Analysis of Five-Level Dstatcom for Harmonic Reduction in Power System Due to Non-Linear Loads

N. Raveendra*[1], V. Madhusudhan[2], A. Jayalaxmi[3]
[1]Mallareddy Engineering College for Women, Hyderabad, Telangana, India
[2]KSRM Engineering College, Kadapah, Andhra Pradesh, India
[3]JNTUH College of Engineering, Department of EEE, Hyderabad, Telangana, India
*Corresponding author, email: raveendra.hod@gmail.com

Abstract
This paper deals with the elimination of harmonics at PCC in the presence of non-linear type of loads. Introduction of five-level DSTATCOM at PCC injects compensating currents for the minimization of harmonic content in the source currents. Non-linear loads when connected to the system draw non-linear components of current leaving undesired harmonics at the source side. DSTATCOM when connected to the system at the coupling point induces compensating currents to nullify harmonics. This paper introduces the simulation modelling of five-level DSTATCOM for harmonic elimination. Matlab/Simulink modelling was done for the system without DSTATCOM and its harmonic contents were shown. The system without DSTATCOM is compared with the system with the presence of DSTATCOM showing their respective THD in the source current. Five level DSTATCOM was validated by considering fixed load and variable load. Simulation work was carried out for three types of systems and results were obtained using Matlab/Simulink.

Keywords: DSTATCOM, THD, point of common coupling (PCC), non-linear, harmonics, power quality.

1. Introduction

An electric distribution system is a component of an electrical system between the majority power supply or sources and therefore the consumer's service switches. The majority power sources area unit set in or close to the load area to be served by the distribution system and will be either generating stations or power substations supplied over transmission lines. Distribution systems will, in general, be divided into six elements, namely, sub-transmission circuits, distribution substations, distribution or primary feeders, distribution transformers, secondary circuits or secondary's, and consumer's service connections and meters or consumer's services. While delivering power to the consumers, power quality is the most important criteria to look for. Power quality is how far the practical system resembles the ideal conditions. Power quality is defined as providing uninterrupted power supply with voltage, frequency and power factor within nominal values. In many of the industrial, consumer durables and service sector power electronic devices are extensively used. Power quality is defined in the IEEE 100 authoritative dictionary [1]. It is at most important to sense, control and treat the power being supplied to the consumers or to educate engineers to reduce the adverse effects of power quality related issues [2-8]. Every electrical connected or operated device is influenced with power quality [9-12].

Power quality issues costs unexpected power failures, equipment overheating, damage to sensitive devices, electronic communication interference, increased system losses, decreased efficiency, need for over sizing of installations and many more. Power quality issues regard harmonics, voltage variations, transients, interruptions, waveform distortions. Addressing these power quality issues is very much primary thing to deliver quality power to the consumers. Harmonics and load imbalances can be cleared effectively by using passive filters or active filters. Passive filters are in use still for compensating harmonic pollution and load imbalances in the system. The efficiency of passive filter is the impedance ratio of filter impedance to the network impedance which is not guaranteed. So, passive filter might not be a best choice to

mitigate harmonics. This problem in passive filters gives scope to active filters to effectively mitigate harmonics.

The general block diagram of active power filter is shown in Figure 1. This active power filter is used to mitigate harmonics in this paper. Non-linear loads in the system draw only non-linear currents from the source leaving remaining components at the connection point. If other loads are connected at that connection point, draws harmonic currents which are undesirable and actually stress the device connected. Active power filters compensate these harmonic contents inducing.
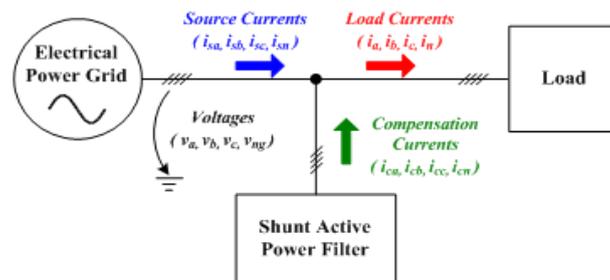
Figure 1. General Block Diagram of Shunt D-STATCOM

Compensating currents, compensation of harmonics using active power filters is done in three stages [13] signal sensing, conditioning of signal and generating gate drive signals. From the output of gate drive signals power circuit can be controlled [14]. Again the internal control strategy decides the gate drive circuit of overall APF to generate compensating currents [15-16]. In this paper instantaneous active and reactive power (PQ) theory is used to control the compensating currents to the system. A simple PI controller is used as internal controller inside the main (external) control circuit in this paper. This paper discusses the effectiveness of APF to mitigate the harmonic pollution in the system by generating compensating currents through PQ control theory. Model of the above said system was build for an 11 KV system with non-linear load. Three cases were considered in this paper, system without APF, system with APF having fixed load and system with APF having variable load and the results were discussed in detail. Models were built for these three cases using Matlab/Simulink with validating results along with THD content in each case.

