A Novel Control algorithm based DSTATCOM for Load Compensation

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Abstract. Distribution Static Compensator (DSTATCOM) has been used as a custom power device for voltage regulation and load compensation in the distribution system. Controlling the switching angle has been the biggest challenge in DSTATCOM. Till date, Proportional Integral (PI) controller is widely used in practice for load compensation due to its simplicity and ability. However, PI Controller fails to perform satisfactorily under parameters variations, nonlinearities, etc. making it very challenging to arrive at best/optimal tuning values for different operating conditions. Fuzzy logic and neural network based controllers require extensive training and perform better under limited perturbations. Model predictive control (MPC) is a powerful control strategy, used in the petrochemical industry and its application has been spread to different fields. MPC can handle various constraints, incorporate system nonlinearities and utilizes the multivariate/univariate model information to provide an optimal control strategy. Though it finds its application extensively in chemical engineering, its utility in power systems is limited due to the high computational effort which is incompatible with the high sampling frequency in these systems. In this paper, we propose a DSTATCOM based on Finite Control Set Model Predictive Control (FCS-MPC) with Instantaneous Symmetrical Component Theory (ISCT) based reference current extraction is proposed for load compensation and Unity Power Factor (UPF) action in current control mode. The proposed controller performance is evaluated for a 3 phase, 3 wire, 415 V, 50 Hz distribution system in MATLAB Simulink which demonstrates its applicability in real life situations.

1. Introduction

Nonlinear loads are increasing day by day with more and more use of power electronics equipments. Due to this, power quality is a major issue arisen in the power distribution system. Custom Power Devices (CPD) have been effectively used to mitigate the power quality issues such as voltage sags, swells, surges, poor power factor, unbalanced load currents and neutral current unbalance. In this regard, DSTATCOM is the most preferred option for load compensation. Load compensation involves management of reactive power for voltage regulation, power factor correction and load balancing.

Controlling the switching angle has been the biggest challenge in DSTATCOM. There are many control techniques adopted for DSTATCOM such as PI Controller and its variants [2], Fuzzy logic based Controller [3], Neural Network [4], Model free predictive Controller [5], Particle Swarm Optimization based control techniques [6] and a combination of these techniques [7,8] etc. Till date, PI controller is widely used in practice for load compensation due to its simplicity and ability. But since PI controller uses trial and error based tuning and Ziegler Nichols based tuning and is well suited for systems with large delays and large time constants, it is difficult to achieve efficient load compensation.

PI Controller also fails to perform satisfactorily under parameters variations, nonlinearities, etc. making it very challenging to arrive at best/optimal tuning values for different operating conditions [9]. Heuristic Fuzzy logic controllers rely on the expert knowledge database with its performance depending on the configuration used [10]. Neural network based techniques are good for tolerating only small perturbations; however they require extensive training (in case of supervised learning) and have been shown to perform poor when the range of the inputs deviate from those used in training conditions [11]. The hysteresis controller has several drawbacks such as variable switching frequency, tendency towards limit cycles, and generation of sub-harmonics etc. [12]. G. W. Moon [13] have introduced predictive current control of DSTATCOM, that uses the system model to predict the output voltages and current based on space vector PWM and uses coordinate transformation. But it does not incorporate any optimality framework.

Model predictive control is a powerful control strategy, used in the petrochemical industry and its application has been spread to different fields, especially hybrid systems [17, 18]. The main advantage of MPC over linear classical controllers is that it can handle various constraints, incorporate system nonlinearities and can be applied to Multiple Input Multiple Output (MIMO) systems [20]. MPC as such cannot be used in power systems, power electronics and drives applications since there is a huge amount of computational effort in order to solve the optimization problem online, which is incompatible with the small sampling times used in the converter control.

However, due to advent of fast processors like DSPs and FPGA, the problem of computational effort can be resolved and power electronics industry can look upon MPC as a good candidate. This work proposes a novel control algorithm, namely FCS-MPC for DSTATCOM application with appropriate modification in the algorithm. It incorporates the model information and has optimization criteria, which can help in optimization of the switching pulses, thus achieving an effective and excellent control of DSTATCOM. Easy implementation, control objective definition flexibility and superior transient performance are the key features of this method [14]. Even though variable switching frequency is considered as one of the drawbacks of this method, the average switching frequency is between 1/5th and 1/4th of the sampling frequency [14]. In this work, no co-ordinate transformation has been used unlike the conventional FCS-MPC used in the literature so far.

