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UPQC With VSI: A Pertinent Tool to Improve Power Quality Using Shunt Compensator

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Abstract: In the distribution system, the load end consists of different kinds of linear and non-linear loads. Use of these non-linear loads invites various power quality issues viz. voltage sag, swell, flicker, imbalance, harmonics, transient, etc. These issues can be mitigated with the help of Passive Filters, Active Filters, Static VAR Compensators (SVC), Flexible A.C Transmission System (FACTS) device, Custom Power Device (CPD), and other devices. Unified Power Quality Conditioner is a CPD used to alleviate power quality issues in the distribution network. UPQC can be divided into series compensator and shunt compensator. Series compensator takes care of voltage related problems (voltage sag, swell, and harmonics in voltage) while shunt compensator takes care of current related problems (current harmonics, neutral current, etc.). The work presented in this paper has been dedicated to improve power quality by alleviating various power quality issues in the distribution network using UPQC WITH VSI USING SHUNT COMPENSATOR. Here, various power quality issues, cause of their production, impact on various power system equipment, and distinct kind of devices used to mitigate them are discussed. The main focus of this work is on UPQC WITH VSI USING SHUNT COMPENSATOR.

Keywords: UPQC, VSI, POWER QUALITY IMPROVEMENT, FACT DEVICE.

I. INTRODUCTION

The primary objective of electric utilities is to provide constant magnitude, sinusoidal power of constant frequency. But in the distribution network, excessive use of non-linear loads leads to degradation of power quality. Power electronic devices (UPS, rectifier, inverter, etc.), arc furnace, LED lights, computer, etc. are the non-linear loads. Lightning and flashover are the natural cause of power quality degradation. Faults taking place in the power system (LG faults, LL faults), failure of any equipment, the connection of the main grid with DG sets (standalone wind farms, solar farms) also reduces the quality of power supplied to the load. The supply of poor power quality to the load causes multiple problems. There may be either voltage related problems (sag, swell, flicker, voltage unbalance, voltage harmonics, interruption, notching) or current related problems (harmonics in load current, neutral current, current imbalance, etc.).

Losses in the line increase when the power of low-quality passes through it. Vibration and noise are produced in the machines. Their efficiency gets reduced due to an increase in losses. Malfunctions of relay, circuit breaker, capacitor banks digital controllers, and data handling equipment due to spurious signals. Losses increases, the temperature inside the machine rises because of heating, insulation of winding may get damage when Negative sequence current flow in the generators and motors. There is interference between the communication system and transmission system due to higher-order harmonics in the power. Polluted power supply to the sensitive loads of the industries reduces the rate of product generation, high economical loss, etc. So, it becomes necessary to maintain a good quality of power across loads [1], [2].

To supply good power, Custom Power Devices are used in the distribution network. Dynamic Voltage Restorer (DVR), Distribution STATCOM, and Unified Power Quality Conditioner are the CPD device. The function of the DVR is to maintain a constant voltage across load during unbalanced voltage conditions. It consists of an inverter that injects voltage in series with the system's voltage. It is connected with the help of a series transformer. The function of the D-STATCOM is to provide load compensation and connected in the shunt of the load. UPQC has the properties of both devices. It can mitigate the voltage related problems as well as current related problems. So it is a single solution to enhance the power quality [1].

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II. UNIFIED POWER QUALITY CONDITIONER (UPQC)

2.1 Introduction

A UPQC, kind of a Custom Power Device (CPD), is proposed as an exhaustive solution to alleviate multiple power quality problems in the distribution system. It is a combination of series and shunt compensators. The series compensator has qualities of Dynamic Voltage Restorer (DVR) and Series Active Power Filter (APF). So, it can mitigate voltage sag, swell, flicker, voltage harmonics, unbalance, transients, etc. The shunt compensator has qualities of D-STATCOM and shunt APF. Thus, it can handle all the current related problems like current harmonics, unbalance, neutral current, etc. and that's the reason that the UPQC is an exhaustive solution. Otherwise, electric utilities have to put no. of pieces of equipment to overcome the power quality problems.

