algorithm, the anti-Hebbian learning rule is presented in the literature which shows the enhanced performance of DSATCOM (Arya et al., 2012). The algorithm uses unit templates for phase angle calculation and is able to work in a reactive power compensation mode of operation. The reference current is calculated by the adaptive equation based on anti-Hebbian rules. Many adaptive theory-based control algorithms have also been developed for DSTATCOM, which is able to capture the changes of load conditions in very less time (Singh and Arya, 2013; Pereira et al., 2011). The limitation of the proposed algorithm is the prediction of constant variables that decides the operating speed and other factors responsible for reference current generation. The algorithm also lacks to predict their behaviour in front of any impulsive noise. The integration of renewable source and distributed generators (DG) also affects the quality of power (Mosobi and Gao, 2021). The converter used for DG integration can be used for PQ enhancement as mentioned in Sharma et al. (2022). The detection of PQ events is a tedious task. The knowledge of PQ events gives an insight of the impact of noise on it. In Dash and Subudhi (2021), a method is proposed for detection of PQ events.

The presence of impulsive noise affects the performance of the smart grid by creating interference in the information flow (Neagu and Hamouda, 2016). Researchers are continuously searching the ways to reduce the effect of impulsive noise in the communication of smart grids. The discussed control algorithms for power quality enhancement require the information flow in the form of low magnitude voltage signal which can be corrupted in the presence of noise.

Versoria-based control finds application in adaptive filtering and is commonly used for echo-cancellation systems with impulsive noise-cancellation features (Huang et al., 2018). Maximising the Versoria function and then using it as a cost function for weight update has many advantages in noise cancellation and improved steady-state behaviour (Huang et al., 2017). Radhika et al. (2020) have done the steady-state mean square analysis of the standard maximum Versoria criteria (MVC), and the results depicts that the algorithm is robust against impulsive noise interference and has reduced complexity.

This paper is an extension of the previous work (Sharma and Rajpurohit, 2020). In Sharma and Rajpurohit (2020), the formulation of MVC for power quality enhancement using DSTATCOM is done. The work was demonstrated in MATLAB/Simulink. In this work, the MVC-based control is used for few more power system conditions like faulty line, sudden load changes, harmonics mitigation of each phase current during unbalance conditions, the performance analysis of the algorithm during dominant nonlinear load as well as when the combination of nonlinear and linear load exists, and many more. Moreover, the algorithm is tested in real-time conditions for application in the industry using OPAL-RT real-time simulator. The performance of the proposed control is tested on various conditions in real-time. A comprehensive analysis of the MVC control algorithm is done with some key features of the algorithm.

The layout of the paper is as follows: in Section 2, a power system distribution side network is designed to supply power to:

1. a nonlinear three-phase load, which is injecting harmonics in the connected power system
2. a combination of nonlinear and linear load
3. an unbalanced load.

The DSTATCOM is modelled to mitigate harmonics, balancing the load, reactive power enhancement, and PCC voltage management during all the cases.

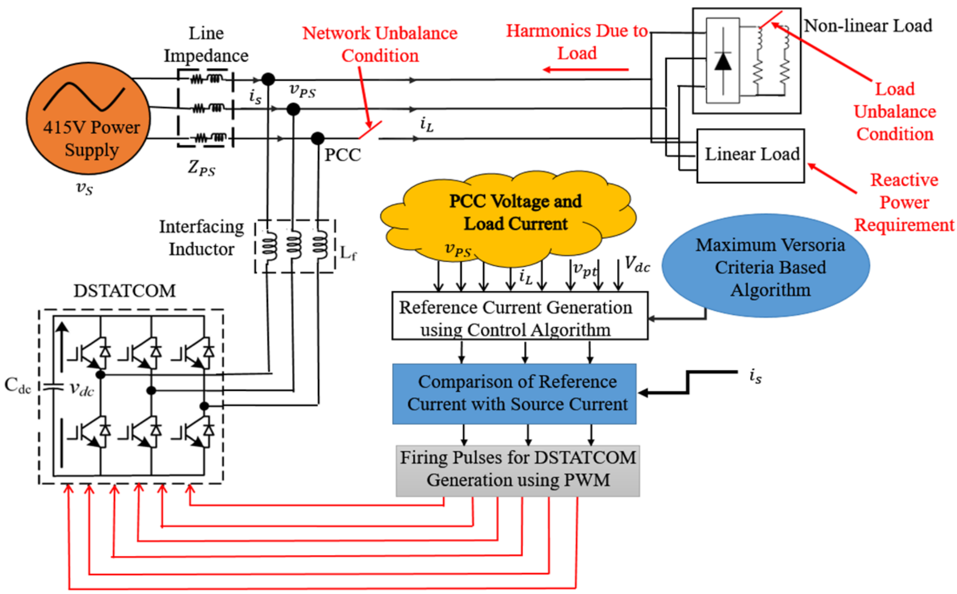
In Section 3, the analysis of the MVC algorithm for impulsive noise elimination is discussed, and the calculation of unit impulse and method for reference current generation for DSTATCOM using MVC is also presented. In Section 4, simulation and real-time performance of the control algorithm are discussed. A comparison of the MVC control with the anti-Hebbian and SRF-based control algorithms is shown to analyse and compare the behaviour of the MVC algorithm with other domain techniques. The results show that the algorithm is able to reduce harmonics, load balancing and reactive power enhancement. The results also show that the performance of the MVC control is better in several features in Section 5. Finally, Section 6 concludes the study.

2 Layout of power distribution network with DSTATCOM

The abundance of power electronic devices at the load gives rise to the injection of harmonics in the current. The polluted current then interacts with the PCC voltage and pollutes the voltage. After that, the harmonics interfere with other devices and start causing problems like overheating and interruption in sophisticated devices. To avoid the problem related to harmonics at the origin itself, DSTATCOM is used in parallel to the load bus at the distribution side of the power system. The power network considered in this work is depicted in Figure 1. Supply voltage is represented by v_s, which shows the 415 V distribution level load bus. The load bus is supplying the source current i_s that is conducted through source impedance Z_{PS}.

The load current i_L is flowing through two types of loads: linear three-phase load (balanced, unbalanced) and three-phase nonlinear load. The balanced reactive load requires only reactive power whereas a nonlinear load imparts integer harmonics in the current, an unbalanced nonlinear load makes the situation even worse by differently changing the magnitude of harmonics in different phases, the network unbalance condition makes the harmonics level in the current even worse. In this work, all of the above conditions are reframed to analyse the behaviour of the control algorithm.

Figure 1 The simplified diagram of power system network for power quality enhancement using DSTATCOM (see online version for colours)



The information of PCC voltage profile v_{PS}, load side currents i_L, and DC link voltage V_{dc}, travels to MVC-based control section, this is the time when the possibility of corruption of the signal due to impulsive noise in the network is high. The sensed signals are then transformed into the reference current signal through the control algorithm. Generated reference signals are then related to actual source current signal and the difference between them forms the pulses of the DSTATCOM through the PWM technique.

The next task of DSTATCOM is to fulfil the reactive power demand of load. Reactive power absorbed by load is calculated by measuring the magnitude of the terminal voltage of PCC and comparing it with a set reference value, the difference is incorporated in the reference current generation. The power loss in the charging and discharging of DC link capacitor is also computed by the subtracting the actual DC link voltage from set reference value, obtained difference is incorporated in reference current generation, which is to be supplied by the DSTATCOM. The DSTATCOM, which is working as another source here, is connected in parallel to the 415 V source. Interfacing inductors L_f is used to connect DSTATCOM to the mains. The inductors are used to filter some higher-level noise from the compensating current injected by the DSATCOM.