The paper is organised as follows. In Section 2, DSTATCOM Control strategy is described, followed by the formulation of the proposed control technique, namely, FCS-MPC for the compensator in Section 3. In Section 4, the simulation results and discussion on the performance of the DSTATCOM are presented. Here, the proposed current control technique is validated in SIMULINK. In Section 5, conclusions are presented.

2. DSTATCOM control strategy

DSTATCOM is operated in current control mode. The control system of DSTATCOM has to generate reference currents that compensate the harmonic, unbalanced and fundamental reactive components of non-linear and unbalanced load supply currents. The aim of current controller is to make the phase currents exactly follow the desired current reference with a minimum ripple current and phase delay. There are various reference current extraction methods available in the literature [16], in which Instantaneous Symmetrical Component theory (ISCT) based method is one of the most effective method compared to other methods.

2.1 Instantaneous Symmetrical Component Theory

ISCT based method is based on the theory of symmetrical components. This is mainly adopted due to the simplicity in formulation and the clarity in the definition of powers unlike the instantaneous p-q theory.

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The main features of this algorithm are:

- It ensures that the source supplies only the load active power and the losses in the inverter.
- Source power factor can be set to any desired value.
- It can practically compensate any kind of unbalance and harmonics in the load, provided we have a high bandwidth current source to track the DSTATCOM current.

Here, the compensation reference current, i_f [15] is

$$i_{fa}^{*} = i_{La} - i_{sa}^{*} = i_{La} - \frac{v_{sa} + \beta(v_{sb} - v_{sc})}{\Delta s}(p_{lav} + p_{loss}) \tag{1}$$

$$i_{fb}^{*} = i_{Lb} - i_{sb}^{*} = i_{Lb} - \frac{v_{sb} + \beta(v_{sc} - v_{sa})}{\Delta s}(p_{lav} + p_{loss}) \tag{2}$$

$$i_{fc}^{*} = i_{Lc} - i_{sc}^{*} = i_{Lc} - \frac{v_{sc} + \beta(v_{sa} - v_{sb})}{\Delta s}(p_{lav} + p_{loss}) \tag{3}$$

where $\Delta s = v_{sa}^2 + v_{sb}^2 + v_{sc}^2$, $\beta = \frac{\tan\phi}{\sqrt{3}}$, p_{lav} is the average load power and p_{loss} is the losses in the inverter . Here, ϕ is the desired power factor angle.

It can be seen from the above equations that, for unity power factor action, $\beta = 0$. For voltage regulation, β is nonzero and source supplies or absorbs the reactive power corresponding to the β value. p_{lav} is calculated from the load power using the moving average filter. Here, p_{loss} is estimated by the PI Controller from the error difference between the actual DC bus voltage and the reference DC link voltage. The PI Controller loop maintains the dc link voltage value at reference value by drawing necessary active power from the ac source. For simulation, the positive sequence components of the PCC Voltage are extracted so that the algorithm is valid even for distorted and unbalanced voltage sources.

2.2 Finite Control Set MPC

Recently, Rodriguez et al. [14] came up with a novel method termed as FCS-MPC for power electronic drives application. The FCS-MPC control strategy is based on the fact that only a finite number of possible switching states can be generated by a static power converter and that models of the system can be used to predict the behavior of the variables for each switching state. This leads to drastic simplification of the optimization problem in MPC.

For the selection of the appropriate switching state to be applied, a selection criterion must be defined. This criterion consists of a cost function that will be evaluated for the predicted values of the variables to be controlled. Prediction of the future value of these variables is calculated for each possible switching state and then the state that minimizes the cost function is selected.

The procedure of switching state selection has been shown in Figure 1. Here, x(k) are the controlled variables. Based on the discrete model of system, the current values of the controlled variables, x(k) are used to predict their future values x(k+1) for all N possible switching states. The predicted values of all the controlled variables x(k + 1) are compared with their reference values x_{ref} (k + 1) in the cost function minimization block. Finally, the switching state (S) that minimizes the cost function will be selected as the next switching state and it will be applied to the converter. t = k is presenting the current state (now), t = k + 1 and t = k + 2 are the next time steps. The sampling time is T_s.

