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Research Paper

D-STATCOM MODELING AND SIMULATION APPLYING CONTROL SCHEMES FOR POWER QUALITY IMPROVEMENT

Kajal Rathore[1]*, Dhananjay Kumar[1] and Sunil Yadav[1]

*Corresponding Author: Kajal Rathore, ✉ rathore_kajal@yahoo.co.in

This paper focuses to design and analyze the Simulink model for the control of Distributed static synchronous compensator (D-STATCOM). It is important for a distribution system to have controllability, voltage stability and good power transfer capability. The voltage source converter based D-STATCOM achieves voltage regulation in the system by absorbing or supplying the required reactive power. The system is modeled using two control strategies, i.e., direct and indirect control which includes d-q transform. The comparative analysis of the control strategies has been done. The results of simulation are demonstrated and analyzed using MATLAB.

Keywords: Reactive power compensation, D-STATCOM, dq-model, Phase shift control, Voltage control, VSC

INTRODUCTION

The rapidly developing power electronics technology provides an opportunity for developing new power equipment for improving the performance of the power system. Flexible AC Transmission System technology (FACTS) uses the latest power electronic devices and methods to control electronically the high-voltage side of the network. FACTS devices can be used for power flow control, voltage regulation, transient stability improvement, and damping of power oscillations. FACTS devices can be of shunt or series or combination of shunt and series types. The shunt devices can be used for voltage regulations, while series devices can be used for regulation of line impedance and series-parallel combination can be used for real and reactive power compensation in addition to regulation of voltage and regulation of line impedance (Hingorani, 1991).

The family of emerging power electronics devices being offered to achieve these custom power objectives is:

- Distribution Static Compensator (D-STATCOM) that protects the distribution system from the effects of fluctuating

[1] Jawaharlal Institute of Technology, Borawan, Madhya Pradesh 451228, India.

voltage, voltage sags and swells and non-linear loads,

- DVR that protects a critical load from disturbances like sags, swells, transients and harmonics originating on the interconnected distribution system,
- Unified Power Quality Conditioner (UPQC), a combination of series and shunt controller, which compensates supply voltage and load current imperfections in the distribution system.

The DSTATCOM is a versatile device for providing reactive power compensation in ac networks. The control of reactive power is achieved via the regulation of a controlled voltage source behind the leakage impedance of a transformer (Lehn and Iravani, 1998). It is similar to a conventional synchronous compensator, which is essentially a synchronous generator where the field current is used to adjust the regulated voltage. The DSTATCOM uses Voltage Source Converter (VSC) to achieve the regulation task. When used in low or medium voltage distribution systems the STATCOM is normally identified as Distribution STATCOM (D-STATCOM). It operates in a similar manner as the STATCOM (FACTS controller), with the active power flow controlled by the angle between the AC system and VSC voltages and the reactive power flow controlled by the difference between the magnitudes of these voltages. As with the STATCOM, the capacitor acts as the energy storage device and its size is chosen based on power ratings, control and harmonics considerations. The D-STATCOM controller continuously monitors the load voltages and currents and determines the amount of compensation required by the AC system for a variety of disturbances.

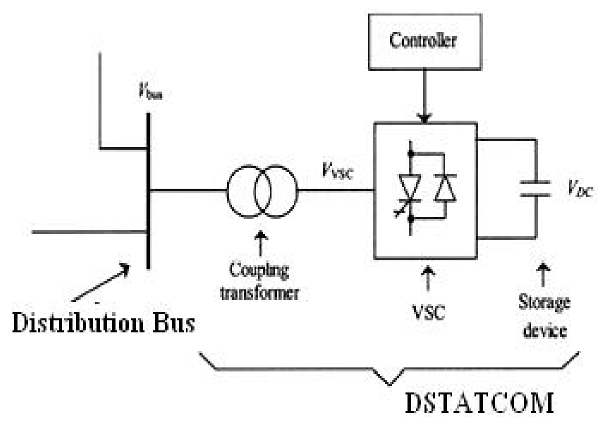
The D-STATCOM is a shunt device. It should therefore be able to regulate the voltage of a bus to which it is connected. The operating principle of a D-STATCOM in this mode has been termed as the D-STATCOM in voltage control mode. This report shows that even though the structure of D-STATCOM used in both current control and voltage control modes is the same, its operating principle is different. In the current control mode it is required to follow a set of reference currents while in the voltage control mode it is required to follow a set of reference voltages. This paper discusses the reference voltage generation scheme and the control of D-STATCOM in the voltage control mode.

