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STUDY OF HYBRID DSTATCOM TOPOLOGY FOR MITIGATION OF HARMONICS IN DISTRIBUTION SYSTEM

A Thesis Submitted

In partial fulfilment of the requirements for the award of the degree of

MASTER OF ENGINEERING

In

ELECTRICAL ENGINEERING

By

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CERTIFICATE

This is to certify that this dissertation titled "Study of hybrid DSTATCOM topology for mitigation of harmonics in distribution system" is being submitted by **Mr. MOIDUL ISLAM LASKAR,** with **Roll No. 002110802022** in partial fulfilment of the requirements for the award of the degree of **Master of Engineering in Electrical Engineering** from JADAVPUR UNIVERSITY, KOLKATA, WEST BENGAL, has been carried out by him under my guidance and supervision. The project, in my opinion, is worthy of its acceptance.

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APPROVAL CERTIFICATE *

The ***Master of Engineering in Electrical Engineering in Power Systems*** *has approved the thesis above as a creditable study. The presentation met the satisfactory requirements to be accepted as a prerequisite to the degree to which it was submitted. The approval does not necessarily mean that the undersigned endorse or approve any statement, opinion, or conclusion made in the thesis, but only approve it for the purpose for which it was submitted.*

Committee on Final

Examination for

Evaluation of the Thesis

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DECLARATION

I certify that the work shall be performed exclusively by the applicant, unless it has been recognized in good time. This thesis constitutes a summary of my previous research, which was never fully or partly presented in order to qualify for the next academic award. Moreover, the content of this thesis is based on work that has been accomplished since the entry into force of the approved research program.

The work was done under the guidance of (Dr.) Sudipta Debnath, Professor, Electrical Engineering Department of Jadavpur University, Kolkata.

The information and data given in the report is authentic to the best of my knowledge.

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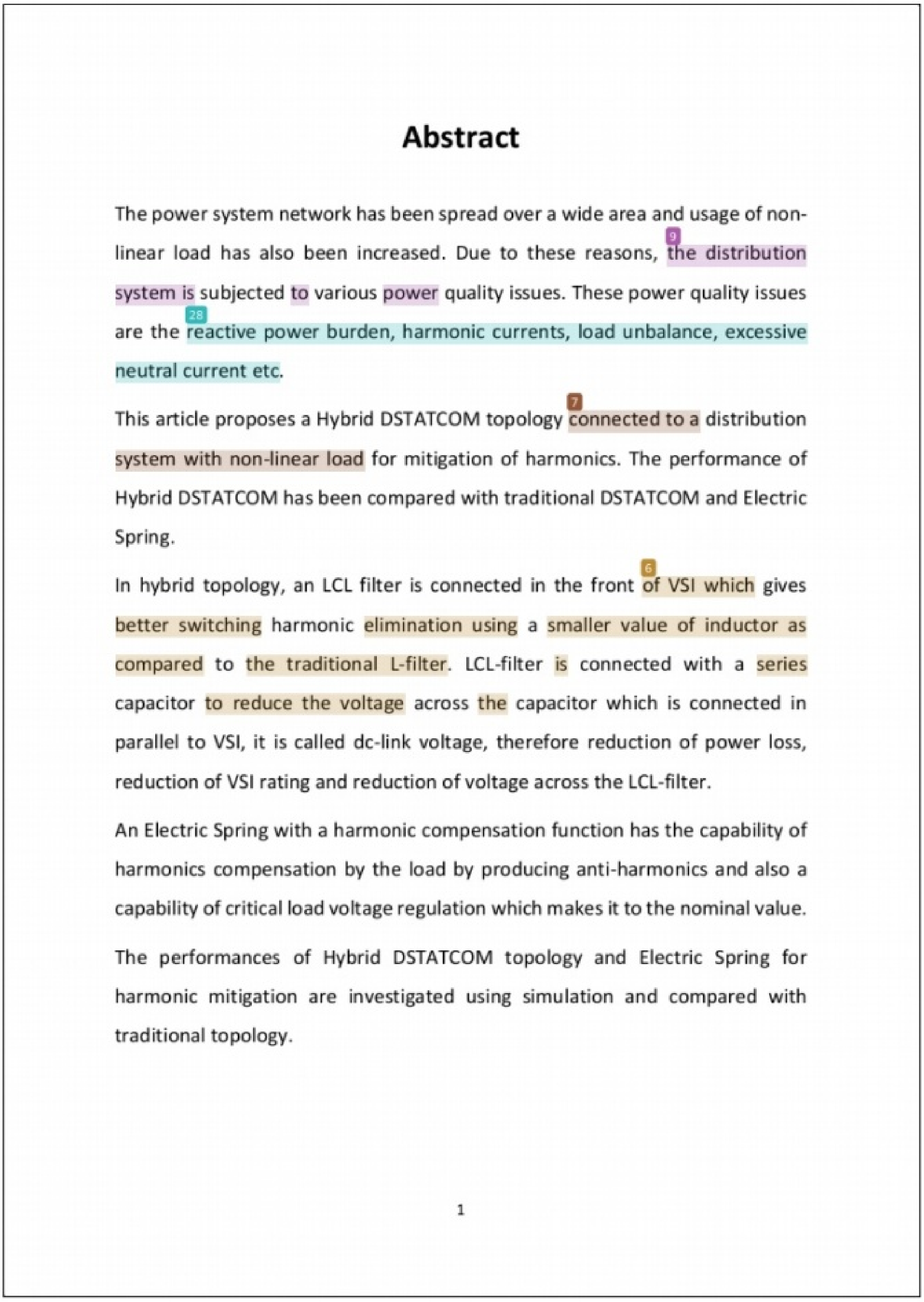