2.2 Construction and Working

The single line representation of UPQC is demonstrated in fig. 2.1. UPQC system consists of two inverters (Series and shunt inverter), series injection transformers, DC link capacitor, and shunt coupling filter (Lsh), ripple filter and LC filter (which works as low pass filter).

The shunt inverter deals with all current related problems like reactive current, harmonics, unbalance, and neutral current. It also maintains a constant voltage across the DC link to its reference value. Another function of shunt inverter is to provide reactive power compensation along with neutral current compensation, load balancing, elimination of harmonics. It is placed across the consumer load and operated in current control mode to inject current at Point of Common Coupling (PCC), so pure sinusoidal current of the desired magnitude can flow through the load.

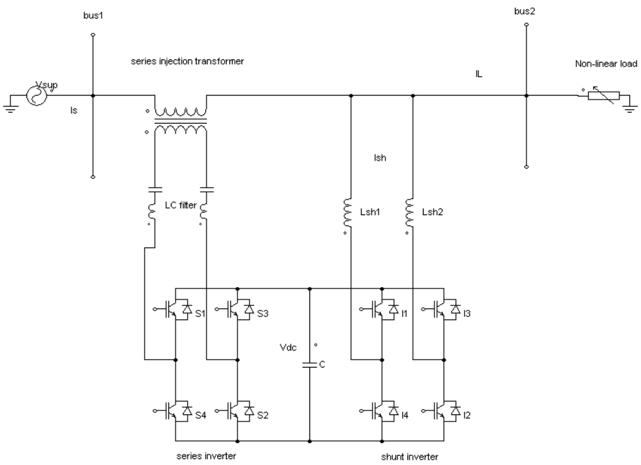

Figure 2.1 Single line UPQC with VSI

The function of the series inverter is to keep PCC voltage insensitive to the source end voltage problems. It is operated in voltage control mode to inject voltage in series with line to achieve a distortion-free sinusoidal voltage of the desired magnitude at the PCC.

Source voltage, source current, load voltage and load current are sensed and given to the controller to produce reference voltage or current signal. Switching signals are generated from the PWM controller by comparing the generated reference signal with the carrier signal and given to switches.

III. SHUNT COMPENSATOR AND CONTROLLER OF UPQC

3.1 Introduction

The power quality (PQ) problems produced in the AC distribution system (due to the use of sensitive equipment in most of the residential, industrial, commercial, and traction applications) can be classified as voltage and current quality problems. As we discussed above that Dynamic Voltage Restorer (DVR), Distribution STATCOM (D-STATCOM), and UPQC are custom power devices (CPD). The D-STATCOM mitigates the current related PQ problems such as increased neutral current, unbalanced current, poor power factor, or poor voltage regulation. The shunt APF mitigates the current harmonics. While the shunt compensator of UPQC does the work of shunt APF and D-STATCOM. This chapter presents the working of shunt compensator, its classification in various categories, its design with its controller, simulation of the shunt compensator in the PSIM environment, and its results.

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3.2 Working of the Shunt Compensator

A shunt compensator takes care of current related PQ issues in the distribution system. It is connected at PCC in shunt (parallel) with the load. A shunt compensator consists of below things:

- A voltage source converter (VSC) or current source converter (CSC)
- Energy storage element (Capacitor C_{DC} for VSC or Inductor L_{DC} for CSC)
- Shunt interfacing inductor (L_{sh})
- RC ripple filter
- Controller