BASIC MODEL OF D-STATCOM

The D-STATCOM system comprises of a VSC, a set of coupling reactors (leakage reactance of the transformer) and a controller. The D-STATCOM generates a controllable ac voltage from the Voltage Source Inverter (VSI) connected to a dc capacitor (energy storage device). The ac voltage appears behind the transformer leakage reactance.

The active and reactive power transfer between the power system and the D-STATCOM is caused by the voltage difference across this reactance. The D-STATCOM is connected to the power network at the Point of Common Coupling (PCC), where the voltage-quality problem is a concern. All required voltages and currents are measured and are fed into the controller to be compared with the reference. The controller then performs feedback control and outputs a set of switching

Figure 1: Basic Block Diagram of D-STATCOM

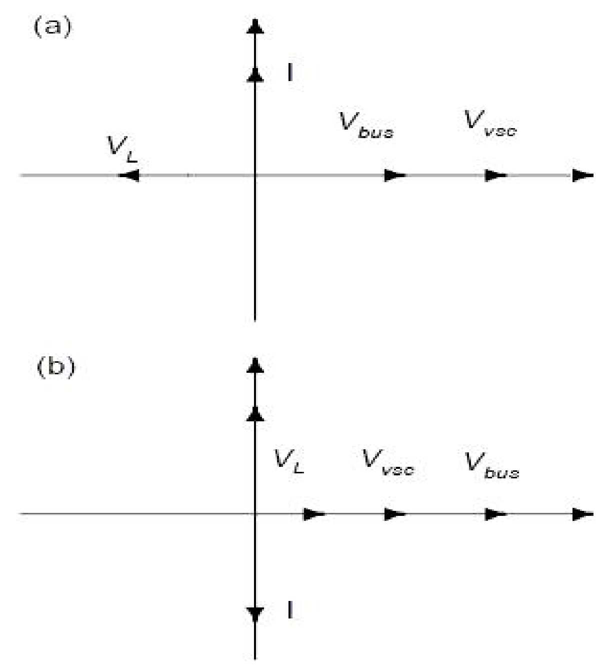


signals to drive the main semiconductor switches (IGBTs) of the power converter accordingly (Introducing Custom Power, 1995). The basic diagram of the D-STATCOM is illustrated in Figure 1.

WORKING PRINCIPLE OF D-STATCOM

D-STATCOM is inserted in transmission line to suppress voltage variation due to deviating load conditions and control reactive power. Basically it is connected in shunt to transmission line with Point of Common Coupling (PCC) in phase with system voltage. It can compensate for inductive and capacitive currents linearly and continuously. Figure 2 shows the vector diagram at the fundamental frequency for capacitive and inductive modes and for the transition states from capacitive to inductive and vice versa. The terminal voltage (V_{bus}) is equal to the sum of the inverter voltage (V_{vsc}) and the voltage across the coupling transformer reactive VL in both capacitive and inductive modes. I mean that if output voltage of DSTATCOM (V_{vsc}) is in phase with bus terminal voltage (V_{bus}) and (V_{vsc}) is greater than V_{bus} D-STATCOM provides reactive power to system.

Figure 2: Vector Diagram of D-STATCOM (a) Capacitive Mode (b) Inductive Mode



And if V_{vsc} is smaller than, D-STATCOM absorbs reactive power from power system V_{bus} and V_{vsc} have the same phase, but actually they have a little phase difference to component the loss of transformer winding and inverter switching, so absorbs some real power from system.

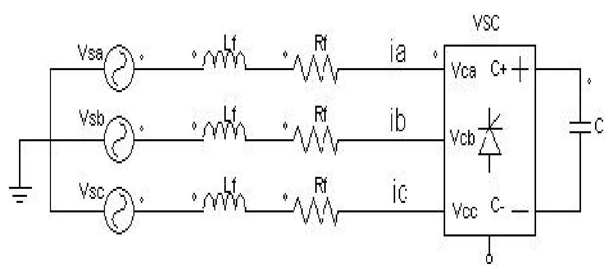
Figure 2 is DSTATCOM vector diagrams, which show inverter output voltageV_I, system voltage V_T, reactive voltage V_L and line current I in correlation with magnitude and phase ¢. Figures 2a and 2b explains how V_I and V_T produces capacitive or inductive power by controlling the magnitude for inverter output voltage V_I in phase with each other.