3 MVC-based control of DSTATCOM

MVC has got applications in adaptive filtering due to its advantage of being used as a suitable and high-efficiency cost function (El-Habrouk et al., 2000). Literature claims that the Versoria cost function has high performance and gives less steady state error (El-Habrouk et al., 2000). The impulsive noise rejection capability of the algorithm makes it to be used in smart grid scenarios (Dash and Subudhi, 2021). The presence of impulsive noise makes the error function unit impulse as shown in equation (3), which makes the update equation zero. Hence, in the presence of impulsive noise interference, the weight update equation at that instant is the previous value, which means the algorithm has rejected the impulsive noise factor.

In this work, the implementation of the MVC cost function as a control algorithm for the computation of fundamental components of active power and reactive power of load current is done. The weight update equation and the process of reference current generation are discussed here.

3.1 Extraction of reference current from polluted load current

The calculation of reference current mentioned above is basically the extraction of active and reactive power weight components from polluted load current. Figure 2 shows the process flow chart of the MVC-based robust control algorithm for calculating reference current and generating driving pulses for DSTATCOM. MVC control does not use PLL for synchronisation of generated reference current to PCC voltage due to its disadvantage of introducing a time delay in the system. Instead of this, for synchronisation, unit magnitude templates (u_{AP}, u_{BP}, u_{CP}) are calculated from PCC voltage. At first, the terminal voltage v_{pt} is to be calculated from the sensed phase voltages (v_{PSA}, v_{PSB}, v_{PSC}) through the formula mentioned in equation (1). The instantaneous individual phase voltage is divided by the terminal voltage to give only the phase angle of the individual phase as shown in equation (2), these are known as in-phase/same phase unit templates. These templates synchronise the calculated active power weight component of polluted load current to supply current.

$$v_{pt} = \sqrt{\frac{2}{3}\left(v_{PSA}^2 + v_{PSB}^2 + v_{PSC}^2\right)} \tag{1}$$

$$u_{AP} = \frac{v_{PSA}}{v_{pt}},\, u_{BP} = \frac{v_{PSB}}{v_{pt}},\, u_{CP} = \frac{v_{PSC}}{v_{pt}} \tag{2}$$

For the calculation of active power weight component of load current MVC-based weight update equation (Neagu and Hamouda, 2016) is used, which is given as equation (3)

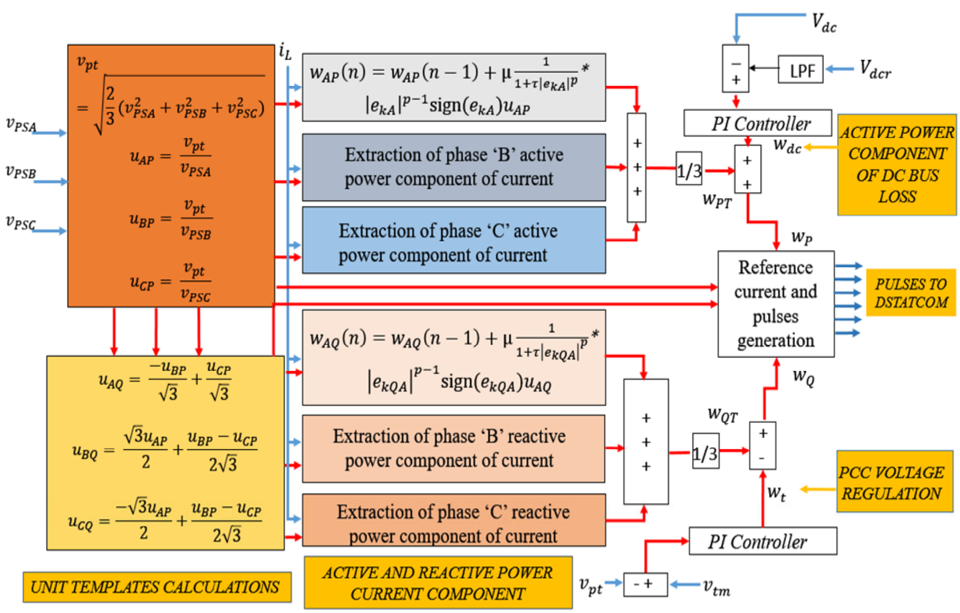
$$w_k = w_{k-1} + \mu \frac{1}{1+\tau\left|e_k\right|^p}\left|e_k\right|^{p-1} sign\left(e_k\right) x_k \tag{3}$$

where x_k is the input vector, e_k is the error between sensed and computed load current, μ is the step size, τ is a constant whose value is given as $\tau = (2a)^{-p}$, where a directly correlates with the steepness of the Versoria, a larger value of a gives steeper Versoria and p is the shape vector.

$$\left.\begin{aligned} w_{AP}(n) &= w_{AP}(n-1)+\mu\frac{1}{1+\tau|e_{kA}|^{p}}*|e_{kA}|^{p-1}\,sign(e_{kA})\,u_{AP} \\ w_{BP}(n) &= w_{BP}(n-1)+\mu\frac{1}{1+\tau|e_{kB}|^{p}}*|e_{kB}|^{p-1}\,sign(e_{kB})\,u_{BP} \\ w_{CP}(n) &= w_{CP}(n-1)+\mu\frac{1}{1+\tau|e_{kC}|^{p}}*|e_{kC}|^{p-1}\,sign(e_{kC})\,u_{CP} \end{aligned}\right\} \tag{4}$$

where $e_{kA} = i_{LA} - w_{AP} * u_{AP}$, $e_{kB} = i_{LB} - w_{BP} * u_{BP}$ and $e_{kC} = i_{LC} - w_{CP} * u_{CP}$.

Figure 2 Flowchart of MVC control algorithm for pulses generation (see online version for colours)



The Versoria term of equation (3) becomes zero in the presence of any impulsive interference or wrong information and reduces the error in case of a large deviation between the actual signal and sensed signal. The use of the weight update equation for the calculation of load current active power weight component (w_{AP}, w_{BP}, w_{CP}) is represented as equation (4)

Total load current active power weight component (w_{PT}) is the average of individual phase's active power as shown in equation (5)

$$w_{PT} = (w_{AP} + w_{BP} + w_{CP})/3 \tag{5}$$

The DC link power loss of the DSTATCOM is calculated by processing the difference between sensed and preset reference value of DC link voltage through a PI controller. The error at the n^{th} sampling instant is given by equation (6).

$$V_{dc}(n) = V_{dcr}(n-1) - V_{dc}(n-1) \tag{6}$$

The PI controller gives the output as an active power weight component which is calculated by processing the error value to proportional gain K_{pd} and integral gain K_{id} of the DC bus PI controller given in equation (7)

$$w_{dc}(n) = w_{dc}(n-1) + K_{pd}\left\{V_{dc}(n) - V_{dc}(n-1)\right\} + K_{id}V_{dc}(n) \tag{7}$$

where w_{dc} is the active power component of the loss of DC bus voltage.