Abstract

The power system network has been spread over a wide area and usage of non-linear load has also been increased. Due to these reasons, [9] the distribution system is subjected to various power quality issues. These power quality issues are the [28] reactive power burden, harmonic currents, load unbalance, excessive neutral current etc.

This article proposes a Hybrid DSTATCOM topology [7] connected to a distribution system with non-linear load for mitigation of harmonics. The performance of Hybrid DSTATCOM has been compared with traditional DSTATCOM and Electric Spring.

In hybrid topology, an LCL filter is connected in the front [6] of VSI which gives better switching harmonic elimination using a smaller value of inductor as compared to the traditional L-filter. LCL-filter is connected with a series capacitor to reduce the voltage across the capacitor which is connected in parallel to VSI, it is called dc-link voltage, therefore reduction of power loss, reduction of VSI rating and reduction of voltage across the LCL-filter.

An Electric Spring with a harmonic compensation function has the capability of harmonics compensation by the load by producing anti-harmonics and also a capability of critical load voltage regulation which makes it to the nominal value.

The performances of Hybrid DSTATCOM topology and Electric Spring for harmonic mitigation are investigated using simulation and compared with traditional topology.

Table of Contents

List of Abbreviations

PQ	Power quality
VSC	Voltage source convertor
DG	Distributed generation
PCC	Point of common coupling
PLC	Programmable logic controllers
ASD	Adjustable speed drives
SPWM	Sinusoidal pulse width modulation
TCR	Thyristor controlled reactor
TSC	Thyristor switched capacitor
FC	Fixed capacitor
SVC	Static power unit Compensator
DSTATCOM	Distribution Static Compensator
HCC	Hysteresis current controller