2. DSTATCOM Configuresuration

Active power filter generates compensating currents and induces these generated compensated currents in to the system thus mitigating harmonics in the system. Unwanted neutral currents might flow caused due to non-linear loads with uncompensated and unbalanced systems. In this case, a three phase APF can deliver compensation. Active power filters are of different types. Series compensators, shunt compensators or combination of both series and shunt compensators called UPQC. Here in this paper shunt active power filter was considered to mitigate the harmonic pollution in the system containing non-linear type of loads. A typical arrangement of 5-level DSTATCOM as shunt active power filter was shown in Figure 2. This is a converter based APF with VSI configuresuration. VSI configuresured APF is low cost, simple, expandable to multi-level and consists of a self-supporting DC Voltage. This shunt active power filter can effectively mitigate harmonics. The shunt APF is controlled by a controller to generate reference currents and also to generate compensating currents. Basically the non-linear components in the load current are first sensed at the load point and the signal is fed to controller. The controller conditions the signal in the system by inducing compensating currents through proper interfacing. Sensing agents senses the load currents at the load point and fed back to the controller. In this paper, PQ theory was used to control the APF. This controller with internal PI controller generates the reference currents and after comparing the original feedback signal with the reference currents, produces error signal. The controller controls the switches of the VSI accordingly and thus the currents will be injected in to the

system through VSI converter. These are called compensating currents or negative currents that compensate the harmonics at the source point.
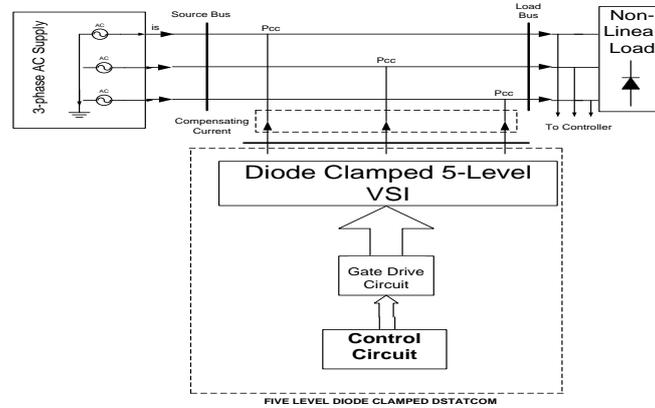

Figure 2. Schematic Arrangement of 5-Level D-STATCOM

3. Control Strategy of DSTATCOM.

D-STATCOM is connected to the power networks at a PCC and measurement of all required voltages and currents are fed into the controller to be compared. The feedback of the outputs were conditioned, if required, by the controller and turn ON the switches in converter. The exchange of real power and reactive power between the D-STATCOM and the power system can be controlled by adjusting the amplitude and phase of the converter output voltage. In the case of an ideal lossless power converter, the output voltage of the converter is controlled to be in phase with that of the power system.

Active power filter should be capable of nullify the variations in component of instantaneous power and also the reactive power of fundamental frequency. A simple control strategy called active and reactive power (PQ) theory can control the APF by defining instantaneous active power and reactive power. The definitions apply in either the αβ0- or dq0-domains and for balanced sinusoidal three-phase systems would yield constant values. There are various representations of the equations such as complex power or a two-dimensional cross product. The total set-up of system with APF along with its control circuit was shown in Figure 3 while only control strategy for APF is shown in Figure 4.
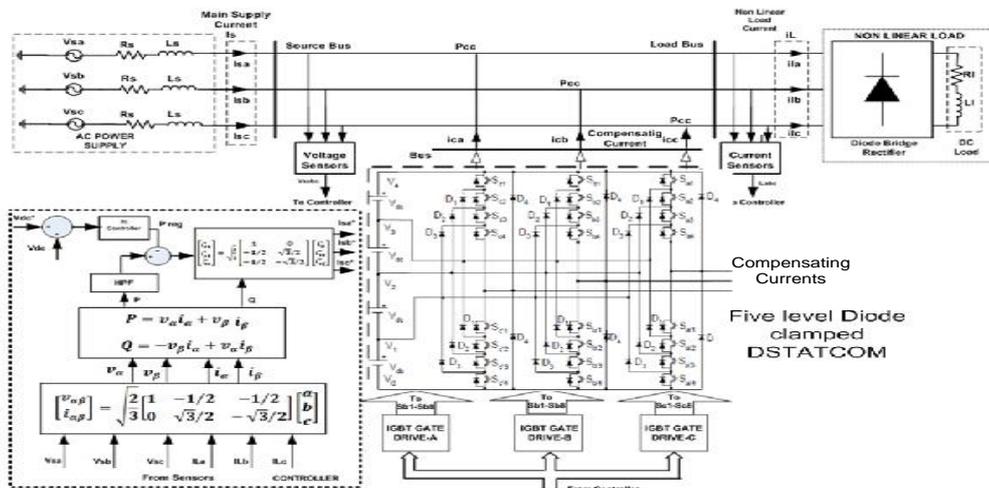
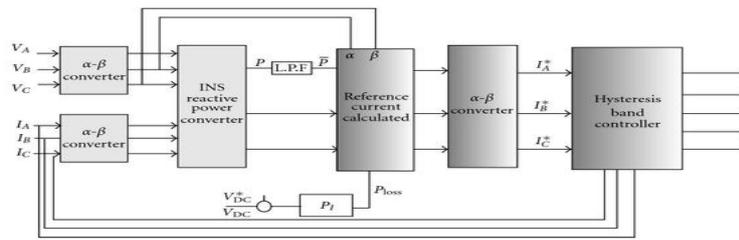Figure 3. 5-Level Diode Clamped DSTATCOM with Control Circuit