The total reference component of active power weight (w_P) is the sum of the average active power weight component (w_{PT}) and DC link power loss component (w_{dc}) as given in equation (8).

$$w_P = w_{PT} + w_{dc} \tag{8}$$

Load current reactive power weight calculation is done by the computation of in-quadrature/90 degree out of phase unit templates (u_{AQ}, u_{BQ}, u_{CQ}) of PCC voltage [equation (9)] from in-phase unit templates.

$$\begin{aligned} u_{AQ} &= -\frac{u_{BP}}{\sqrt{3}} + \frac{u_{CP}}{\sqrt{3}} \\ u_{BQ} &= \frac{\sqrt{3}u_{AP}}{2} + \frac{(u_{BP} - u_{CP})}{2\sqrt{3}} \\ u_{CQ} &= -\frac{\sqrt{3}u_{AP}}{2} + \frac{(u_{BP} - u_{CP})}{2\sqrt{3}} \end{aligned} \tag{9}$$

After that MVC-based weight update equation as mentioned in equation (3) is applied to calculate the load current reactive power weight components (w_{AQ}, w_{BQ}, w_{CQ}) as given in equation (10)

$$\left.\begin{aligned} w_{AQ}(n) &= w_{AQ}(n-1) + \mu\frac{1}{1+\tau\left|e_{kAQ}\right|^p} * \left|e_{kAQ}\right|^{p-1} sign\left(e_{kAQ}\right)u_{AQ} \\ w_{BQ}(n) &= w_{BQ}(n-1) + \mu\frac{1}{1+\tau\left|e_{kBQ}\right|^p} * \left|e_{kBQ}\right|^{p-1} sign\left(e_{kBQ}\right)u_{BQ} \\ w_{CQ}(n) &= w_{CQ}(n-1) + \mu\frac{1}{1+\tau\left|e_{kCQ}\right|^p} * \left|e_{kCQ}\right|^{p-1} sign\left(e_{kCQ}\right)u_{CQ} \end{aligned}\right\} \tag{10}$$

where $e_{kAQ} = i_{LA} - w_{AQ} * u_{AQ}$, $e_{kBQ} = i_{LB} - w_{BQ} * u_{BQ}$ and $e_{kQC} = i_{LC} - w_{CQ} * u_{CQ}$.

Total load current reactive power weight component (w_{QT}) is the average of individual phase's reactive power as shown in equation (11).

$$w_{QT} = \left(w_{AQ} + w_{BQ} + w_{CQ}\right)/3 \tag{11}$$

PCC voltage magnitude is regulated to avoid the voltage magnitude dip condition due to reactive power consumption of the load. This is done by comparing the sensed voltage (V_{tm}) and reference voltage (V_{pt}) at the nth sampling instants shown in equation (12) and processing the difference through proportional gain K_{qd} and integral gain K_{id} of the PCC voltage PI controller.

$$V_{pt}(n) = V_{tm}(n-1) - V_{pt}(n-1) \tag{12}$$

Requirement of reactive power (w_t) for PCC voltage management is given as equation (13).

$$w_t(n) = w_t(n-1) + K_{qd}\left\{V_{pt}(n) - V_{pt}(n-1)\right\} + K_{iq}V_t(n) \tag{13}$$

The complete reference reactive power weight component (w_Q) is obtained by making DSTATCOM supply reactive power required for maintaining PCC voltage at reference value. Hence, the terminal voltage regulation component (w_t) is subtracted from the average reactive power weight component (w_{QT}) s given in equation (14).

$$w_Q = w_{QT} - w_t. \tag{14}$$

3.2 Calculation of three-phase current and driving pulses for DSTATCOM

Calculated components of active and reactive power is converted to reference current by multiplying it with in-phase and in-quadrature unit templates respectively, as mention in equation (15).

$$\begin{aligned} i_{SAP} &= w_P * u_{AP} \\ i_{SBP} &= w_P * u_{BP} \\ i_{SCP} &= w_P * u_{CP} \\ i_{SAQ} &= w_Q * u_{AQ} \\ i_{SBQ} &= w_Q * u_{BQ} \\ i_{SCQ} &= w_Q * u_{CQ} \end{aligned} \tag{15}$$

The addition of active (i_{SAP}, i_{SBP}, i_{SCP}) and reactive (i_{SAQ}, i_{SBQ}, i_{SCQ}) component of reference current will give the total reference current $(i_{SA}^*, i_{SB}^*, i_{SC}^*)$ as shown in equation (17).

$$\begin{aligned} i_{SA}^* &= i_{SAP} + i_{SAQ} \\ i_{SB}^* &= i_{SBP} + i_{SBQ} \\ i_{SC}^* &= i_{SCP} + i_{SCQ} \end{aligned} \tag{16}$$

The actual grid current (i_{SA}, i_{SB}, i_{SC}) are then compared with the total calculated reference current $(i_{SA}^*, i_{SB}^*, i_{SC}^*)$. The difference is the amount of compensation required from the DSTATCOM, hence is used to generate pulses with PWM technique.

4 Results and discussion

This section is dedicated to the analysis of MVC algorithm for various real time situations of power system network. The tools that are used for analysis are of two categories: MATLAB/Simulink for software-based analysis and OPAL-RT real-time simulator for real time application analysis. The operating conditions of power system network are mentioned in Table 1. The analysis is done in two combinations:

1 the load is the combination of nonlinear and three-phase balanced linear load

2 the load is the combination of nonlinear load and three-phase unbalanced linear load.

The nonlinear loads are injecting harmonics in the supply current and raise the level of total harmonics distortion (THD) more than the standard of IEEE 519. The linear load is the combination of resistive and reactive loads. The cases are considered when the reactive power requirement is high and when it is low. THD calculation and reactive power analyses of the system are done. After that load unbalancing and network unbalancing combinations are considered for the performance analysis of the proposed algorithm.

Table 1 Power system network parameters for simulation and real-time cases

Parameters	*Ratings*
AC line voltage and frequency	415 V and 50 Hz
Source impedance	R_s = 0.1 Ω, L_s = 1.8 mH
Load	*Case 1*
	Linear load: 10 KW, 1–10 KVAR
	Nonlinear load: R_1 = 50 Ω, L_1 = 100 mH
	Case 2
	Linear load: 10 KW, 8 KW, 6 KW
	Nonlinear load: R_1 = 50 Ω, L_1 = 100 mH
DC link voltage	700 V
Interfacing inductance	L_f = 3 mH
Switching frequency	20 kHz

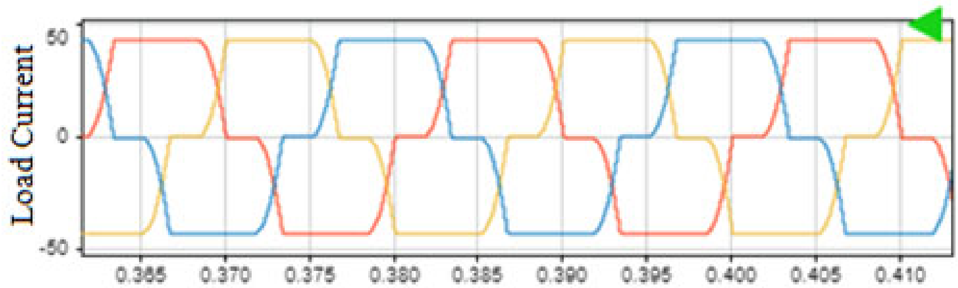
4.1 Case 1: nonlinear load with balanced three phase linear load

In this case, the load consists of nonlinear load and linear balanced three-phase load. Figure 3 presents the profile of three-phase load current, three-phase source current (after compensation), anti-harmonics current injected by DSTATCOM, and DC link voltage. The presence of harmonics in the load current makes it non-sinusoidal in nature. DSTATCOM is injecting majorly those anti-harmonics which are dominant in load current, that is making the supply current sinusoidal again. The DC link voltage is constant which depicts the stable condition of the DSTATCOM. Hence, the algorithm is able to generate the reference current from the polluted load current and provide the necessary compensation to the network by maintaining stable DC link.

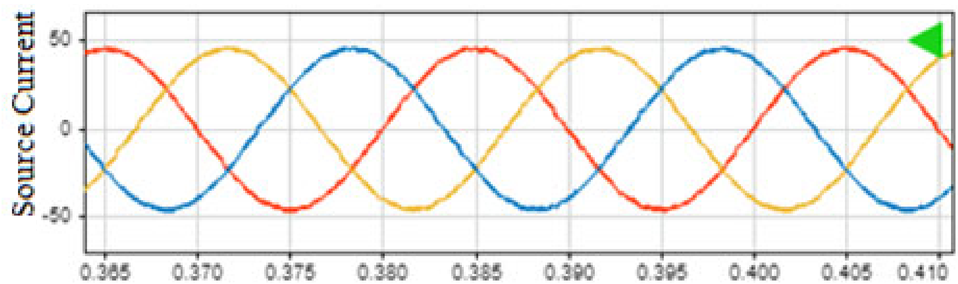
The load current is corrupted by the dominant 5th and 7th order harmonics in the current as shown in Figure 4. The presence of harmonics of the level of 16% (5th harmonics) and 10% (7th harmonics) along with other harmonics makes the waveform of current almost trapezoidal in shape with the THD level 19.57%. The level of THD is far more than the standards of IEEE 519.