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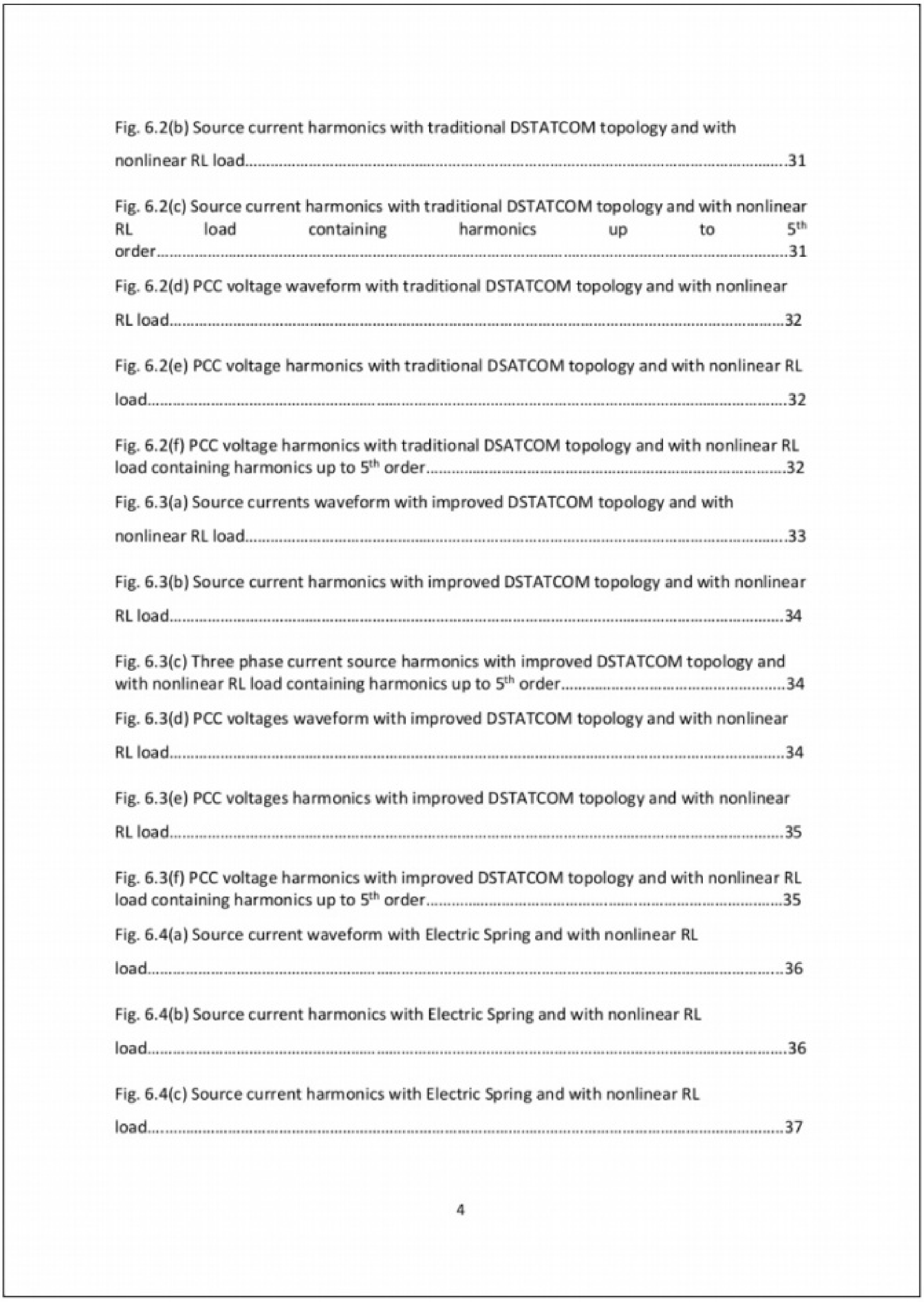