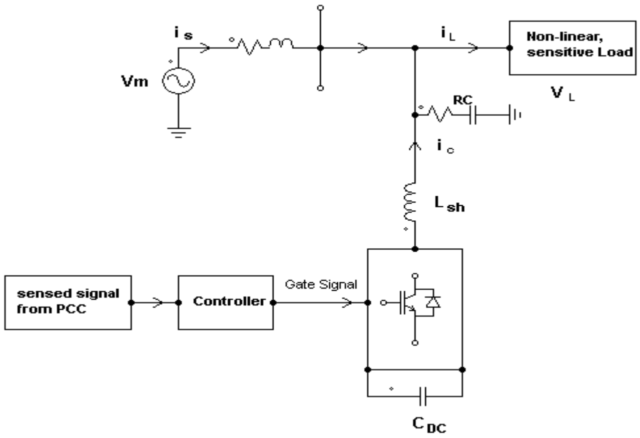

Figure 3.1 Shunt compensator of UPQC

A shunt compensator works on the principle of injecting the signal of opposite polarity and equal magnitude of that signal present at the PCC. The current signal at PCC may have harmonics, higher current in neutral, etc. problems because of non-linear load, fault in the system, or any other reason. To overcome these issues shunt compensator is connected at PCC in parallel with the load. Voltage and current signals are sensed at PCC and given to the controller of the compensator. The controller generates the gate signal according to that and VSC switches operate in that manner. The generated current by VSC is injected and cancel out the harmonics present in the current signal at PCC. In such a way a sinusoidal current signal is obtained at PCC.

3.3 Classification of Shunt Compensator

Shunt compensator of UPQC can be classified in a similar way of classification of UPQC. Below fig.3.2 and fig.3.3 shows the classification of the shunt compensator of UPQC based on the type of converter, their topology, and the supply system.

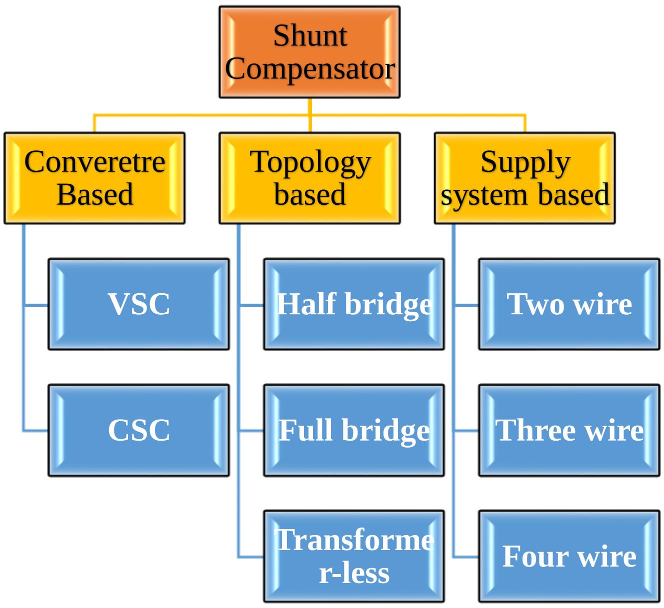

Figure 3.2 Classification of Shunt Compensator of UPQC

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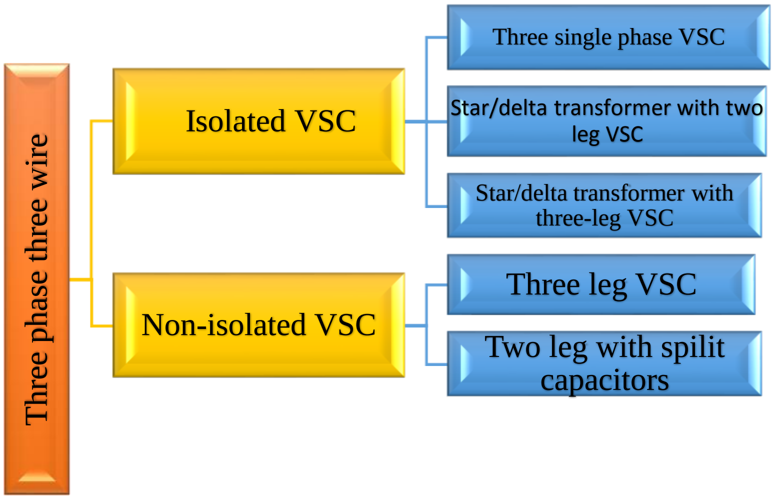