Figure 4. Control Circuit Driving D-STATCOM

3.1. Estimation of Reference Source Current

The instantaneous currents can be written as:

$$i_s(t) = i_l(t) - i_c(t) \tag{1}$$

Source voltage is given by:

$$v_s(t) = v_m \sin \omega t \tag{2}$$

if a non-linear load is applied, then the load current will have a fundamental component and harmonic components which can be represented as:

$$i_L(t) = \sum_{n=1}^{\infty} I_n \sin(n\omega t + \phi_n) = I_l \sin(n\omega t + \phi_l) + \sum_{n=2}^{\infty} I_n \sin(n\omega t + \phi_n) \tag{3}$$

The instantaneous load power can be given as:

$$\begin{aligned}
p_L(t) &= v_s(t) * i_l(t) \\
&= v_m i_l \sin^2 \omega t * \cos \phi_1 + v_m i_l \sin \omega t * \cos \omega t * \sin \phi_1 \\
&+ v_m \sin \omega t * \sum_{n=2}^{\infty} I_n \sin(n\omega t + \phi_n)
\end{aligned} \tag{4}$$

$$= P_{fund}(t) + P_{reac}(t) + P_{har}(t) \tag{5}$$

the real (fundamental) power drawn by the load is:

$$P_{fund}(t) = v_m i_l \sin^2 \omega t * \cos \phi_1 = v_s(t) * i_s(t) \tag{6}$$

the source current supplied by the source, after compensation is

$$i_s(t) = \frac{P_{fund}(t)}{v_s(t)} = i_l \cos \phi_1 \sin \omega t = I_m \sin \omega t \tag{7}$$

The desired source currents, after compensation, can be given as

$$i_{sa}^*(t) = I_{sp} \sin \omega t$$

$$i_{sb}^*(t) = I_{sp} \sin(\omega t - 120^o)$$

$$i_{sc}^{*}(t) = I_{sp}\sin(\omega t + 120^{o})$$ (8)

where I_{sp} (=$I_1\cos\Phi_1$+I_{sl}) the amplitude of the desired source current, while the section angle is obtained from the supply voltages & load currents. Hence, the waveform and phases of the supply currents area unit best- known and only the magnitudes of the supply currents would like to be determined. This peak value of the reference current has been calculable by control the DC aspect electrical device voltage of the CMC. This capacitor voltage is compared with a reference worth and the error is processed in a very PI controller. The output of the PI controller has been considered as the amplitude of the required supply current, and the reference currents are calculable by multiplying this peak worth with sin vectors in section with the supply voltages.

3.2. DC Link Voltage Control using PI Controller

The load requires real power from ac source is supplied with DSTATCOM configureuresuration and few losses like switching losses, losses in reactor and dielectric losses. The DSTATCOM switching is done by reference source current is used here it has two elements those are real first harmonic component and losses in DSTATCOM. The first harmonic component of load current being extracted from p-q theory and SRF theory. The losses of DSTATCOM is estimated mistreatment a proportional–integral (PI) controller over the dc bus voltage of the DSTATCOM. To compute the second element of the reference active current, a reference dc bus voltage (Vdc*) is compared with the sensed dc bus voltage (Vdc) of DSTATCOM. Which, in the nth sampling instant, is expressed as:

$$v_{dcl}(n) = v_{dc}^{*}(n) - v_{dc}(n)$$ (9)

This error signal vdcl(n) is processed in a PI controller, and the output {Ip(n)}at the nth sampling instant is expressed $I_{p(n)} = I_{p(n-1)} + K_{pdc}\{v_{dcl(n)} - v_{dcl(n-1)}\} + K_{idc}v_{dcl(n)}$ (10) Where K_{pdc} and K_{idc} are the proportional and integral gains of the PI controller. The output of this PI controller accounts for the losses in DSTATCOM, and it is considered because of the loss element. This component (I_p(n)) will be adscititious with the common real power for dominant DSTATCOM by p-q theory. Figure 5 shows the block diagram illustration of PI controller.

The dc-link capacitor has slow dynamics compared to the compensator, since the capacitor voltage is sampled at each zero crossing of section offer voltage. The sampling can conjointly be performed at 1 / 4 cycles relying upon the symmetry of the dc-link voltage wave form. The drawback of this typical controller is that its transient response is slow, especially for fast-changing masses. Also, the design of PI controller parameters is sort of tough for a fancy system and, hence, these parameters are chosen by trial and error. Moreover, the dynamic response during the transients' is whole hooked in to the values of Kpdc and Kidc, when Pdc is comparable to Plavg. To overcome the disadvantages of the aforementioned controller, an energy-based dc-link voltage controller is planned.
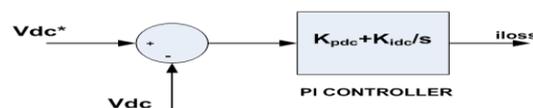

Figure 5. PI Controller Block Representation

4. Matlab/Simulink Results and Discussions

Simulation models were built considering three cases. Models for the system without APF, system with five-level APF having fixed load and the model system with APF with variable load were developed. Results were also discussed in detail. Results for the source voltage, load

current containing non-linearity, source currents with disturbances, induced filter currents by VSI based APF, power factor and DC link voltage of VSI converter are shown for all cases. Table 1 shows the system parameters used to develop the models. As case 1, system without DSTATCOM was shown and as case 2, system with 5-level DSTATCOM having fixed load was shown. Case 3 discusses the 5-level DSTATCOM with variable load with respective results. Models were developed using Matlab/Simulink.