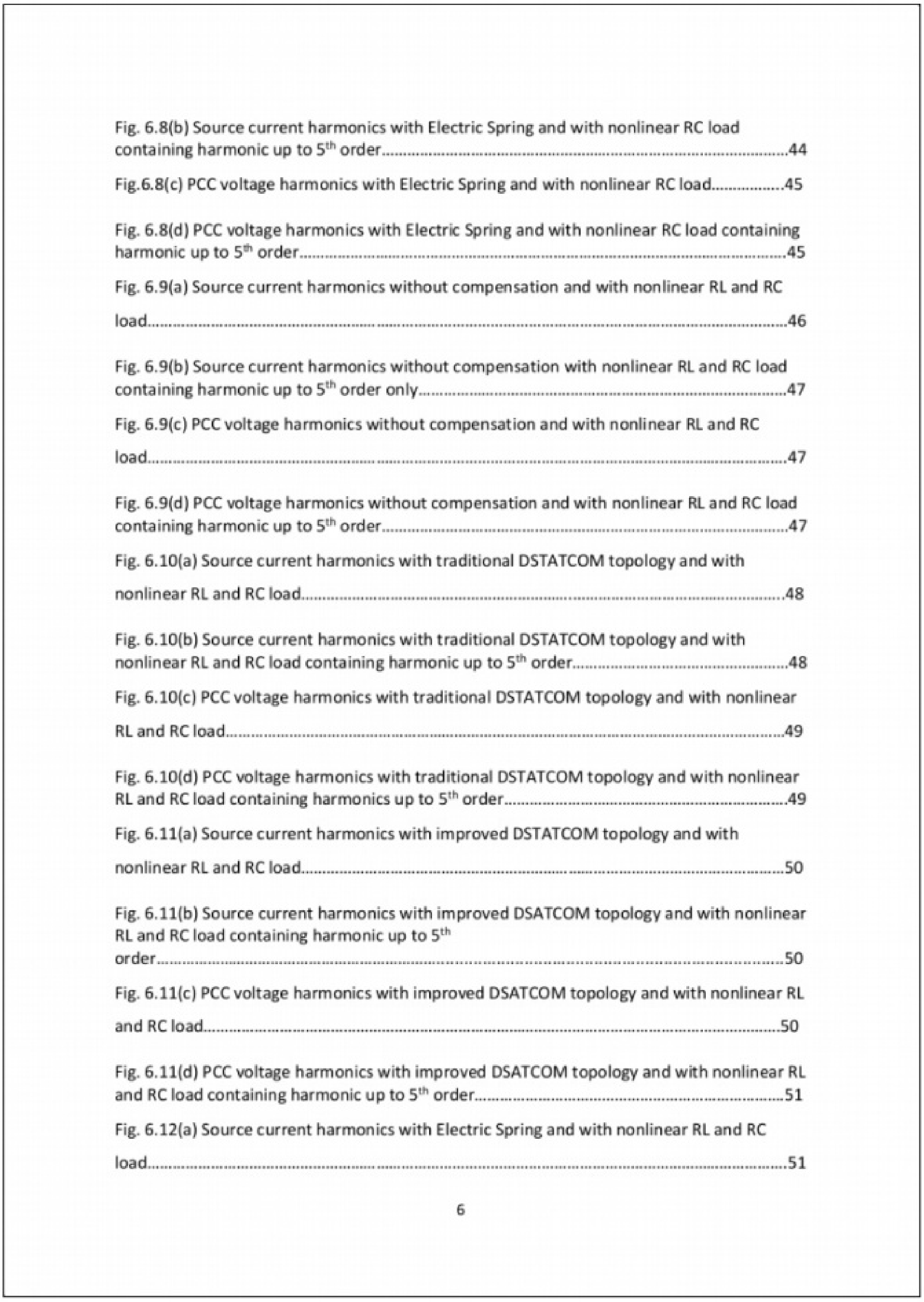

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