Figure 3.3 Classification of Three-phase Three-wire shunt compensator

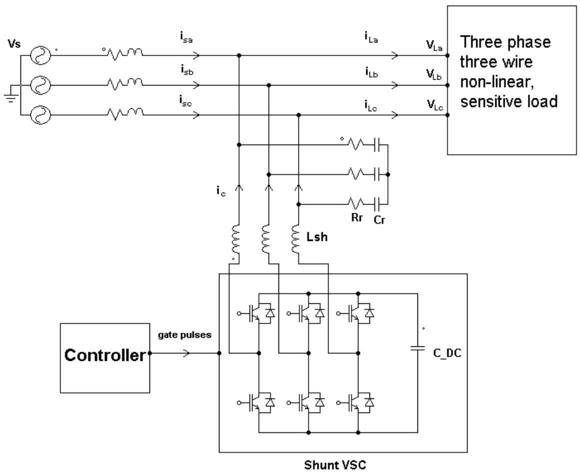

Figure 3.4 Three-Phase Three-wire Shunt Compensator

3.4 Design of Shunt Compensator

To design a shunt compensator, we have to find many parameters like voltage across DC bus, the value of the capacitor connected at there, the magnitude of interfacing inductor. Following equations 1, 2, and are used to find these parameters [1].

- Selection of DC bus voltage:-

  $V_{DC} = (2 * \sqrt{2} * V_{LL}) / (\sqrt{3} * m)$ ------------- (1)

- Selection of DC bus capacitor:-

  $\frac{1}{2} * C_{DC} * (V_{DC}^2 - V_{DCL}^2) = 3\, k_1 VaIt$ ------------- (2)

- Selection of Inductor for VSC

  $L_{sh} = (\sqrt{3} * m * V_{DC}) / (12 * a * f_s * I_{cr.pp})$ ------------ (3)

3.5 Design of Shunt Controller

Steps to design the shunt controller are discussed below. Fig.3.5 shows the shunt controller.

- Sensed load current ILA, i_{Lb}, and i_{Lc} are transformed in the dq0 reference frame using eqn.4.

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$$\begin{bmatrix} i_{Lq} \\ i_{Ld} \\ i_{L0} \end{bmatrix} = \frac{2}{3} \times \begin{bmatrix} \cos\theta & \cos(\theta-\frac{2\pi}{3}) & \cos(\theta+\frac{2\pi}{3}) \\ \sin\theta & \sin(\theta-\frac{2\pi}{3}) & \sin(\theta+\frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \qquad \text{--------- (4)}$$