The FFT analysis of supply current after providing compensation is shown in Figure 5. The dominant harmonics level is reduced from 16% to 0.4% for the 5th harmonics and 10% to 0.2% for the 7th harmonics. The total THD reduction of current is 1.53% from 19.57%, which is below the 5% level of the IEEE 519 standard. Hence, the algorithm is able to compensate for the harmonics level of the load current and can be used to suppress load harmonics at the PCC.

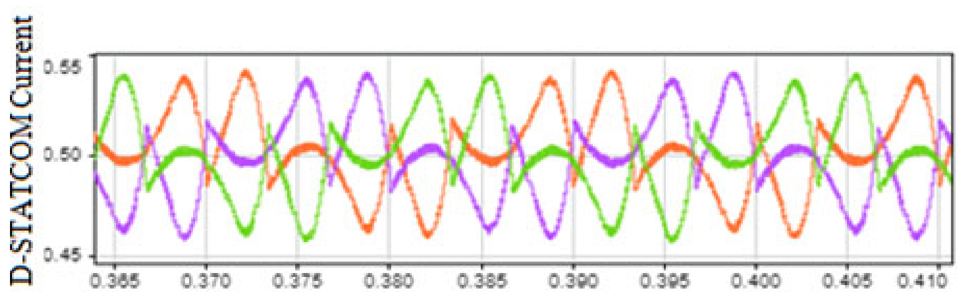
Figure 3 Profile of (a) load current, (b) source current, (c) DSTATCOM current and (d) DC link voltage during Case 1 (see online version for colours)



(a)



(b)



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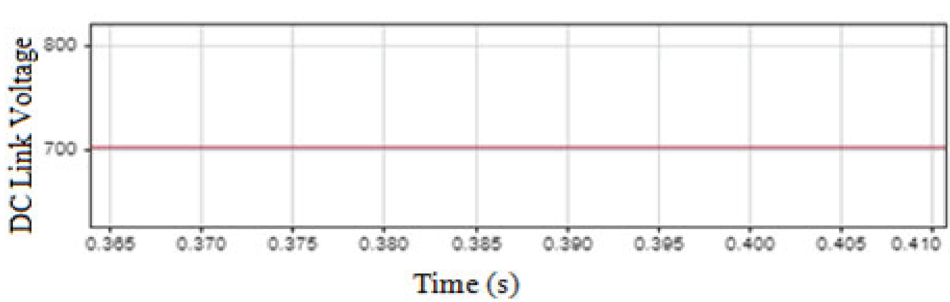


(d)

Figure 4 FFT analysis of load current during Case 1 (see online version for colours)

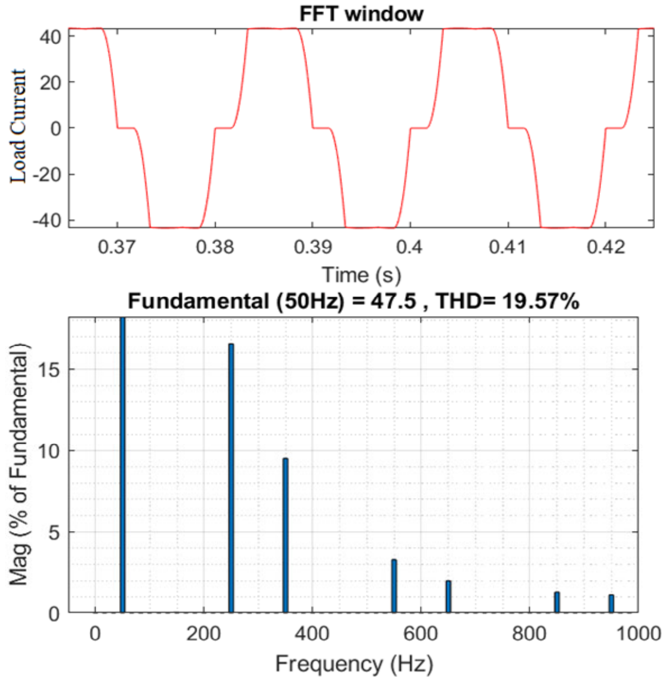


Figure 5 FFT analysis of source current after compensation during Case 1 (see online version for colours)

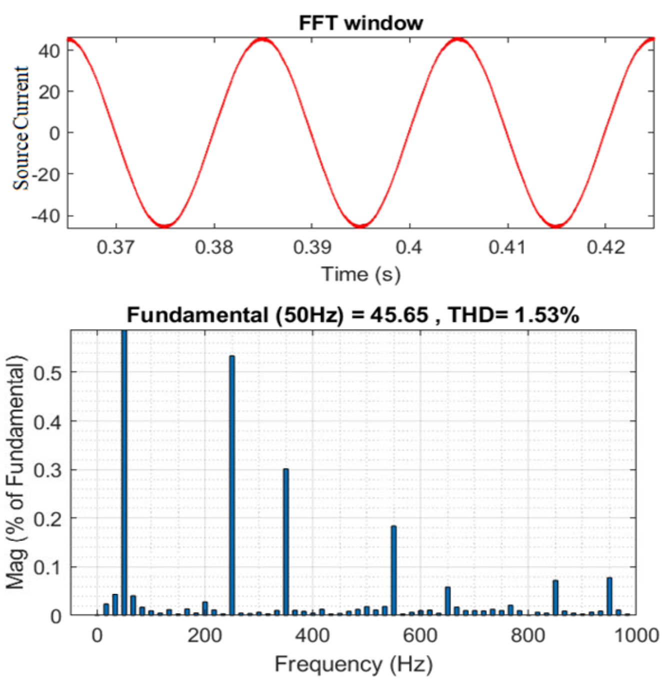
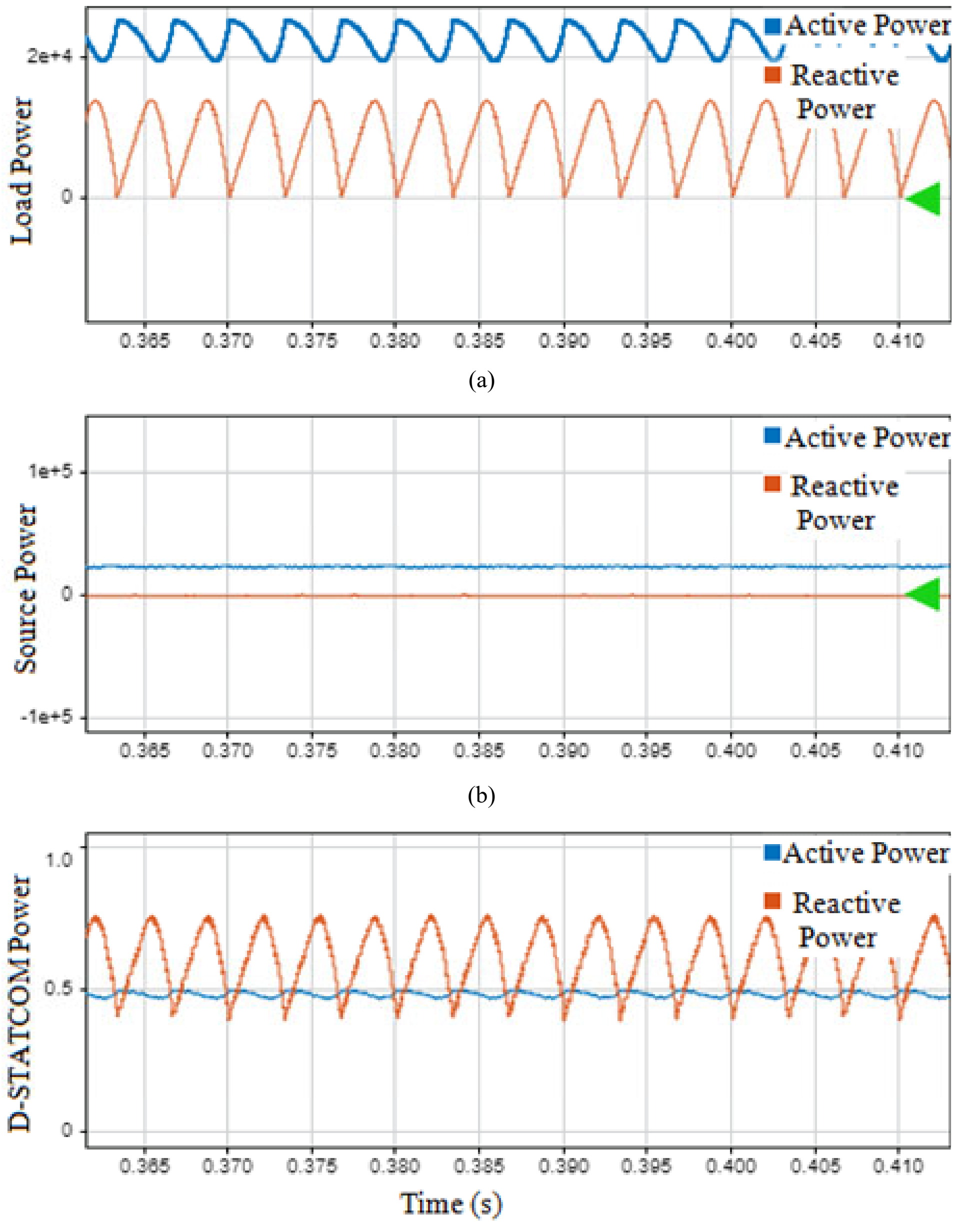