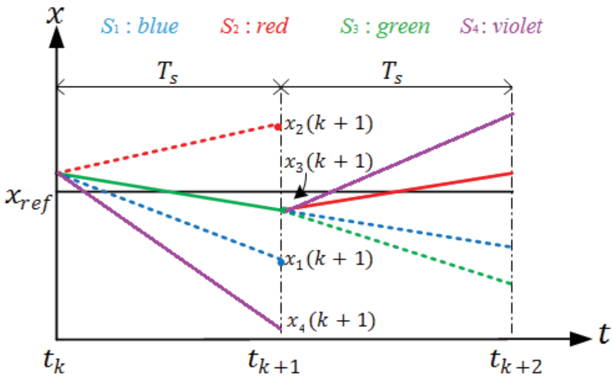

Figure 1. FCS-MPC Operating Principle

Assume that the FCS-MPC is applied to a converter with four possible switching states (S_1, S_2, S_3 and S_4) and the reference is constant in a short period of time. The distance between the controlled variable and its reference value is taken as the cost function that should be minimized in order to track the reference. The controlled variable at the next step time is predicted for all the switching states. However, choosing S_3 provides the least distance to the reference value x_{ref}; as a result, it will be applied to the converter at time t_{k+1}. Subsequently, all the process will be shifted one step forward. By repeating the procedure once again for t_{k+2}, S_2 will be selected due to its minimum distance with x_{ref}. Thus, the whole procedure will be repeated again.

3. FCS-MPC Based Proposed Methodology

In this paper, Finite Control Set MPC is applied to DSTATCOM as a current controller. This is a servo tracking problem from control point of view, where the actual DSTATCOM current should follow the reference compensation current. Figure 2 shows the basic block diagram for the predictive current control applied to the DSTATCOM.

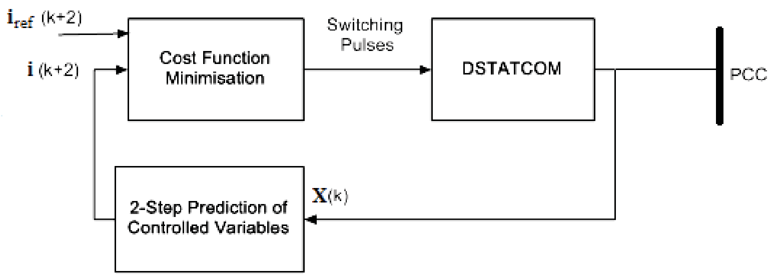

Figure 2. Block diagram for FCS-MPC based DSTATCOM

By striking a trade-off between accuracy and the computational efforts for the algorithm, 2 step ahead predictions has been considered.

The current control is performed in the following steps:

- The reference current $\mathbf{i}_{ref}$ (k) is obtained using ISCT based theory and the DSTATCOM current and other variables **X** (k) are measured or sensed.
- By two-step prediction of the system model, value of **i** (k +2) is predicted for each of the voltage vectors.

- The cost function is evaluated for each voltage vector and the one that minimizes the current error is selected and its corresponding switching state signals are applied to the Insulated Gate Bipolar Transistor (IGBT) Switches.

In short, the actual compensation DSTATCOM current is made to track the reference current (generated by ISCT based algorithm) using FCS-MPC as the current controller.

3.1. *DSTATCOM System Modeling for Prediction*

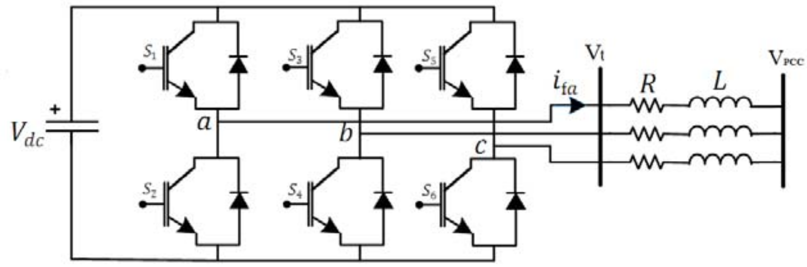

Figure 3. DSTATCOM Power Circuit

Here, we have considered a 3-phase 2-level voltage source inverter configuration with DC Link Capacitor as shown in Figure 3. R and L represent the internal losses and the coupling transformer inductance, respectively. i_{fa} is the DSTATCOM injected current in phase A. IGBT Switches with antiparallel diodes have been selected as the power switches. There shall be 8 switching states out of which two states are not possible:

- Both the switches of each legs of the inverter are simultaneously ON as it leads to short-circuiting of DC link capacitor
- Both the switches of each legs of the inverter are simultaneously OFF as it leads to turning off of the inverter, consequently no power is transferred.