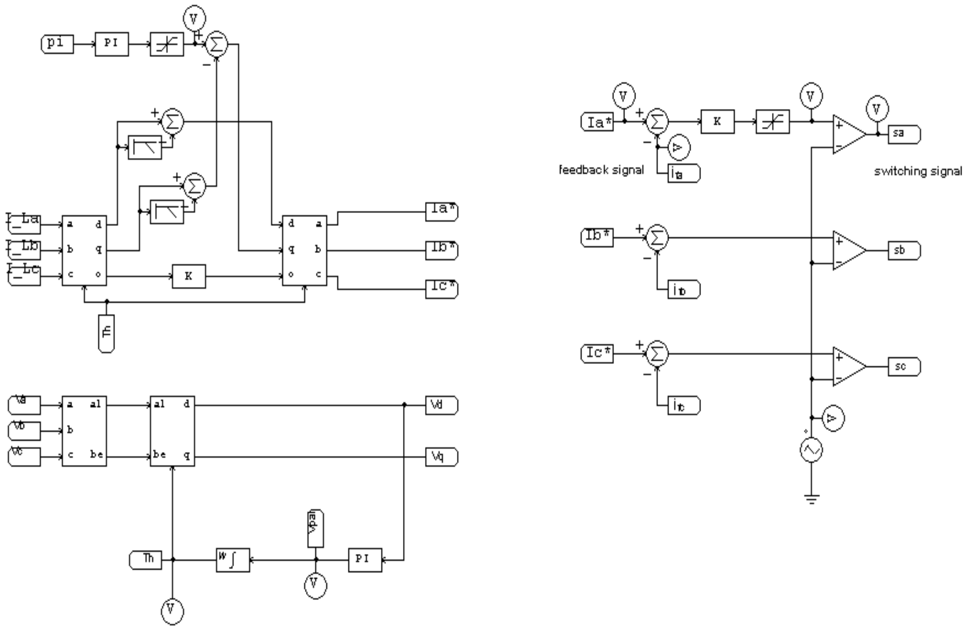

Figure 3.5 Shunt controller

- If the source current has harmonics, then the transformed dq component also has AC and DC component as shown in eqn.13.

$$i_q = i_{qDC} + i_{qAC}$$
$$i_d = i_{dDC} + i_{dAC} \qquad \text{----------- (5)}$$

- With the help of low pass filter (LPF) harmonic components are extracted. AC mains must deliver the mean value of the direct axis component meeting the active power component of current to maintain a constant voltage across the capacitor and meeting the losses of APF.

$$i_d^* = i_{dDC} + i_{Loss} \qquad \text{----------- (6)}$$

- Eqn.14 gives the reference value of current in the dq0 frame, which is transformed in the abc frame using eqn.7.

$$\begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 1 \\ \cos(\theta-\frac{2\pi}{3}) & \sin(\theta-\frac{2\pi}{3}) & 1 \\ \cos(\theta+\frac{2\pi}{3}) & \sin(\theta+\frac{2\pi}{3}) & 1 \end{bmatrix} \times \begin{bmatrix} i_{Lq} \\ i_{Ld} \\ i_{L0} \end{bmatrix} \qquad \text{----------- (7)}$$

- This reference current is given to the comparator to generate switching signal and these are given to the switches of shunt inverter.

3.6 Simulation and Results with Shunt Compensator

Here the shunt compensator is designed for the 50 kVA load with R_L = 6.272 Ω. Table-3.1 is the excel sheet of the parameters for the shunt compensator.

Fig.3.8 shows the FFT analysis of the current waveform shown in figure. Below table 5 shows amplitude and % of 5th, 7th, 11^{th,} and 13th w.r.t fundamental current derived from FFT analysis. Table 5 also shows the comparison of each harmonic component in terms of before connecting the compensator and after connecting the compensator.

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Table 3.1 Parameters for the design of shunt compensator

Shunt APF/D-STATCOM										Design of LC filter					
Before LC filter					After LC filter					L	0.103409	H	0.12	H	
Vs	415	V			Vs	415	V			C	3.49E-06	F	3.01E-06	F	
Vsa	238	V	8.95%	THD	Vsa	237.65	V	8.83%	THD						
Isa	70	A	25.50%	THD	Isa	69.5	A	24.35%	THD	V_DC	677.6922	700	V		
p.f	0.953				p.f	0.954				C_DC	0.309553	F			
V_dc	546	V			V_dc	545.9	V			Ish	69.5	A			
I_dc	87	A			I_dc	87	A			Lsh	0.001173	H			
P_dc	50246.16	W			P_dc	49974.73	W								
P_ac	47630.94	W			P_ac	47270.72	W								
S	49980	VA			S	49550.03	VA								
Q	15142.46	VAR			Q	14855.42	VAR								
R_L	6.272	Ω			I_rip	5.06%									
I	69.90273	A			V_rip	4.58%									
Z	3.427625	Ω			m	1									
Rs	0.001714	Ω													
Ls	0.00054	H													
I_rip	17.24%														
V_rip	17.40%														
m	1				fs	10000									
					a	1.2									
					ripple in I:	10%									
					t	0.08	s								