Figure 6 Active power and reactive power of (a) load, (b) source and (c) DSTATCOM during Case 1 (see online version for colours)



(c)

The active power and reactive power calculation of the load, source, and DSTATCOM is shown in Figure 6 for Case 1. The load reactive power demand is fulfilled by the DSTATCOM depending on its capacity. The active power is supplied by the source.

Along with the reactive power demand of the load, the voltage management of PCC is also done.

Figure 7 FFT analysis of load current during high reactive power load of Case 1 (see online version for colours)

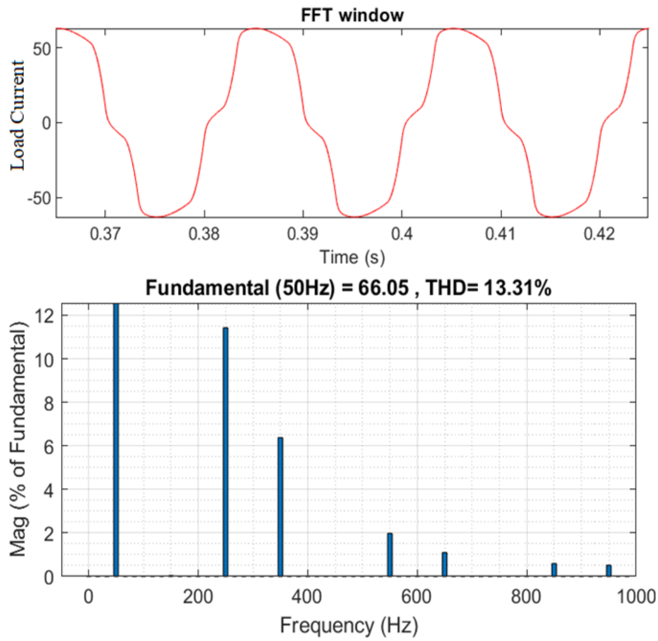
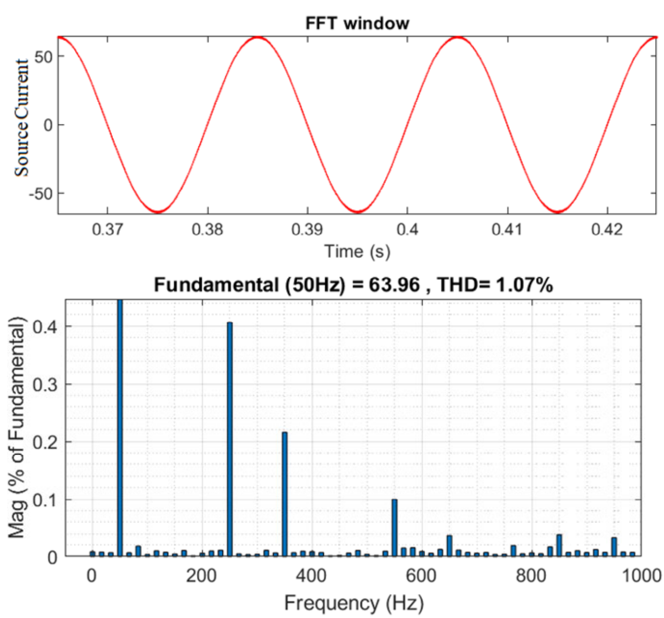
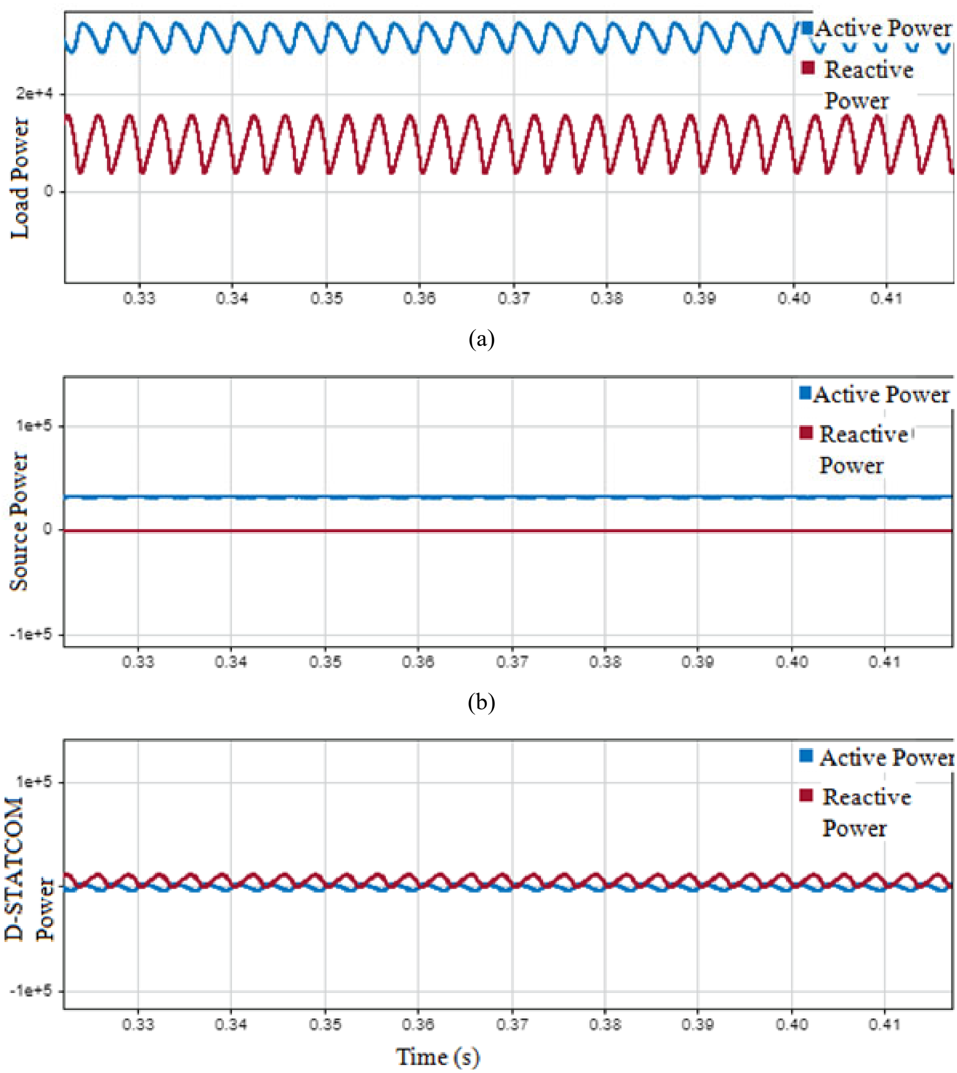