MATHAMATICAL MODELING OF D-STATCOM

Modeling Equations are given as:

$$R_f I_a + L_f \, di_a/dt = V_{sa} - V_{sc} \quad ...(1)$$

Figure 3: Simplified Single Line Diagram of D-STATCOM



$$R_f I_b + L_f \, {di_b}/{dt} = V_{sb} - V_{cb} \quad ...(2)$$

$$R_f I_c + L_f \, {di_c}/{dt} = V_{sc} - V_{cc} \quad ...(3)$$

Here,

V_{sa}, V_{sb}, V_{sc} : Voltage at the PCC

V_{sa}, V_{cb}, V_{cc} : Inverter output voltage

L_f: Filter inductance

R_f: Equivalent filter resistance

C : DC Link Capacitor

Designing Equations

a) $Q_{STAT} = \sqrt{3} V I_C$

b) $V_{DC} = 2\sqrt{2} V / \sqrt{3} Ma$

c) $L_{AC} = {\sqrt{3} Ma V_{DC}}/{12 a f_s I_{p-p}}$

d) Capacitor designing

$$C_{DC} = 3 V_S \Delta I_L T / \left(V_{DC}^2 - V_{DC1}^2\right)$$

Here,

I_C = D-STATCOM Line Current

V = Line Voltage

Ma = Modulation Index

V_{DC} = DC Link Voltage

Q_{STAT} = Power Rating

L_{AC} = AC Inductor

a = Over Current Factor (1.2)

Park's Transformation: This block performs the *abc* to *dq* transformation on a set of three-phase signals. It computes the direct axis V_d, quadrature axis V_q, and zero sequence V_0 quantities in a two axis rotating reference frame according to the following transformation:

$$V_d = 2/3 * \left[V_a \sin \mu t + V_b \sin(\mu t - 2\text{®}/3) + V_c \sin(\mu t + 2\text{®}/3)\right) \quad ...(4)$$

$$V_q = 2/3 * \left[V_a \cos \mu t + V_b \cos \mu t - 2\text{®}/3) + V_c \cos \mu t + 2\text{®}/3\right) \quad ...(5)$$

$$V_0 = 1/3 * \left[V_a + V_b + V_c\right] \quad ...(6)$$

where µ = rotation speed (radian/second) of the rotating frame. This transforms three quantities (direct axis, quadrature axis and zero-sequence components) expressed in a two axis reference frame back to phase quantities. The following transformation is used:

$$V_a = V_d \sin \mu t + V_q \cos \mu t + V_0 \quad ...(7)$$

$$V_a = V_d \sin(\mu t - 2\text{®}/3) + V_q \cos(\mu t - 2\text{®}/3) + V_0 \quad ...(8)$$

$$V_c = V_d \sin(\mu t + 2\text{®}/3) + V_q \cos(\mu t + 2\text{®}/3) + V_0 \quad ...(9)$$

where µ = rotation speed (radian/second) of the rotating reference frame.

VARIOUS CONTROL SCHEMES

Satisfactory performance, fast response, flexible and easy implementation are the main objectives of any compensation scheme. The control strategy of D-STATCOM is mainly implemented in the following steps (Masand *et al.*, 2006; and Singh, 2006):

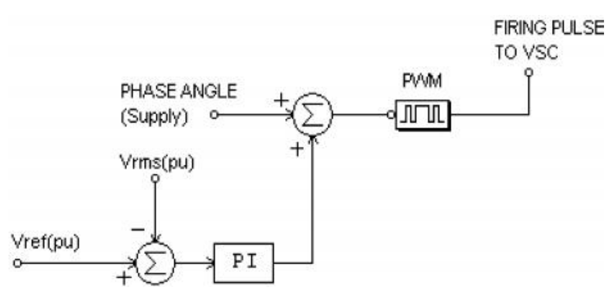
- Measurements of system variables and signal conditioning
- Extraction of reference compensating signals
- Generation of firing angles for switching devices

Basically all the above steps will be applied in every control scheme but methods of measurement of signal variables, extraction of reference, and generation of firing pulses will be different for different control schemes. Two control schemes are implemented and compared here are Phase Shift Control and Decoupled Current Control.

Phase Shift Control

In this control algorithm the voltage regulation is achieved in a D-STATCOM by the measurement of the RMS voltage at the load point and no reactive power measurements are required. Figure 4 shows the block diagram of the implemented scheme (Masand *et al.*, xxxx).