Table 1. System Parameters.

Parameter	Value
Source Voltage (Ph-Ph RMS)	11 KV
Source Impedance	0.1+j0.282 Ω
Load Impedance	200+j37.6 Ω
DC Link Capacitance	1500 µF
Proportional Gain	0.8
Integral Gain	0.5

4.1. Without Active Power Filter

The model of system without active power filter was shown in Figure 6 and the corresponding source voltage is was shown in Figure 7.
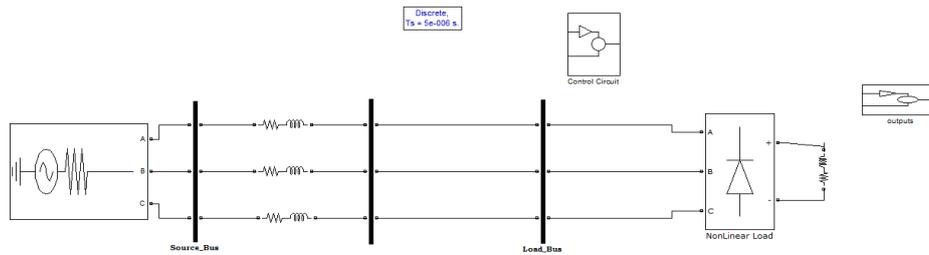
Figure 6. Simulink Model of System without APF of Source Voltage
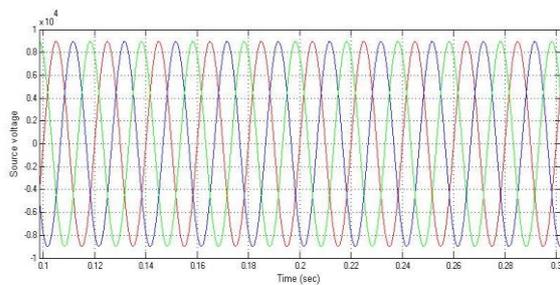
Figure 7. Simulink Result of Source Voltage   Figure 8. Simulink Result of Load Current
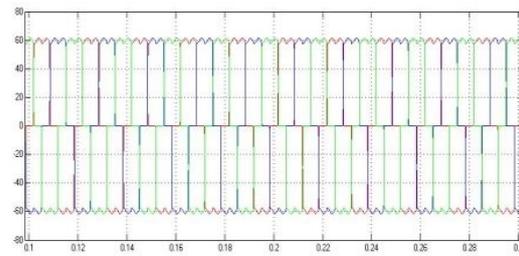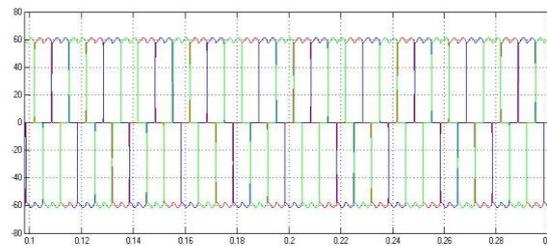
Figure 9. Simulink Result of Source Current
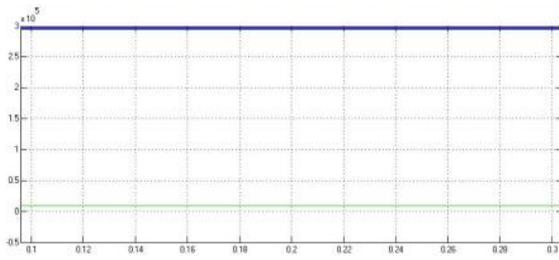
Figure 10. Simulink Result of Load Active and Reactive Power
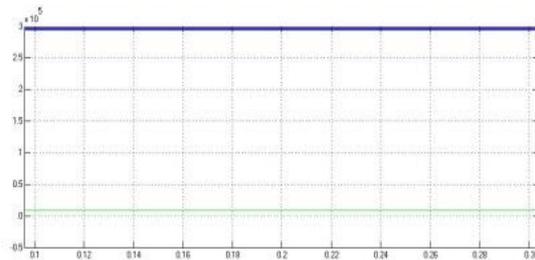
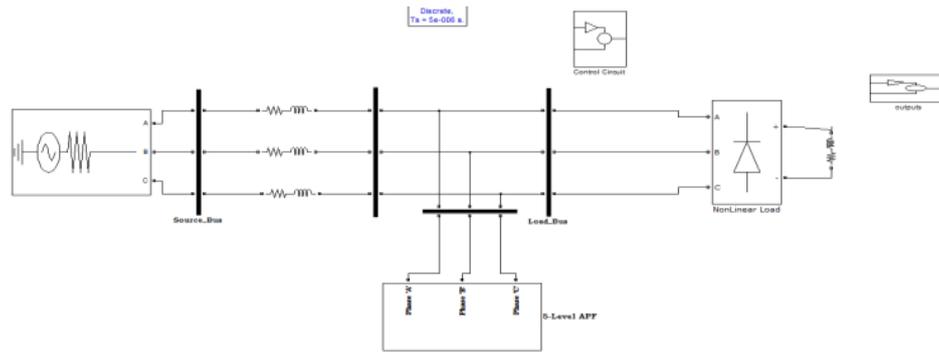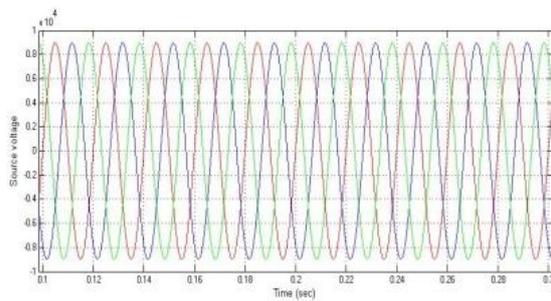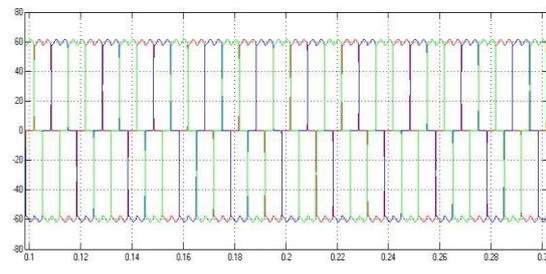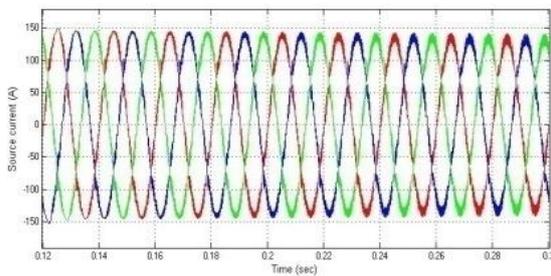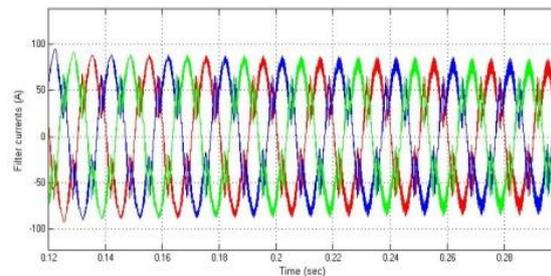
Figure 11. Simulink Result of Source Active and Reactive Power