Thus, avoiding the above two switching states and referring to the Figure 3, switching signals can be defined as follows :

$$S_a = \begin{cases} 1 & \text{if } S_1 \text{ on and } S_4 \text{ off} \\ 0 & \text{if } S_1 \text{ off and } S_4 \text{ on} \end{cases} \tag{5}$$

$$S_b = \begin{cases} 1 & \text{if } S_2 \text{ on and } S_5 \text{ off} \\ 0 & \text{if } S_2 \text{ off and } S_5 \text{ on} \end{cases} \tag{6}$$

$$S_c = \begin{cases} 1 & \text{if } S_3 \text{ on and } S_6 \text{ off} \\ 0 & \text{if } S_3 \text{ off and } S_6 \text{ on} \end{cases} \tag{7}$$

The relation between the DSTATCOM output terminal voltage and the DC Link voltage V_{dc} can then be written as

$$\begin{bmatrix} v_{fa} \\ v_{fb} \\ v_{fc} \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 2S_a & -S_b & -S_c \\ -S_a & 2S_b & -S_c \\ -S_a & -S_b & 2S_c \end{bmatrix} \left[V_{dc} \right] \tag{8}$$

Using vector space analysis, the mathematical equation for the DSTATCOM power circuit can be written as

$$v_t = L\frac{di_f}{dt} + Ri_f + v_{pcc} \tag{9}$$

where v_t, i_f and v_{pcc} are the DSTATCOM terminal voltage, DSTATCOM current and point of common coupling voltage vectors, respectively.

The DSTATCOM current derivative can be discretised as follows using Eulers forward approximation method:

$$\frac{d\boldsymbol{i}_f}{dt} \approx \frac{\boldsymbol{i}_f(k+1) - \boldsymbol{i}_f(k)}{T_s} \tag{10}$$

which is substituted in the equation (9) to get the predicted output DSTATCOM current for each of the seven voltage vector values. Here, Ts is the sampling time. This expression is given by

$$i_f(k+1) = \left(1 - \frac{RT_s}{L}\right) i_f(k) + \frac{T_s}{L}(v_t(k) - v_{pcc}(k)) \tag{11}$$

Now, the expression for 2-step ahead predicted DSTATCOM output current can be written as follows:

$$i_f(k+2) = \left(1 - \frac{RT_s}{L}\right) i_f(k+1) + \frac{T_s}{L}(v_t(k+1) - v_{pcc}(k+1)) \tag{12}$$

3.2. Cost Function

Here, we need to track instantaneously the DSTATCOM reference current and the error between the reference and the measured values of the same should be reduced. The cost function for the algorithm is chosen as

$$G = \| i_{ref}(k+2) - i_{pred}(k+2) \| \tag{13}$$

Figure 4 shows the flow chart for the FCS-MPC based algorithm for DSTATCOM.

Table 1. System Parameters.

Parameters		3 Phase system (50μs)
Source		415V, 50Hz
Source Impedance		1Ω , 0.01H
Loads:		
1. RL Loads	(A)	(30 + j 22) Ω
	(B)	(120 + j125.6) Ω
	(C)	(60Ω + j31.4) Ω
2. Full Bridge rectifier with RL Load		150Ω , 300mH
RC Filter		5Ω , 10μF
DSTATCOM leakage filter RL		0.0476Ω , 0.6mH
DC Capacitor		500μF
V_{dcref}		750V