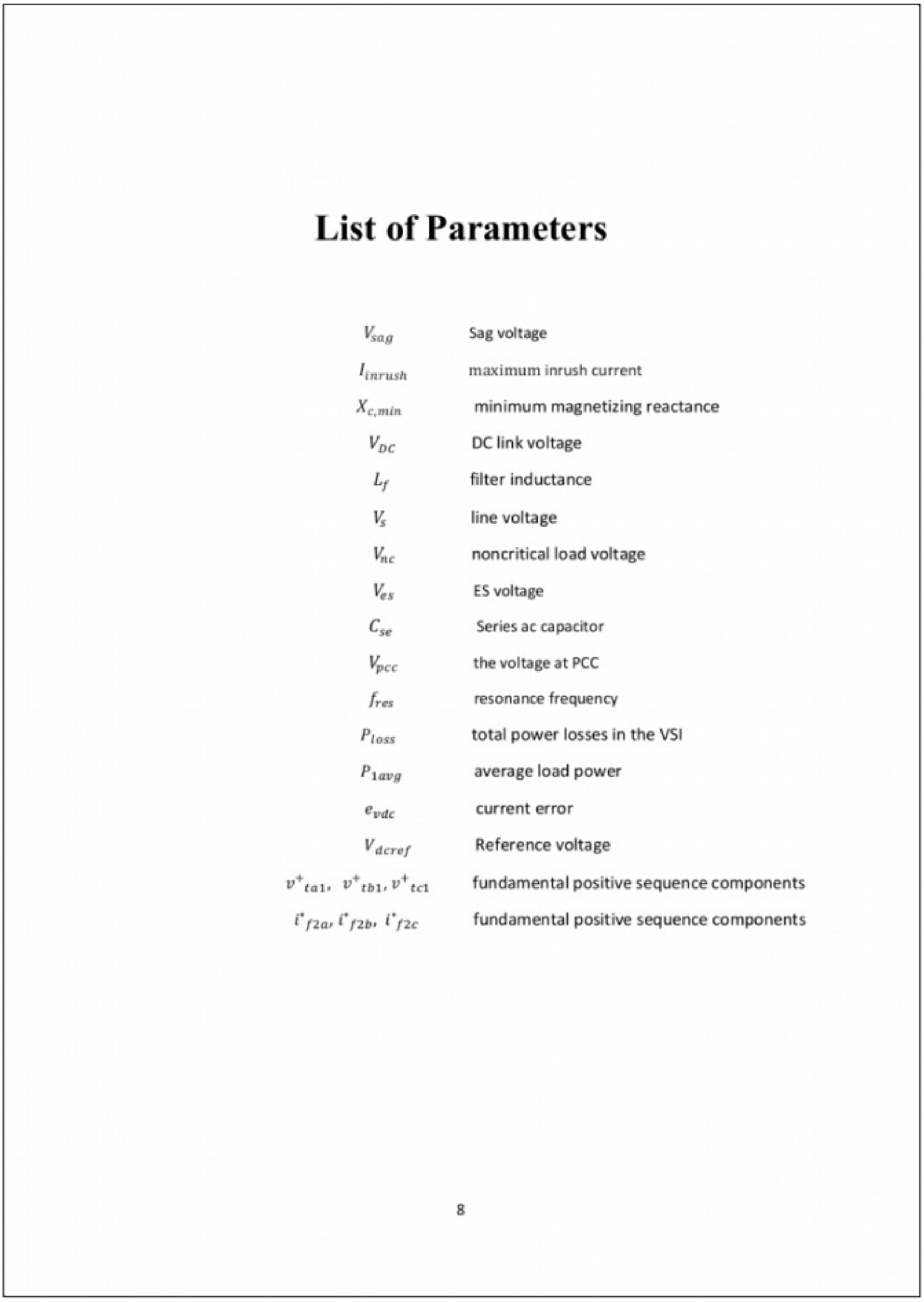