Figure 4: Block Diagram of Phase Shift Control



Sinusoidal PWM technique is used which is simple and gives a good response. The error signal obtained by comparing the measured system RMS voltage and the reference voltage, is fed to a PI controller which generates the angle which decides the necessary phase shift between the output voltage of the VSC and the AC terminal voltage. This angle is summed with the phase angle of the balanced supply voltages, assumed to be equally spaced at 120 degrees, to produce the desired synchronizing signal required to operate the PWM generator. In this algorithm the DC voltage is maintained constant using a separate dc source.

Decoupled Current Control p-q Theory

This algorithm requires the measurement of instantaneous values of three phase voltage and current. Figure 5 shows the block diagram representation of the control scheme. The compensation is achieved by the control of direct axis and quadrature axis currents and . Using the definition of the instantaneous reactive power theory for a balanced three phase three wire system, the quadrature component of the voltage is always zero, the real (*P*) and the reactive power (*Q*) injected into the system by the D-STATCOM can be expressed under the *dq* reference frame as:

$$P = V_d I_d + V_q I_q \quad ...(10)$$

$$Q = V_q I_d + V_d I_q \quad ...(11)$$

Since $V_q = 0$, i_d and i_q completely describes the instantaneous value of real and reactive powers produced by the D-STATCOM when the system voltage remains constant. Therefore the instantaneous three phase current measured is transformed by *abc* to *dq*0 transformation block. The decoupled d-axis component i_d and *q*-axis component i_q are regulated by two separate PI regulators. The instantaneous i_d reference and the instantaneous i_q reference are obtained by the control of the *dc* voltage and the terminal

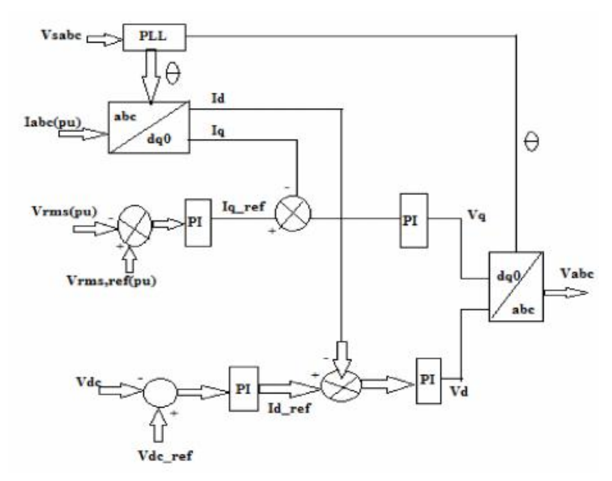


Figure 5: Block Diagram of Decoupled Theory Based Control of D-STATCOM

voltage measured. Thus, instantaneous current tracking control is achieved using four PI regulators. A Phase Locked Loop (PLL) is used to synchronize the control loop to the ac supply so as to operate in the *abc* to *dq*0 reference frame.

MODELLING AND SIMULATION RESULTS

In this work, the performance of VSC based power devices acting as a voltage controller

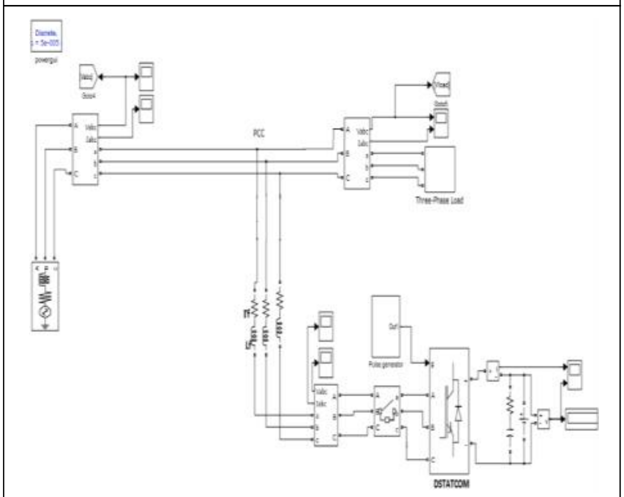


Figure 6: Simulink Model for Phase Shift Control

is investigated. The D-STATCOM model can be seen in Figure 6 which comprised of distribution bus, a VSC and the controller. The controller scheme is applied to generate the switching pulse for VSC.