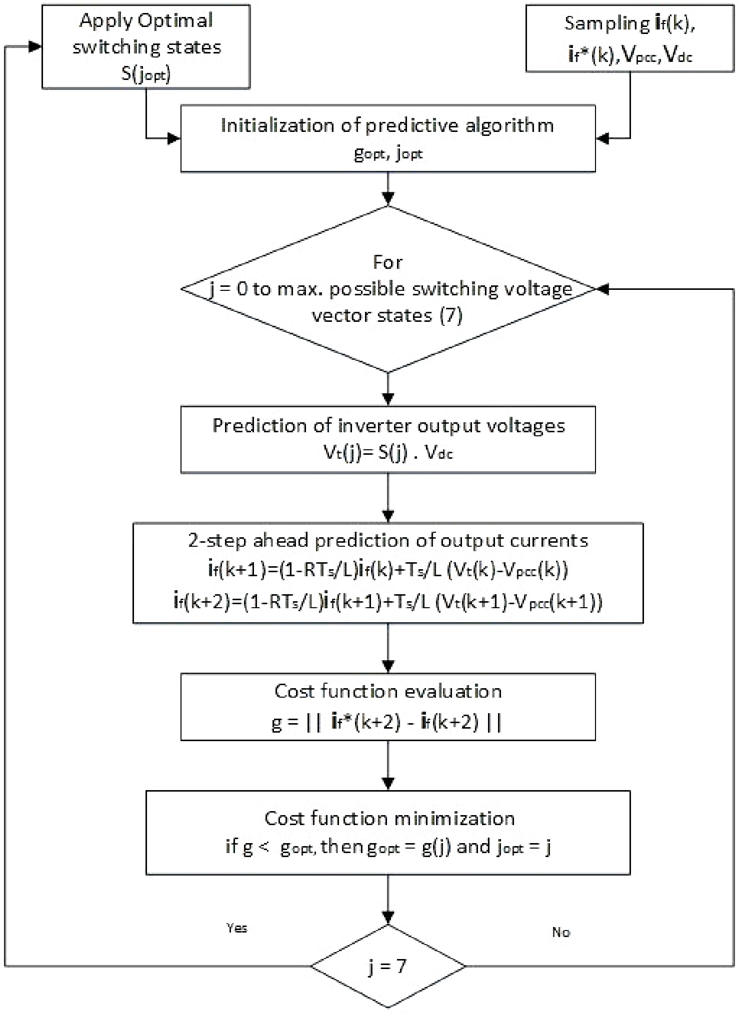

Figure 4. Flow chart for FCS-MPC based algorithm for DSTATCOM

4. Simulation Results

To verify the performance of the DSTATCOM, power distribution system compensated by DSTATCOM has been modeled in the SIMULINK using SimPowerSystem Block as shown in Figure 5. A 3-phase 3-wire 415V distribution system is taken as the initial test case with the parameters as shown in Table 1. A set of simulations were carried out for a base case without DSTATCOM but with RC Filter connected to the distribution network. RC Filter is used to reduce the higher order harmonics and the switching ripples in the PCC Voltage due to fast switching action of DSTATCOM.

The load is both unbalanced and nonlinear throughout the simulation. From 0.4 to 0.5 s, linear load of phase B at Node C is disconnected using a circuit breaker. From 0.4 to 0.6 s, linear load of phase A at Node C is disconnected using a circuit breaker.