Figure 8 represents the load current and Figure 9 represents source current. Figure 10 shows the active and reactive components of load and Figure 11 shows the source active and reactive powers. Blue indicates active component of power and green indicates reactive component. Figure 12 represents the load power factor and Figure13 represents source power factor.
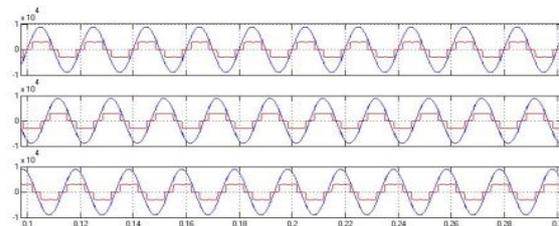
Figure 12. Simulink Result of Load Power Factor
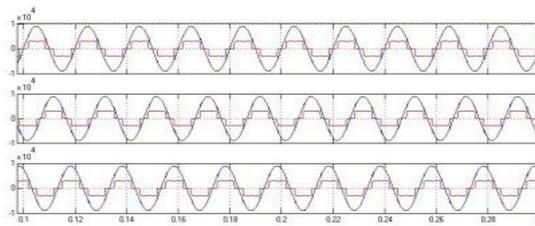
Figure 13. Simulink Result of Source Power Factor
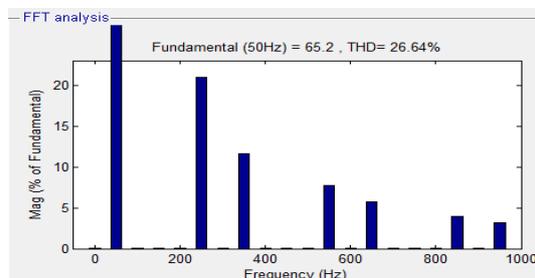
Figure 14. Simulink Result Sowing THD in Load Current
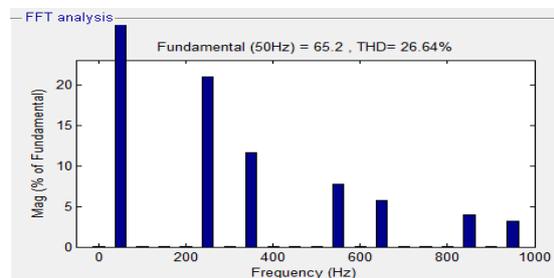
Figure 15. Simulink Result Showing THD in Source Current

4.2. With 5-Level DSTATCOM and Fixed Load

The model of system with active power filter having fixed load was shown in Figure16 and the corresponding source voltage is was shown in Figure 17.