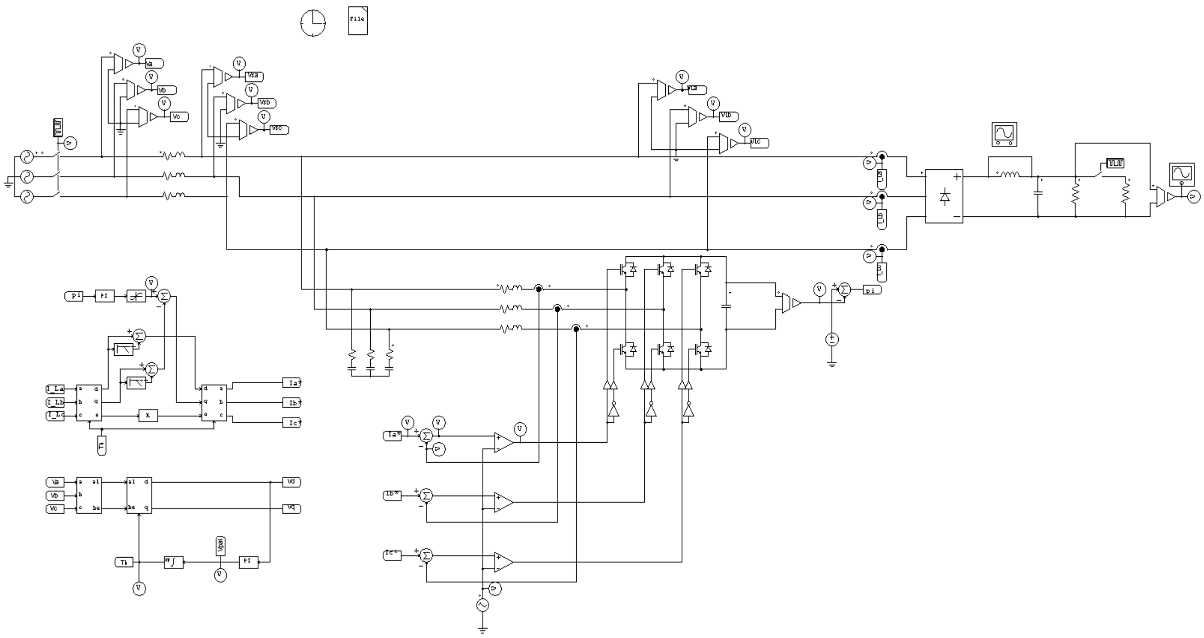
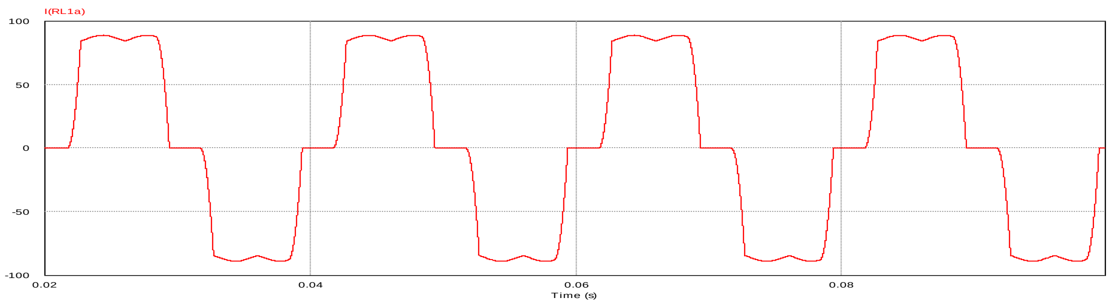


Figure 3.7 Three-phase three-wire system with Shunt Compensator



Time	from	0.2 s	Fundamental Frequency	50 HZ
Time	to	1 s	I $_{(RL1a)}$	24.32 %
R_L		6.272 Ω	I $_{(RL1a)}$ vs. Vsa (P.F)	0.954