Phase Shift Control

It does not have a self supporting dc bus and requires a separate dc source to pre-charge the *dc* side capacitor and maintain its voltage during the operation of D-STATCOM. It assumes that the supply side voltage is balanced and without harmonics, since fundamental wave form is used to obtain the phase angles of the supply wave form. There is no provision for harmonic suppression in

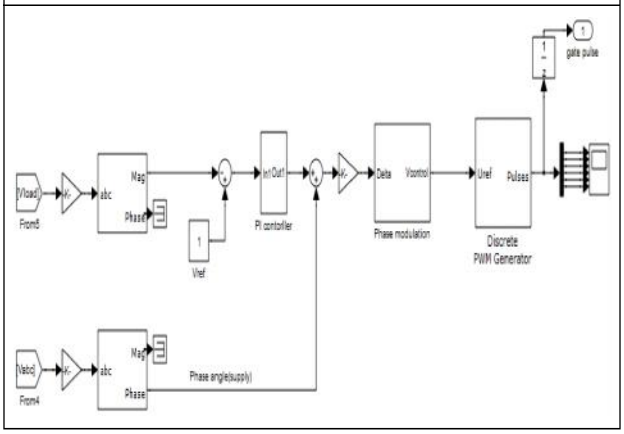


Figure 7: Simulink Model of Controller for Phase Shift Controller

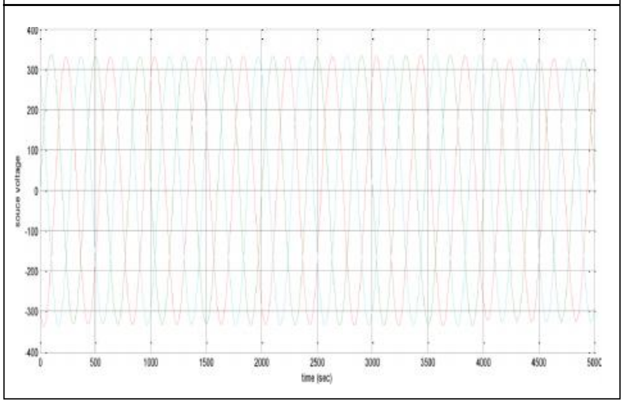


Figure 8: 3-Phase Source Voltage at PCC

Figure 9: Voltage of Separate Pre-Charged Capacitor

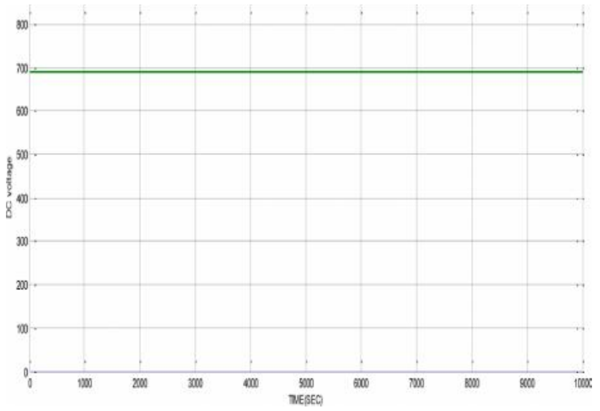


Figure 10: Inverter Output Voltage

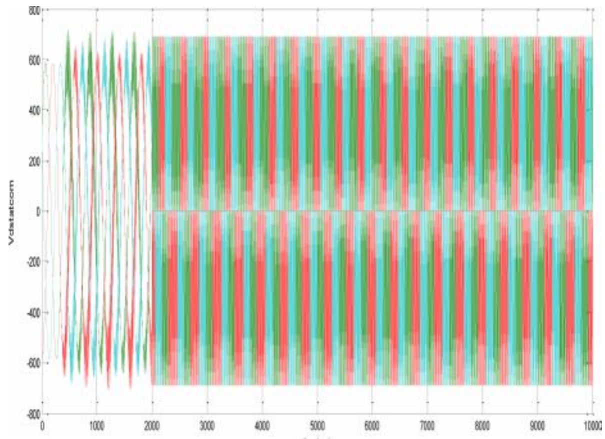


Figure 11: Compensated Output Voltage and Current

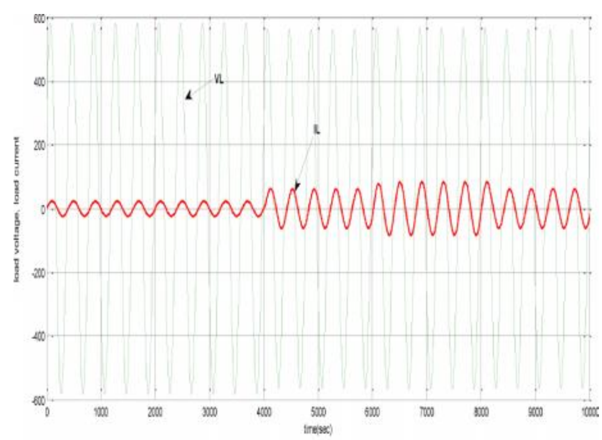
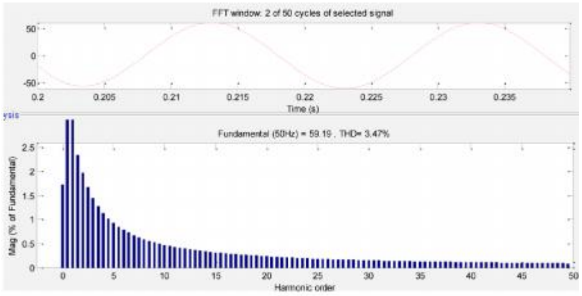
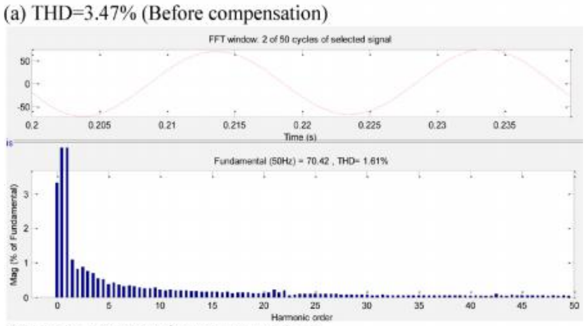


Figure 12: Total Harmonic Distortion (Linear Load) (a) Before Compensation (b) After Compensation