Figure 16. Simulink Model of System with Five Level APF Having Fixed Load

Figure 17. Simulink Result of Source Voltage   Figure 18. Simulink Result of Load Currents

Figure 19. Simulink Result of Source Current   Figure 20. Simulink Result of Filter Current with Five Level APF Having Fixed Load
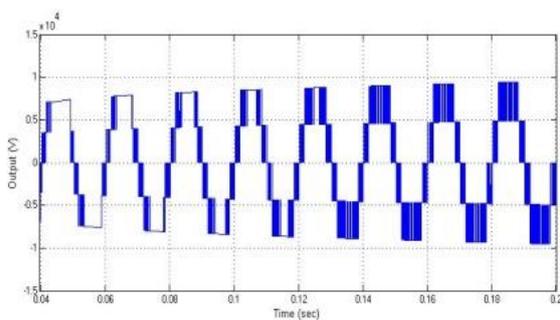

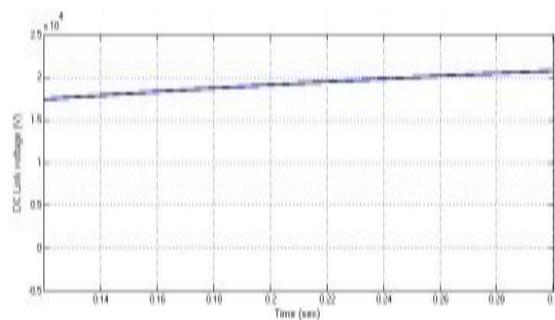Figure 21. Simulink Result of Output for Five Level APF   Figure 22. Simulink Result of DC Link Voltage

Figure18 represents the load current and Figure19 represents source current. Figure 20 shows the filter currents induced by the five level DSTATCOM with Figure 21 showing output of five level DSTATCOM with fixed load. Figure 22 represents the simulink result of DC link voltage.
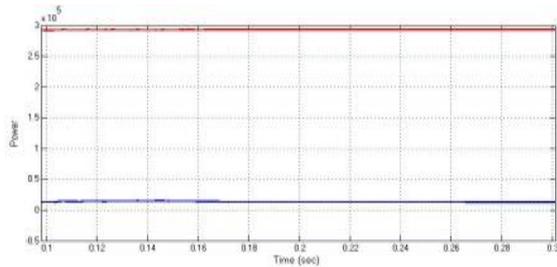
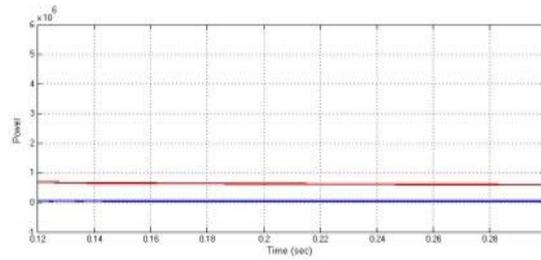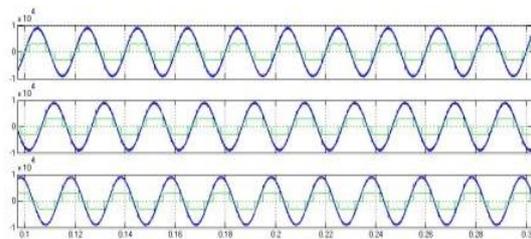Figure 23. Simulink Result of Load Active And Reactive Power

Figure 24. Simulink Result of Source Active and Reactive Power

Figure 23 shows the active and reactive components of load and Figure 24 shows the source active and reactive powers. Red indicates active component of power and blue indicates reactive component.

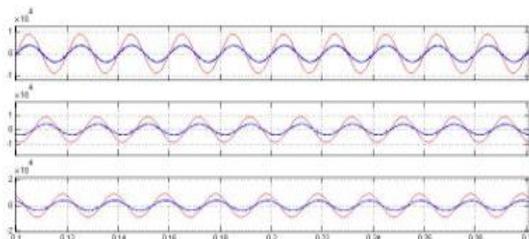Figure 25. Simulink Result of Load Power Factor

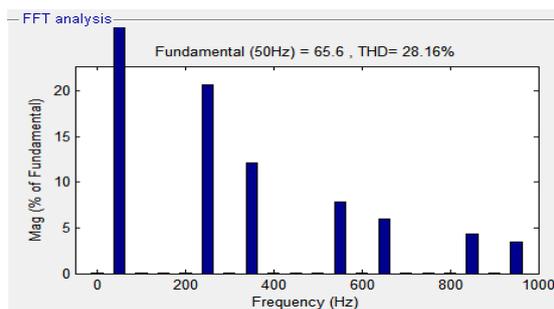Figure 26. Simulink Result of Source Power Factor

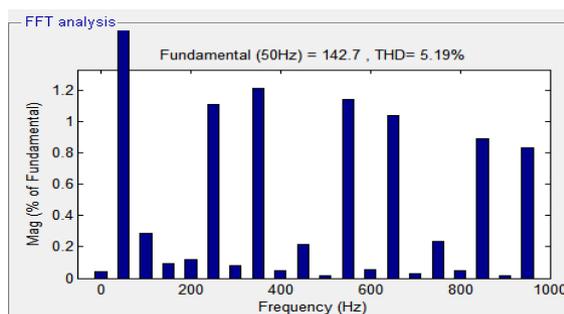Figure 27. Simulink Result Showing THD of Load Current

Figure 28. Simulink Result Showing THD in Source Current

Figure 25 represents the load power factor and Figure 26 represents source power factor. Figure 27 shows the THD in load current for the system without DSTATCOM which contains 28.16 % of harmonics. Also the source current without APF contains 5.19 % of THD harmonics as shown in Figure 28. With the presence of five level DSTATCOM, the total harmonic distortion in the source current is reduced when compared to the system without APF.