Figure 8 FFT analysis of supply current after compensation (see online version for colours)



In Case 1, one more analysis is done, when the reactive power requirement of the load is higher than the above case. This is the common scenario in the power system when the reactive power requirement of the load is suddenly increased during the season of winter. Figure 7 shows the FFT analysis of the load current during a high reactive power load. The waveform of the current has been changed from the above case and the magnitude of the current has also increased. With the increase in the magnitude of the current, the value of THD has gone down to 13.31% from 19.57% in the above case. The FFT window shows that the dominance of individual harmonics is less than that of the above case.

Figure 9 Active and reactive power of (a) load, (b) source and (c) DSTATCOM during high reactive power load of Case 1 (see online version for colours)



(a)

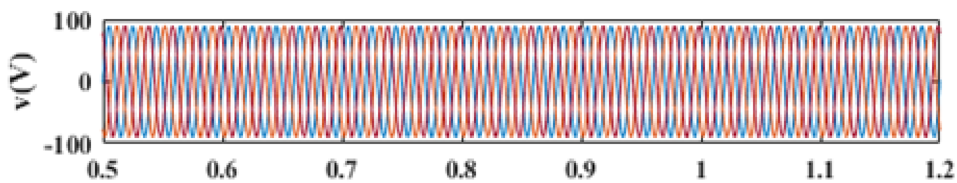
(b)

(c)

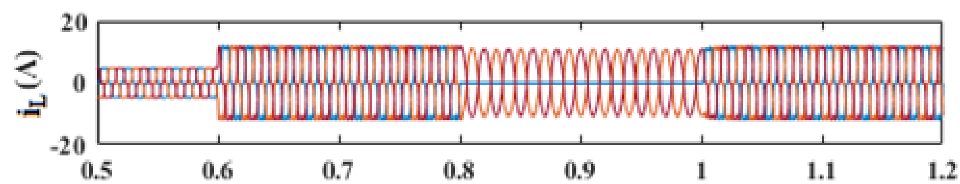
Figure 8 shows the FFT analysis of source current after compensation when a high reactive power load is supplied. The THD of the source current has reached the value of 1.07% which is lesser than the above case when nonlinear load is dominating. This further shows the performance of the algorithm in cases when high reactive power is to be supplied from DSTATCOM.

Figure 9 shows the active and reactive power of load, source, and DSTATCOM when a high reactive power load is supplied by the power system network. The requirement of the reactive power of the load has increased so the supply through DSTATCOM. The source reactive power supply remains low as in the above case.

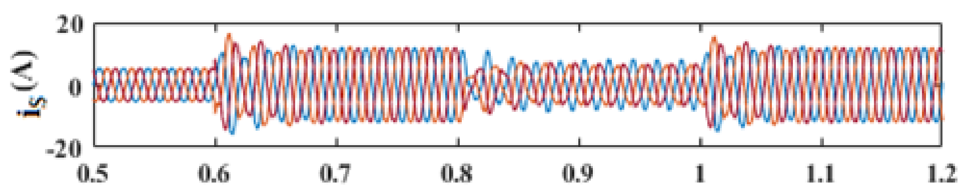
Figure 10 Profile of (a) three-phase PCC voltage, (b) three phase load current, (c) three phase source current after compensation and (d) DC link voltage during Case 2 (see online version for colours)



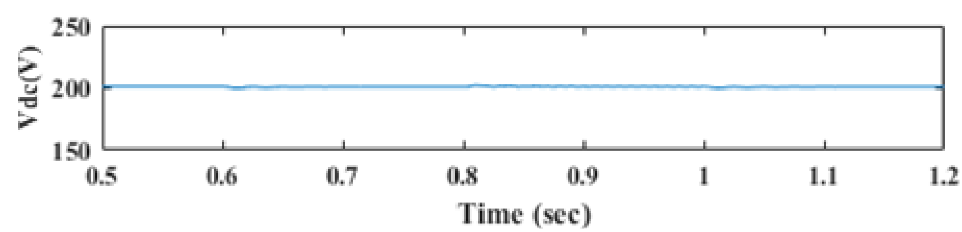
(a)



(b)



(c)

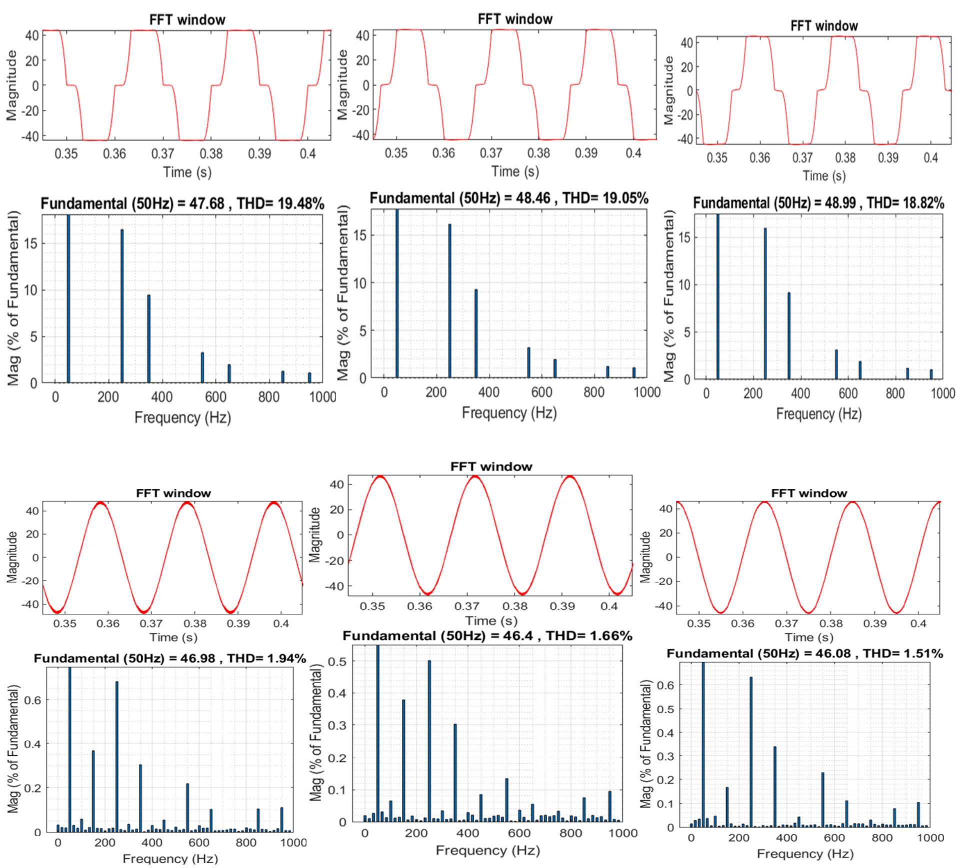


(d)

4.2 Case 2: three-phase nonlinear load with balanced three-phase linear load

In this case, the load is the combination of a three-phase balanced nonlinear load and an unbalanced linear load. The unbalanced load current produces unbalanced harmonics in the load currents, which leads to a non-similar THD level of the load current. Figure 10 shows the unbalanced polluted load current and unbalanced compensated source current. The FFT analysis of the current of individual phases before and after compensation is shown in Figure 11. The THD level of current in Phase ‘a’ is 19.48% which is reduced to the level of 1.94%, the THD level of current in Phase ‘b’ is 19.05% which is reduced to 1.66%, and the THD level of current in Phase ‘c’ is 18.82 which is reduced to 1.51%. The analysis shows that the algorithm can compensate the harmonics when the level of THD is different in different phases.