List of Parameters

V_{sag}	Sag voltage
I_{inrush}	maximum inrush current
$X_{c,min}$	minimum magnetizing reactance
V_{DC}	DC link voltage
L_f	filter inductance
V_s	line voltage
V_{nc}	noncritical load voltage
V_{es}	ES voltage
C_{se}	Series ac capacitor
V_{pcc}	the voltage at PCC
f_{res}	resonance frequency
P_{loss}	total power losses in the VSI
P_{1avg}	average load power
e_{vdc}	current error
V_{dcref}	Reference voltage
$v^{+}_{ta1},\ v^{+}_{tb1}, v^{+}_{tc1}$	fundamental positive sequence components
$i^{*}_{f2a}, i^{*}_{f2b}, i^{*}_{f2c}$	fundamental positive sequence components

Chapter 1

Introduction

1.1 Overview

Common power quality problems nowadays are poor voltage regulation, poor power factor, harmonics, unbalanced loading, excess neutral current, etc. Harmonic intrusion is mainly due to the non-linear loads and electronic devices. The presence of inductive load causes the reduction of power factor and poor voltage regulation.

To solve these problems in systems there are many devices viz DVR, UPQC etc. have been used. For load current-based power quality issues a shunt-connected device DSTATCOM is used. It injects compensating current for various issues viz. voltage sag, harmonics voltage swell, poor power factor, unbalanced loading, poor voltage regulation etc.

DSTATCOM is composed of a voltage source inverter (VSI) that gives the electrical phenomenon. It can supply the required reactive power at PCC of the distribution system for compensating the reactive power. Earlier, thyristor-based systems were used to mitigate the harmonics, compensate for the reactive power and reduction of the voltage flicker. But there are some problems with thyristor-based systems, these are the possibility of occurrence of resonance, large in size and fixed compensation. To solve these problems DSTATCOM is used. It is used for solving the problems of harmonic distortions, voltage fall/dip, flickers, swell etc. It mitigates the harmonics by injecting harmonics compensation current in the system supplied. Recently, for compensation for the power quality issues of critical loads inverter-based technology, Electric Spring (ES) has been used using various control methods. Electric Spring can mitigate the harmonic of critical loads using non-critical loads. Non-critical load is connected to the ES called a smart load scheme which can compensate under voltage and overvoltage conditions. Electric Springs with improved control schemes can compensate for the harmonics and maintain the nominal value of critical load voltage. The performance for voltage regulation and harmonics compensation ES has been investigated through simulation studies.

1.2 Power quality

The ability of Power quality is to supply the effective power to the consumers and consume the power by equipment which supplied to the line. Power quality is the measure and enhancement of sinusoidal waveforms at the rated frequency and rated voltage. Modern equipment is more sensitive to any changes in power quality.

Power electronic equipments are rather more sensitive instruments which are less tolerant to disturbances in voltage quality. The common perpetrators are voltage dips, the interruption short interruptions etc. The reason behind equipment malfunctions are the high-frequency transients.