4.3. With 5-level DSTATCOM and Variable Load
The model of system with 5-level DSTATCOM having variable load was shown in Figure 29 and the corresponding source voltage is was shown in Figure 30.
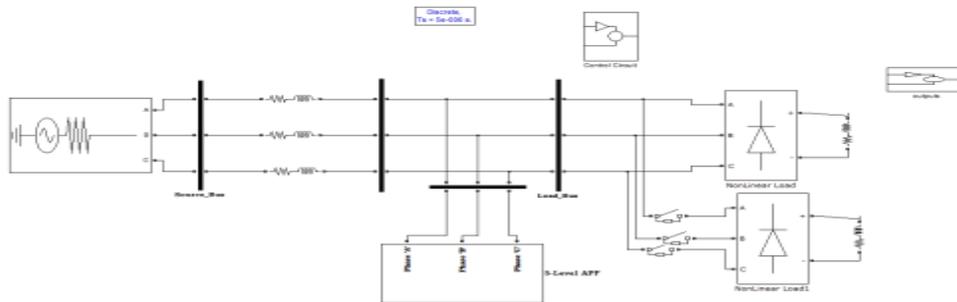

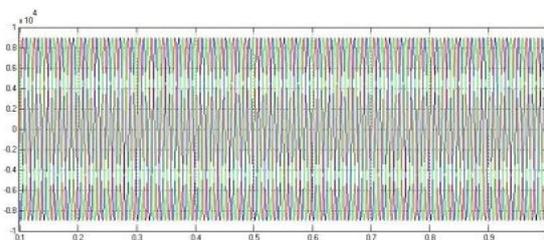Figure 29. Simulink Model of System with 5-level DSTATCOM Having Variable Load

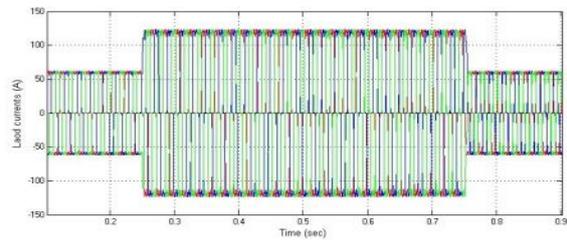Figure 30. Simulink Result of Source Voltage
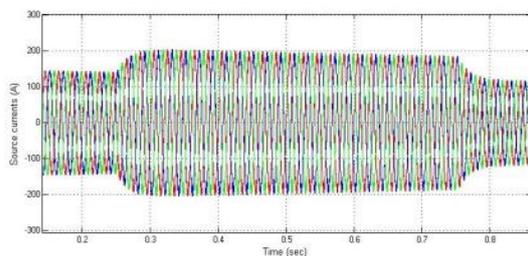

Figure 31. Simulink Result of Load Currents

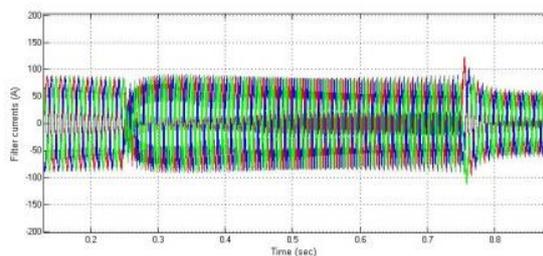Figure 32. Simulink Result of Source Current

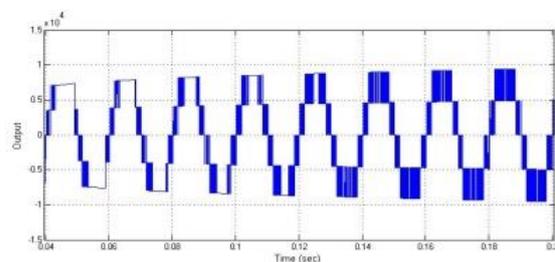Figure 33. Simulink Result of Filter Currents

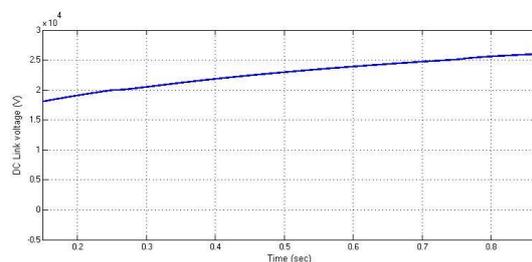Figure 34. Simulink Result of Output for 5-Level lll APF