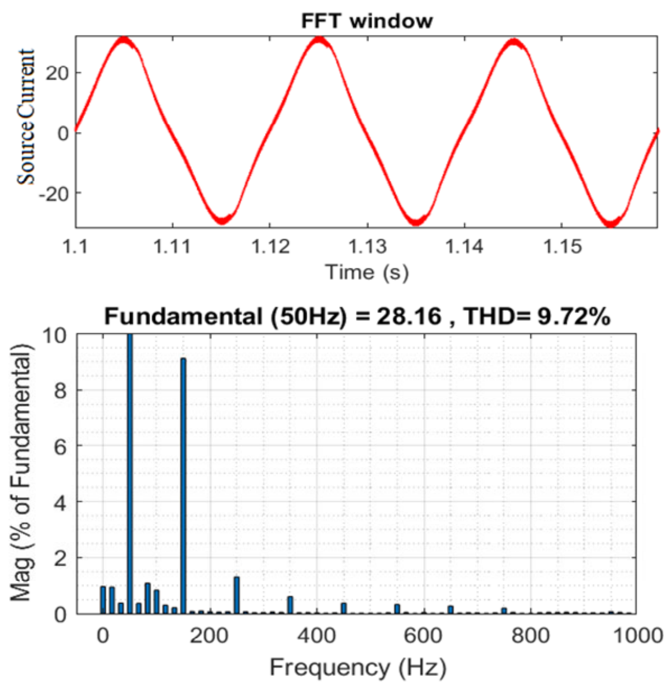
Figure 11 FFT analysis of (a) Phase ‘a’, (b) Phase ‘b’ and (c) Phase ‘c’ of load and source current during Case 2 (see online version for colours)



(a) (b) (c)

The condition of the network unbalanced is also considered. This is a common condition when one of the phases goes down due to any fault in the system. At the time of the fault, the DSTATCOM makes the supply system balance depending on its capacity, but the presence of 3rd harmonics in the system makes the THD level of current far more than the prescribed limits of IEEE 519 standards as shown in the FFT analysis of compensated current in Figure 12.

Figure 12 FFT analysis of supply current during network unbalanced condition (see online version for colours)



4.3 *Real time validation of MVC control for DSTATCOM*

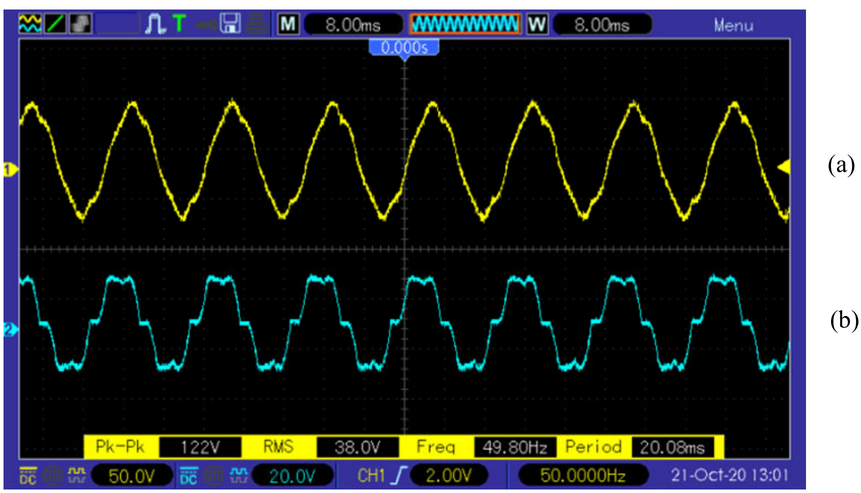
The DSTATCOM with MVC control algorithm is validated for real-time applications using OPAL-RT a real-time simulator. OPAL-RT real-time simulator (OP4510) has an E-3, 4-core, 3.5 GHz processor which gives a resolution of 10 ns and possible minimum time steps of 250 ns for building the model in FPGA. The real-time validation promises a similar kind of behaviour of the control algorithm during the actual implementation. The real-time validation is done on low voltage levels to see the effects of dominant harmonics incorporation in smaller currents. Table 2 shows the low voltage level parameters of the power system network used for real applications.

Figure 13(a) shows the source current after compensation and Figure 13(b) is the load current which is different from the MATLAB/Simulink waveform. The load is a nonlinear load with resistance more than the inductance. The source current was non-sinusoidal before compensation but it become sinusoidal after compensation. The performance of the control algorithm is tested for sudden load change and load unbalancing in real time environment to claim the accuracy of the control algorithm. Figure 14 shows the operation of sudden load change. Due to a sudden decrease in current, the load current suddenly increases which in turn increases the source current. This operation is very common in power system network operation, hence the DSATCOM must have the capability to ensure proper operation in sudden load injection. The stability of the DSTATCOM should be maintained during this operation of the power system network.

Table 2 Power system network parameters

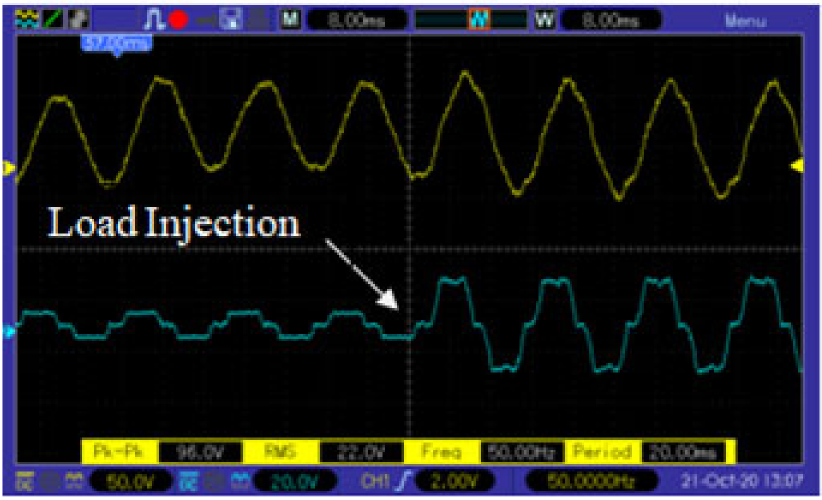
Parameters	*Ratings*
AC line voltage and frequency	110 V and 50 Hz
Source impedance	$R_s = 0.05\ \Omega$, $L_s = 1.1$ mH
Load	$R_1 = 30\ \Omega$, $L_1 = 200$ mH
	$R_2 = 30\ \Omega$, $L_2 = 200$ mH
DC link voltage	200 V
Interfacing inductance	$L_f = 3$ mH
Switching frequency	20 kHz

Figure 13 (a) Source current after compensation (b) Load current (see online version for colours)



The stability of the DSTATCOM during load injection can be inspected by observing the graph of the DC capacitor voltage during load injection. Figure 15 shows the behaviour/fluctuation in DC capacitor voltage at sudden load injection. This can be observed from Figure 15 that a very minute disturbance in the DC link voltage is seen at the time of load injection. Hence, the control algorithm maintains stability during load injection. The load balancing ability of the algorithm is verified in real-time as shown in Figure 15 and Figure 16. At the time when phase 'a' of load current becomes faulted at that time the source current is balanced by DSTATCOM depending on its capacity. The deviation is seen at the DC link voltage of DSTATCOM at the time of load balancing. After some time, the control algorithm can restore the DC link voltage level. FFT analysis of load current and source current after compensation is shown in Figure 17 source current before compensation has many harmonics but DSTATCOM is able to compensate for the harmonics. The FFT window shows that the load current carries many harmonics comparable to the fundamental component. After compensation, the fundamental component is present in the FFT window.