Figure 3.8 Current at PCC before connecting compensator

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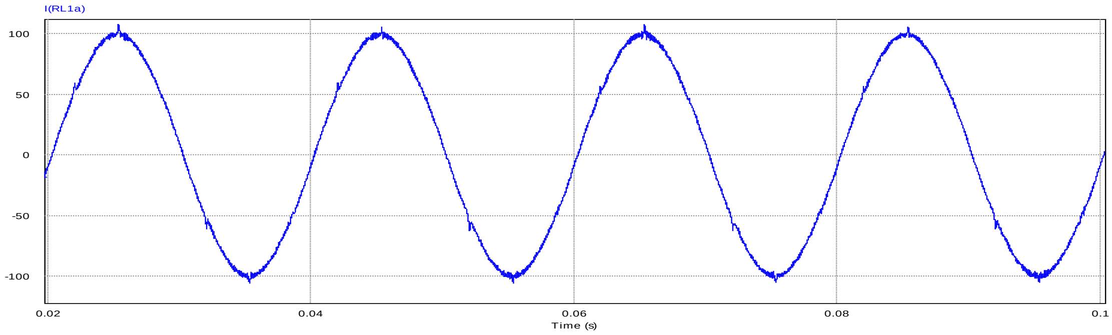

Time	from	0.2 s		Fundamental Frequency	50 HZ
Time	to	1 s		I (RL1a)	1.91 %
I (RL1a) vs. Vsa (p.f.)		0.988			

Figure 3.9 Current at PCC after connecting compensator

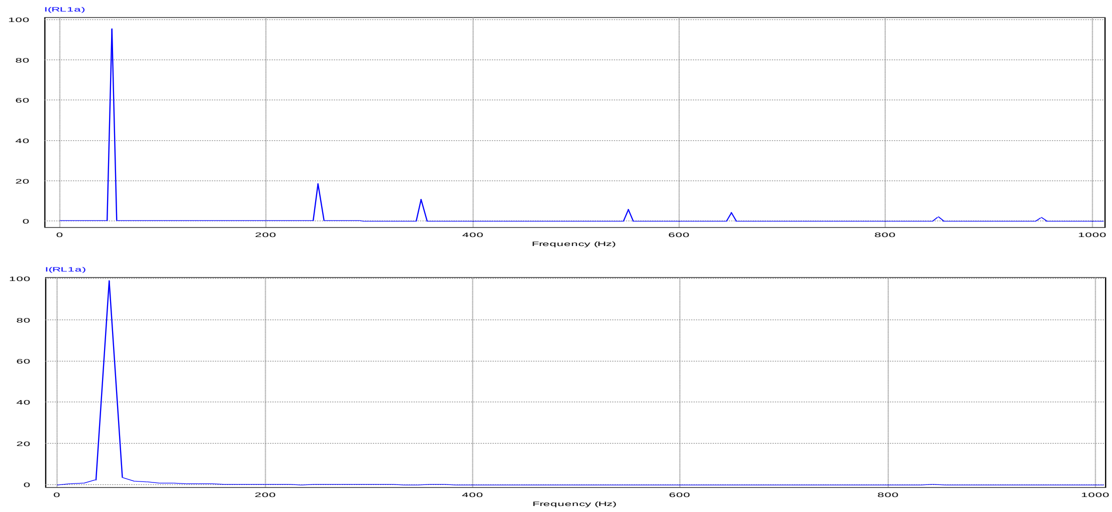

Figure 3.10 FFT Analysis

Table 3.2 Harmonic analysis for shunt compensator

	Amplitude		%	
	Before	After	Before	After
fundament	89.63	96.4		
5th	20.19	0.42	22.53	0.44
7th	9.17	0.21	10.23	0.22
11th	5.95	0.25	6.64	0.26
13th	3.26	0.16	3.64	0.17
			24.32	1.91

From data shown in Table 3.2, we can conclude that the compensator is successfully reducing the harmonics. THD in current at PCC are reduced to 1.91% from 24.32%.

3.6.1 Robustness Test of Shunt Compensator

To check the robustness of the shunt compensator, the load at the terminal is increased to 200%.