Figure 35. Simulink Result of DC Link Voltage

Figure 31 represents the load current and Figure 32 represents source current. Figure 33 shows the filter currents induced by the five level DSTSTCOM with Figure 34 showing output of five level DSTATCOM with fixed load. Figure 35 represents the simulink result of DC link voltage.
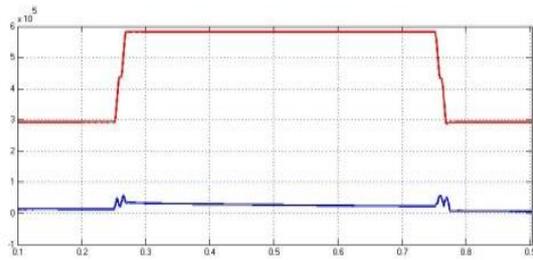
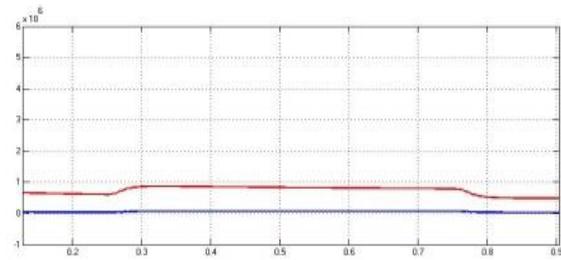Figure 36. Simulink Result of Load Active and Reactive Power

Figure 37. Simulink Result of Source Active and Reactive Power

Figure 36 shows the active and reactive components of load and Figure 37 shows the source active and reactive powers. Red indicates active component of power and blue indicates reactive component. Figure 38 represents the load power factor and Figure 39 represents source power factor.
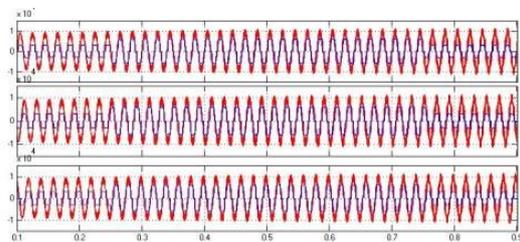

Figure 38. Simulink Result of Load Power Factor
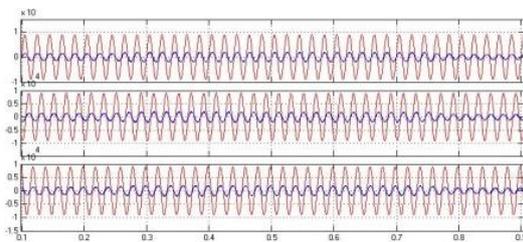

Figure 39. Simulink Result of Source Power Factor
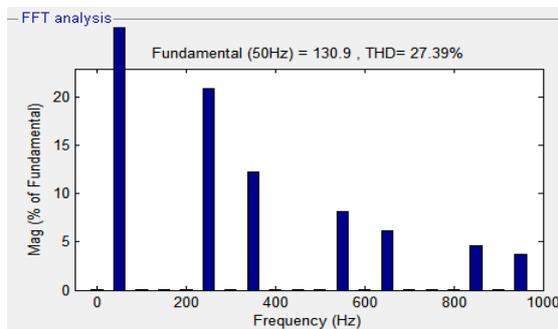
Figure 40. Simulink Result Showing THD in Load Current
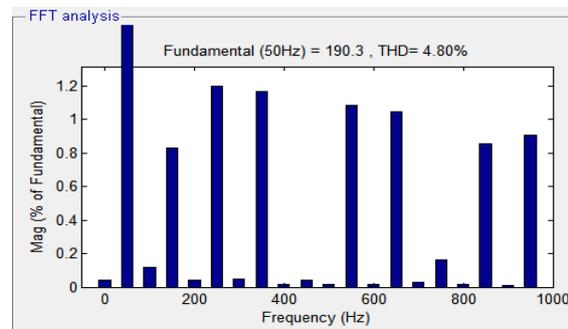
Figure 41. Simulink Result Showing THD in Source Current

Table 2. THD Comparision.

Condition of the system	THD of Source current at PCC
System without APF	26.64 %
System with APF having fixed load	5.19 %
System with APF having variable load	4.80 %

Figure 40 shows the THD in load current for the system without APF which contains 27.39 % of harmonics. Also the source current without APF contains 4.80 % of THD harmonics as shown in Figure 41. With the presence of 5-level DSTATCOM, even though the load is varied, the THD value is maintained under normal values.

Table 2 represents the THD value comparisons for different cases. When there is no DSTATCOM in the system containing non-linear loads, the THD is high and when DSTATCOM is connected the THD drops to acceptable values.

5. Conclusion

Use of 5-level DSTATCOM can mitigate power quality issues in the system which induces compensating currents in to the system. Shunt active power filter DSTATCOM was employed in this paper to compensate the harmonic components in source currents. The basic diagram of 5-level DSTATCOM connected system was discussed along with its operation. This operation of 5-level DSTATCOM was validated while considering different cases like fixed connected load and variable connected load. Models were developed for the system without 5-level DSTATCOM and its results were discussed in detail. Models for the system with 5-level DSTATCOM having fixed and variable loads were also developed using Matlab/Simulink and the results for these cases were discussed in detail showing source voltage, load current, source current. THD values for source currents were tabulated for different cases. Compensating currents produced by the filter, DC link voltage of VSI converter along with power factor were also discussed. THD is found to be within nominal values when 5-level DSTATCOM was connected to the system with non-linear loads. Results validate the application of shunt APF 5-level DSTATCOM for different load conditions.

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