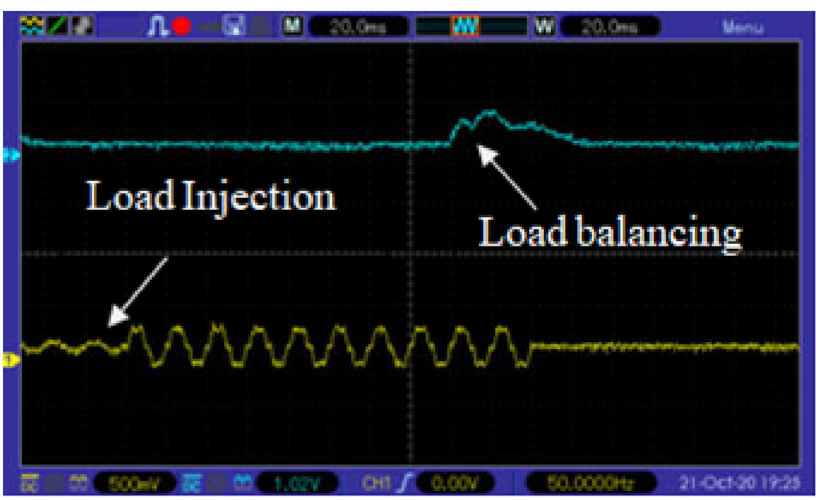
Figure 14 Performance of (a) source current and (b) load current at sudden decrease in load during real time (see online version for colours)



(a)

(b)

Figure 15 Performance of (a) DC link capacitor voltage and (b) load current during sudden decrease in load and fault at the system (see online version for colours)



(a)

(b)

Figure 16 Load balancing operation of (a) source current and (b) load current in real time (see online version for colours)

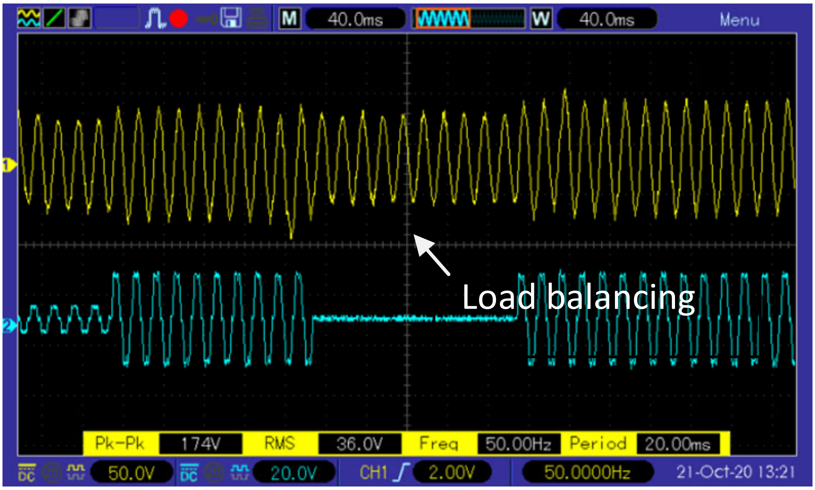
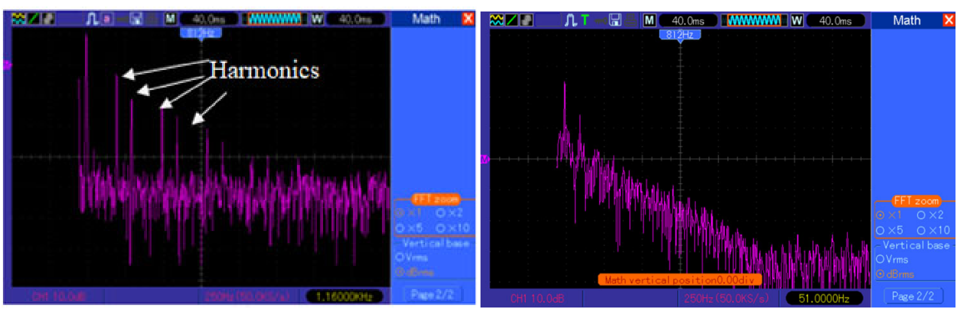


Figure 17 FFT analysis of (a) load current and (b) after source current after compensation in real time (see online version for colours)



(a) (b)

5 Performance comparison of MVC control algorithm with adaptive anti-Hebbian and SRF control algorithm

The MVC control algorithm is compared with anti-Hebbian and SRF theory-based control. SRF theory is a basic robust theory used for control algorithms whereas anti-Hebbian is the latest theory which involves weight updation techniques for fundamental reference current generation. Comparison of MVC with SRF will discuss the robustness of the algorithm whereas comparison with anti-Hebbian will tell about the accuracy of MVC control algorithm.

FFT analysis shows that the harmonics level in load current is 19.57% as shown in Section 4. The MVC-based control algorithm can mitigate the harmonics of load current and the THD of current reaches the value of 1.53%, the SRF theory has also mitigated the harmonics and the THD value reaches 4.05%, and the THD value of current after compensation is 3.86% while using anti-Hebbian control algorithm

The other parameter used for comparison is the complexity of the modelling of the control algorithm. SRF has a PLL which introduces time and frequency evaluation, hence it is complex to model, anti-Hebbian-based control algorithm has variables whose selection is a tedious task, whereas the MVC control algorithm has very few mathematical operations and is easy to model. The next parameter is the sampling time to build in hardware, MVC control algorithm builds in 45 µs whereas SRF and anti-Hebbian build in 60 µs. hence MVC control algorithm has high speed as compared to the other two algorithms. Weight convergence time will decide the reaction of the algorithm to any change in system operating conditions. As can be seen from Figure 14, the MVC algorithm reacts very fast during load change and load balancing, whereas the anti-Hebbian algorithm has many variables, so it requires much time to get stable and the weight value oscillates. Hence, the weight converging of the MVC algorithm is faster than anti-Hebbian. The comparative performance is shown in Table 3.

Table 3 Performance analysis of MVC-based control

Features	*MVC*	*Anti-Hebbian*	*SRF*
Modelling burden	Few mathematical operations	Variable selection is difficult	PLL required (complex)
Sampling time (µs)	45	60	-
Total harmonic distortions (THD) of load current	1.53%	3.86%	4.05%
Weight convergence	Fast	Oscillations	Not applicable

6 Conclusions

DSTATCOM rely on the accuracy of control algorithm for the generation of reference current. In the proposed work, MVC-based control drives DSTATCOM due to its ability to operate effectively in the presence of impulsive noise. Performance analysis of the DSTATCOM shows that the MVC algorithm can mitigate harmonics and achieve a THD as low as 1.53%. The algorithm targets dominant 5th and 7th harmonics of the load current and suppresses them to less than 1%. MVC algorithm can do load balancing, during heavy current applications 50 A (peak to peak). The algorithm gives the ability to achieve stability during one phase fault of the system, which makes it more prominent to operate under faulty conditions. The MVC algorithm helps to maintain load voltage at 415 V and also achieves power factor correction. The algorithm is easy to implement in real-time and the response in real-time shows high performance. The algorithm has been validated for many real-time operating conditions of power systems like load balancing, sudden load change, voltage management, etc. The algorithm has maintained the stability of the power system in all abovementioned cases in real-time and Simulink environment also. MVC algorithm has shown its robustness in maintaining stable operation which makes it ready for industrial applications.

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