From the current waveform, we can conclude that shunt compensator is also working effectively during dynamics even though the load is increased to 200%.

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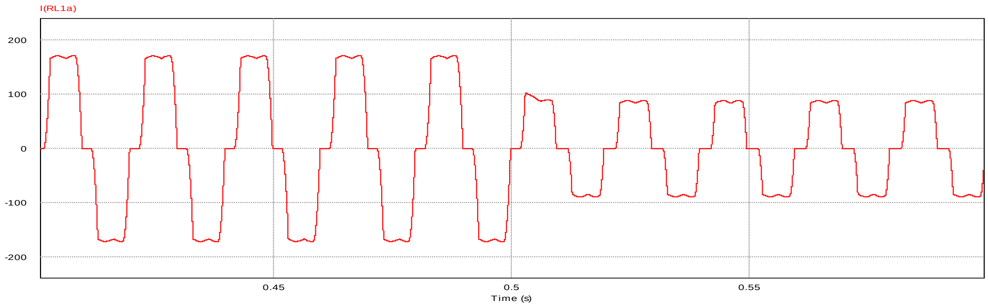
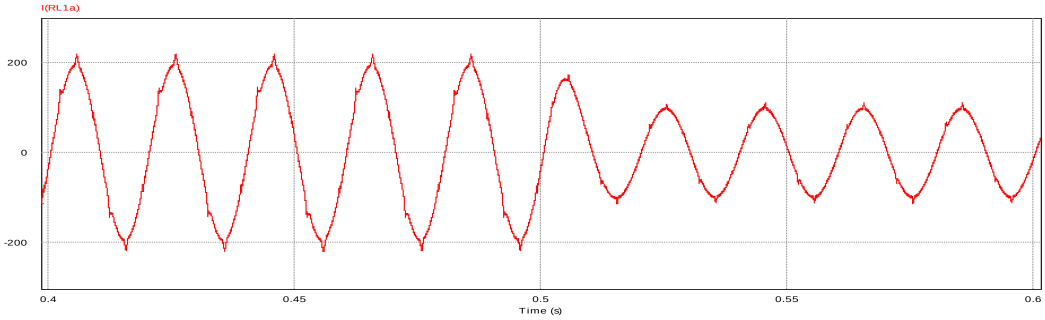


Time from	0.4 s	Fundamental Frequency	50 HZ
Time to	0.6 s	I (RL1a)	(0.4 s to 0.5 s) = 21.49 %
I (RL1a) vs. Vsa (p.f)	0.90		(0.5 s to 0.6 s) = 24.32 %
		R_L	6.272 ‖ 6.272 = 3.136 Ω

Figure 3.11 Current at PCC with 200% of load without the controller



Time from	0.4 s	Fundamental Frequency	50 HZ
Time to	0.6 s	I (RL1a)	(0.4 s to 0.5 s) = 2.91 %
I (RL1a) vs. Vsa (p.f)	0.93		(0.5 s to 0.6 s) = 3.97 %

Figure 3.12 Current at PCC with 200% of load with the controller

IV. CONCLUSION

In this paper, the working of shunt compensator, its classification in various categories, its design with its controller, simulation of the shunt compensator in the PSIM environment, and its results has been found. the shunt compensator is designed for the 50 kVA load with R_L = 6.272 Ω. As per table 5, amplitude and % of 5^{th}, 7^{th}, $11^{th,}$ and 13^{th} w.r.t fundamental current derived from FFT analysis. Also, the comparison of each harmonic component in terms of before connecting the compensator and after connecting the compensator we can conclude that the compensator is successfully reducing the harmonics. THD in current at PCC are reduced to 1.91% from 24.32%. From the current waveform, we can conclude that shunt compensator is also working effectively during dynamics even though the load is increased to 200%. Without connecting compensator, harmonics in current from 0.4 sec to 0.6 sec is near about 25%. While after using compensator value of harmonic in current from 0.4 sec to 0.6 sec is near about 3%.

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