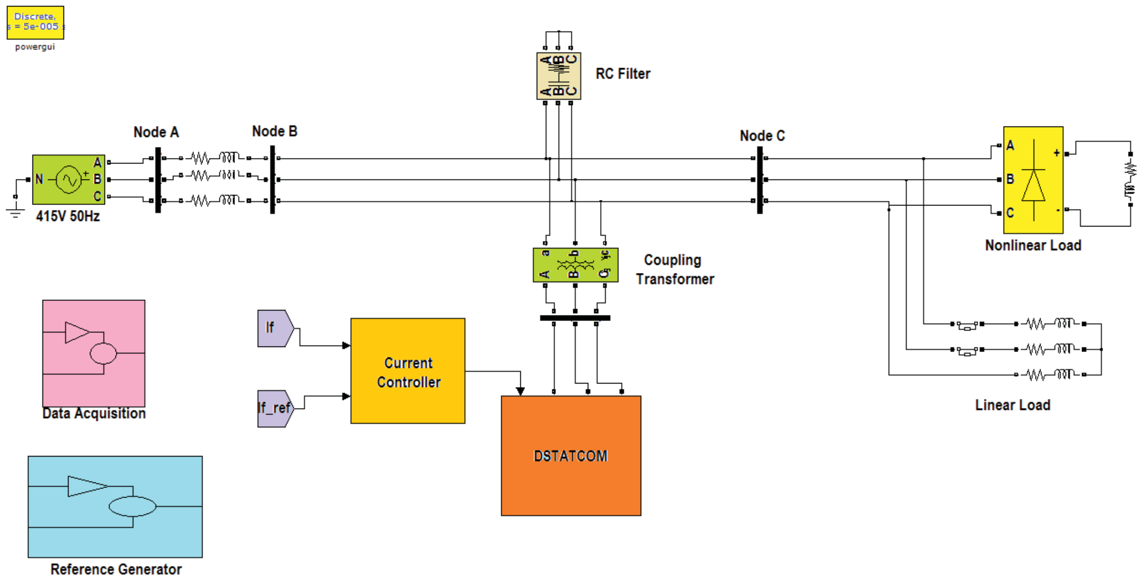

Figure 5. SIMULINK Model of the Test system.

Figure 6 shows that the PCC Voltage (V_{PCC}) is having harmonics due to nonlinear loads and the source current (i_S) is unbalanced due to the load current (i_L) characteristics for the base case scenario without DSTATCOM.

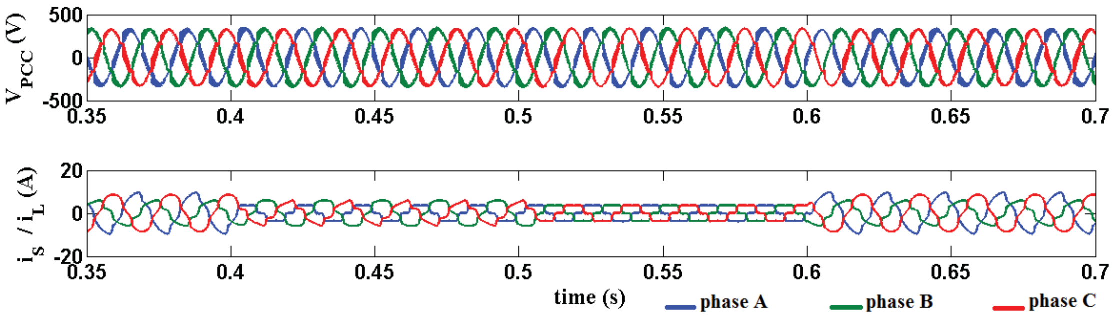

Figure 6. PCC voltage and load/source current before compensation.

A DSTATCOM was connected to the distribution system with the proposed control algorithm. K_p and K_i values for the DC voltage controller were obtained using Oscillation test based Ziegler Nichols tuning method. The simulation result showing the dynamic performance of DSTATCOM is shown in Figure 7. It was observed that the DSTATCOM was able to inject compensation current (i_D) in such a way that the source current becomes balanced and sinusoidal. Also, the PCC Voltage is almost maintained at the reference peak voltage value of 338V. Harmonics in PCC voltage has been considerably reduced. The DC link capacitor voltage (V_{dc}) of the DSTATCOM is maintained at the reference value of 750 V at the steady state following the disturbance period. Figure 8. shows the unity power factor action of DSTATCOM.