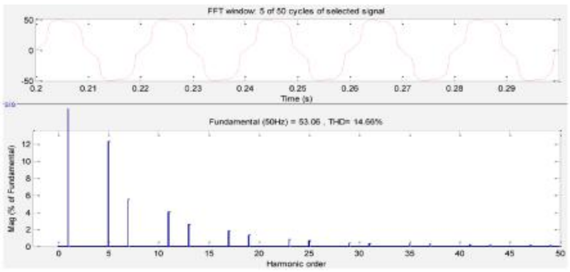


(a) THD=3.47% (Before compensation)

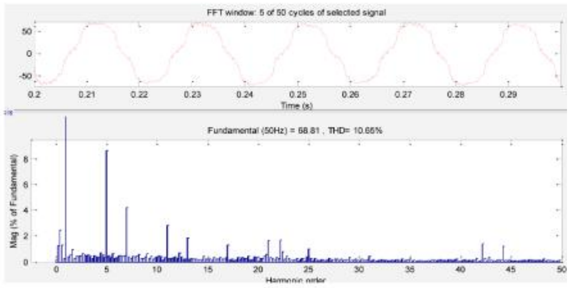


(b) THD=1.61% (After compensation)

Figure 13: Total Harmonic Distortion (Nonlinear Load) (a) Before Compensation (b) After Compensation



(a)THD= 14.66% (Before compensation)



(b)THD=10.65% (After compensation)

case the load connected to PCC is nonlinear. This method results in generation of active power by the VSC along with the var.

Decoupled Current Control

The advantageous features of this scheme are:

It incorporates a self supporting dc bus. The active and reactive power control achieved through and control are decoupled from each other. The dc bus control or regulation are decoupled from the ac bus control like voltage regulation or power factor correction and load balancing.

Switching of devices of VSC is done at fixed frequency. Thus switching losses can be limited within the rating of the devices. This type of control is inherently linear and robust and uses PI or PID controls.