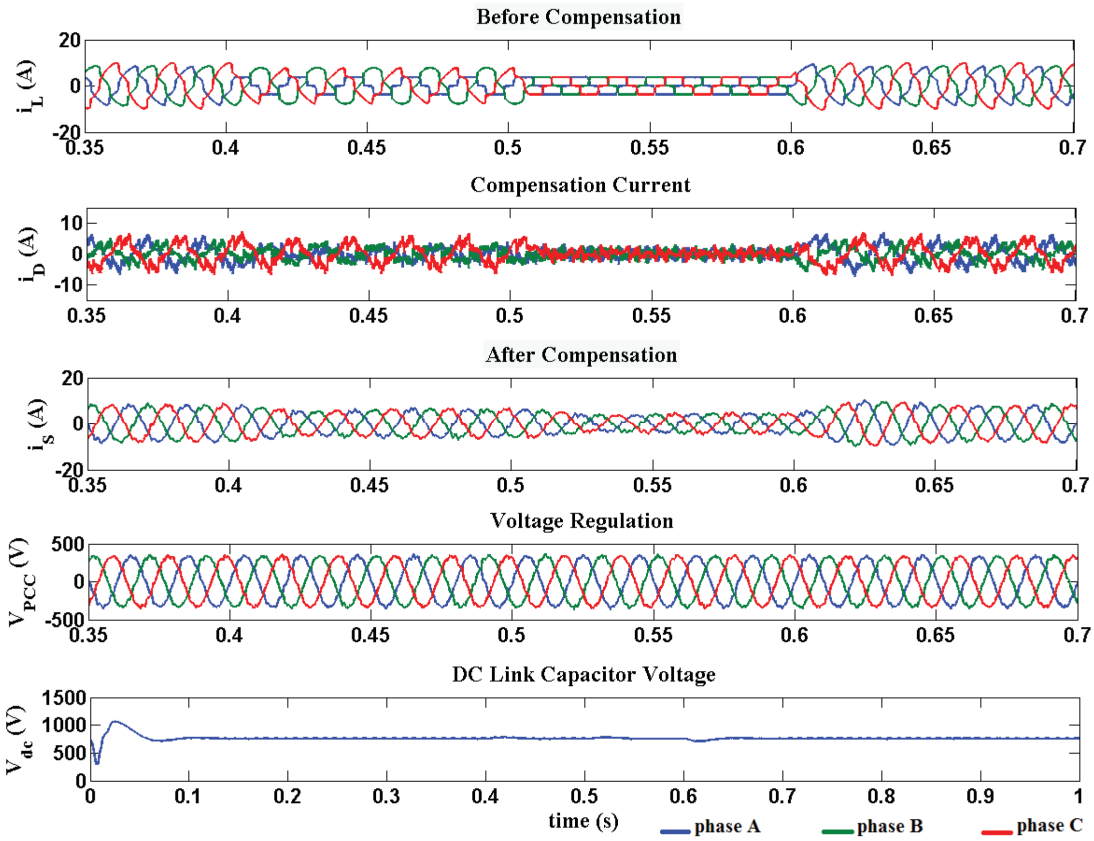

Figure 7. Performance of DSTATCOM with Proposed Algorithm.

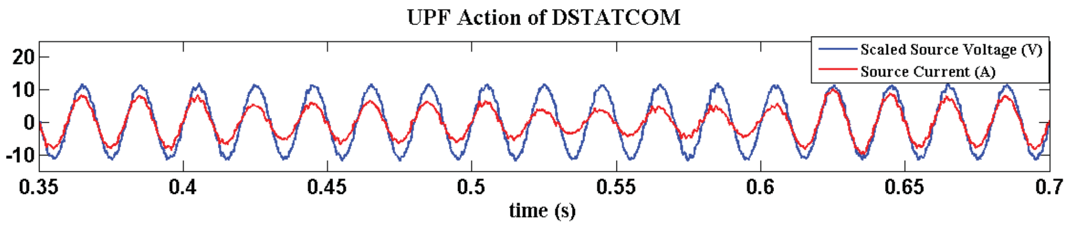

Figure 8. UPF action of DSTATCOM.

Table 2. %THD Comparison.

	Voltage %THD		Current %THD	
	Base Case	FCS-MPC	Base Case	FCS-MPC
Phase A	12.83	3.88	9.75	4.72
Phase B	9.42	3.74	15.81	4.48
Phase C	12.19	3.78	9.89	4.45

Comparison of the % Total Harmonic Distortion (%THD) values between FCS-MPC based DSTATCOM system and the base case scenario has been tabulated in the Table 2. Clearly, the %THD values has been considerably reduced and within the IEEE standard limit.

5. Conclusion

This paper proposes a new control technique, namely, Finite Control Set Model Predictive Controller (FCS-MPC) with ISCT based reference current extraction method for DSTATCOM. The proposed control technique is very simple and yet powerful, able to control the DSTATCOM without any additional modulation stage. This allows faster dynamic response compared to the classical controllers. It avoids additional coordinate transformation used in the conventional FCS-MPC method.

It was able to balance the source current under unbalanced load conditions as well as suppress the voltage harmonics along with maintaining the PCC voltage within the prescribed limit. In addition, unity power factor action is also verified. The secondary control objective to maintain the required reference voltage across the DC Link capacitor was also achieved. The %THD values below the IEEE-519:1992 validate the quality of the proposed control scheme. The V_{dc} control can be incorporated inside the FCS-MPC algorithm to make the control system much simpler and effective for future smart power distribution systems.

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