Figure 14: Simulink Model for Decoupled Current Controller

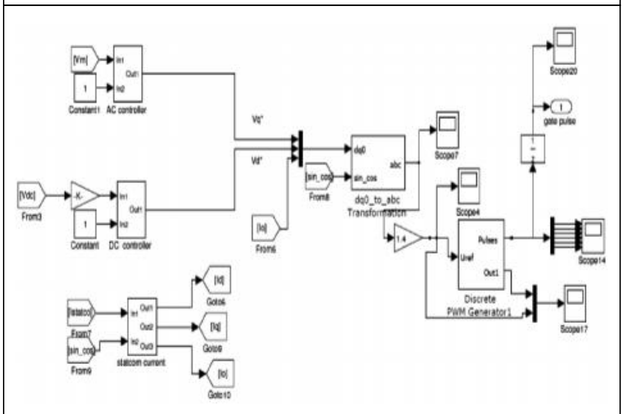
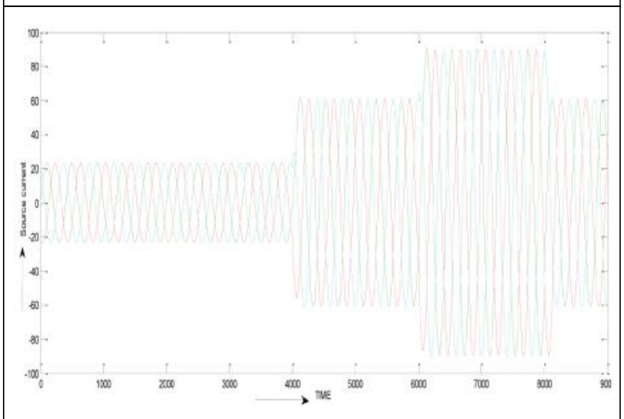


Figure 15: Source Current Waveform



The results can be seen for various parameters like voltage, current before and after applying the controller for compensation.

Figure 16: Before Compensation (a) Load Voltage and Load Current (Linear) (b) Load Voltage and Load Current (Nonlinear)

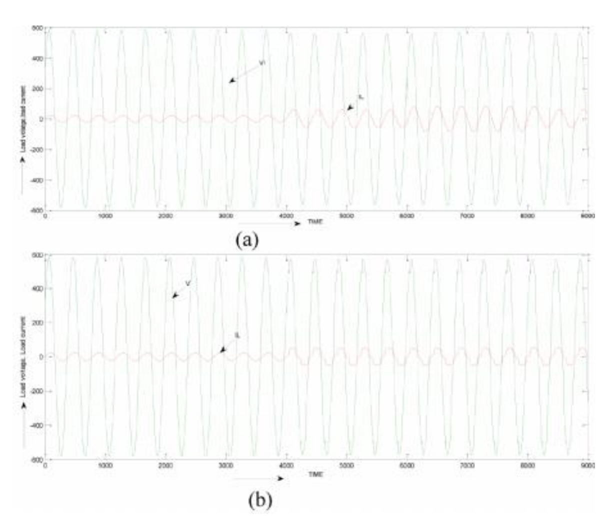


Figure 17: After Compensation (a) Load Voltage, Load Current (Linear), (b) Load Voltage, Load Current (Nonlinear)

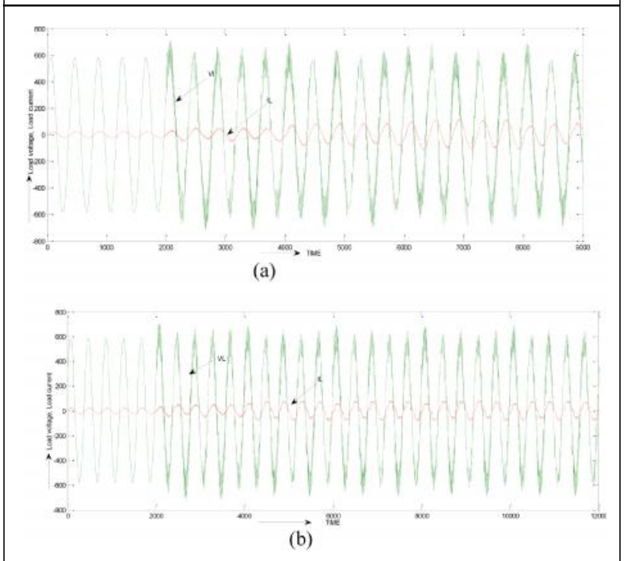
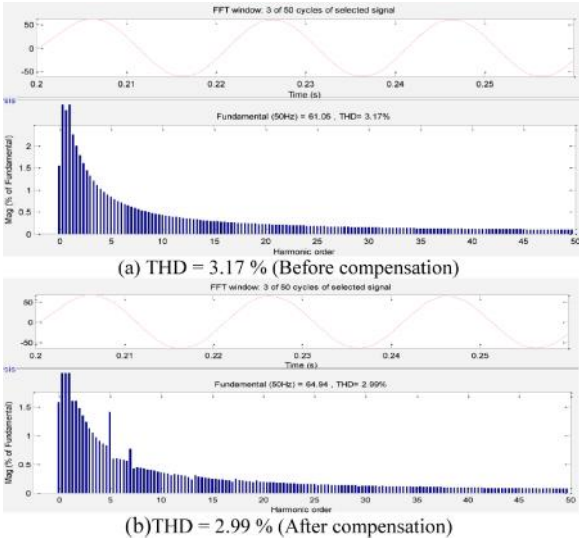


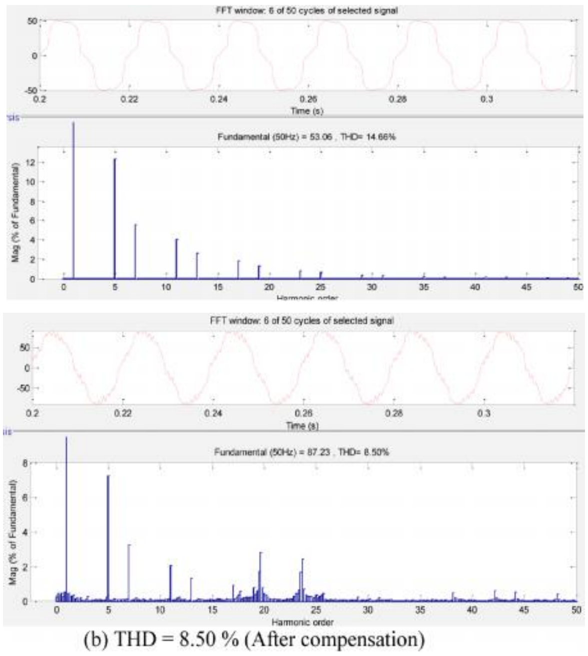
Figure 18: Total Harmonic Distortion (Linear Load) (a) Before Compensation (b) After Compensation



(a) THD = 3.17 % (Before compensation)

(b)THD = 2.99 % (After compensation)

Figure 19: Total Harmonic Distortion (Nonlinear Load (a) Before Compensation (b) After Compensation



(b) THD = 8.50 % (After compensation)

CONCLUSION

Detailed modeling is presented and results are discussed with different control studies.

Table 1

S. No	Parameters	Phase Shift Control	Decoupled Current Control
1.	Reactive power compensation	Average	Partial
2.	Performance under nonlinear loads	Contains undesired harmonics	Not Satisfactory
3.	Applicable for single phase systems	Yes	No
4.	Harmonic compensation	Less	Average
5.	PWM switching frequency	Fixed	Fixed
6.	Self supporting DC Bus	No	Yes
7.	Generation of firing pulses	Sine PWM	Sine PWM
8.	Power factor Linear Load	0.8 to 0.94 (linear)	0.8 to 0.94 (linear)
9.	Power factor Non Linear Load	0.8 to 0.92 (Nonlinear)	0.8 to 0.95 (Nonlinear)
10.	Response time	Less	More
11.	Control scheme	Easy	Complex

These Power devices provide solutions to power quality at the medium and low voltage distribution network level. This project presents the detailed modeling of one of the custom power products, D-STATCOM is presented using instantaneous P-Q theory and phase shift theory used for the control of D-STATCOM are discussed. These control algorithms are described with the help of simulation results under linear loads and nonlinear loads. It was observed that undersized capacitor degrades all three aspects. On the other hand, an oversized capacitor may also lead to a PWM control with a sluggish response but it will reduce D-STATCOM harmonic generation and transient overshooting. It is concluded that a D-STATCOM though is conceptually similar to a STATCOM at the transmission level; its control scheme should be such that in addition to complete reactive power compensation, power factor correction and voltage regulation the harmonics are also checked, and for achieving improved power quality levels at the distribution end.

FUTURE WORK

- This work presents a detailed modeling and analysis of one of the custom power device D-STATCOM. Instantaneous Decoupled Current Control or instantaneous *p-q* theory and phase shift control is discussed and verified through detailed simulations by developing the models in MATLAB Simulink using the Simpower system control tool boxes. Now we are posing a challenge to complete if the remaining control strategies which include the synchronous frame theory, regulation of Bus and DC link voltage, and ANN based Adaline theory. These control strategies are implemented and studied in detail through various simulations then it would be of immense help for the real time implementation of the D-STATCOM across all over the globe.
- If thrown light on other custom power devices like the Dynamic Voltage Regulator (DVR), and Unified Power Quality Conditioner (UPQC), applying different strategies then we can bring a revolution in the control of power in the distribution systems.

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