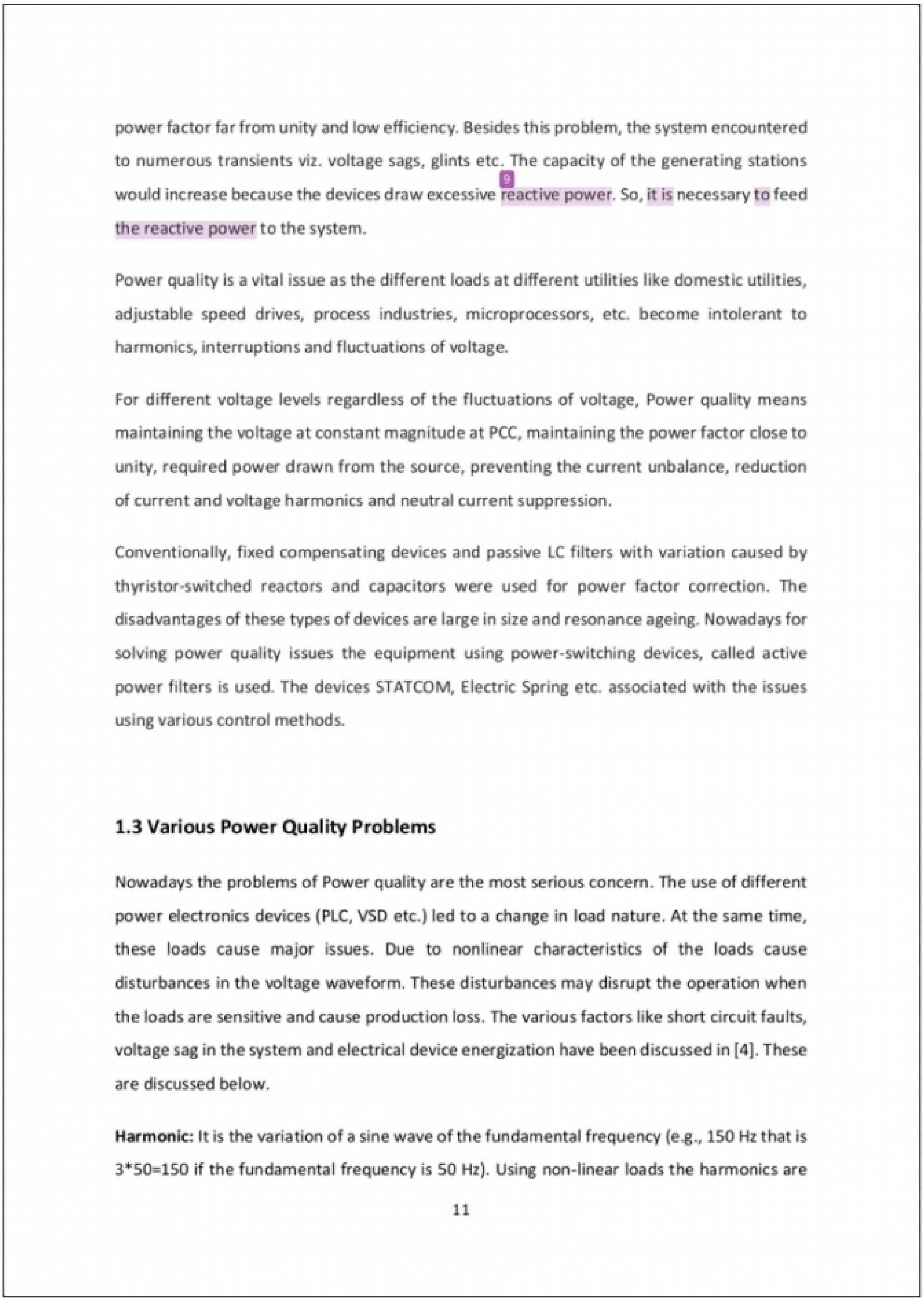
Equipments are used for low-power circuits and high-power equipment that produces current disturbances and broad spectrum of distortion. This indicates the harmonic distortion in the system.

Also, the sources of disturbance (waveform distortions) are energy-efficient equipments like energy-saving lamps, Adjustable speed drives etc., that are very sensitive to the disturbances. These issues become economic issues when these issues make the barrier to large-scale integration sources and equipments.

Due the several power quality problems there is a need for quality indicators for supplying good quality of power to the customers.

With the use of power switching devices, viz thyristors, GTOs, IGBTs etc., the controlling of power has become advantageous. These types of controllers are used to supply the power to loads, viz. HVDC systems, PC power providers, furnaces, etc.

Due to non-linear loads, the electronic devices draw the harmonics current and reactive power from the supply which causes unbalance, excessive neutral currents in the supply,



power factor far from unity and low efficiency. Besides this problem, the system encountered to numerous transients viz. voltage sags, glints etc. The capacity of the generating stations would increase because the devices draw excessive [9] reactive power. So, it is necessary to feed the reactive power to the system.

Power quality is a vital issue as the different loads at different utilities like domestic utilities, adjustable speed drives, process industries, microprocessors, etc. become intolerant to harmonics, interruptions and fluctuations of voltage.

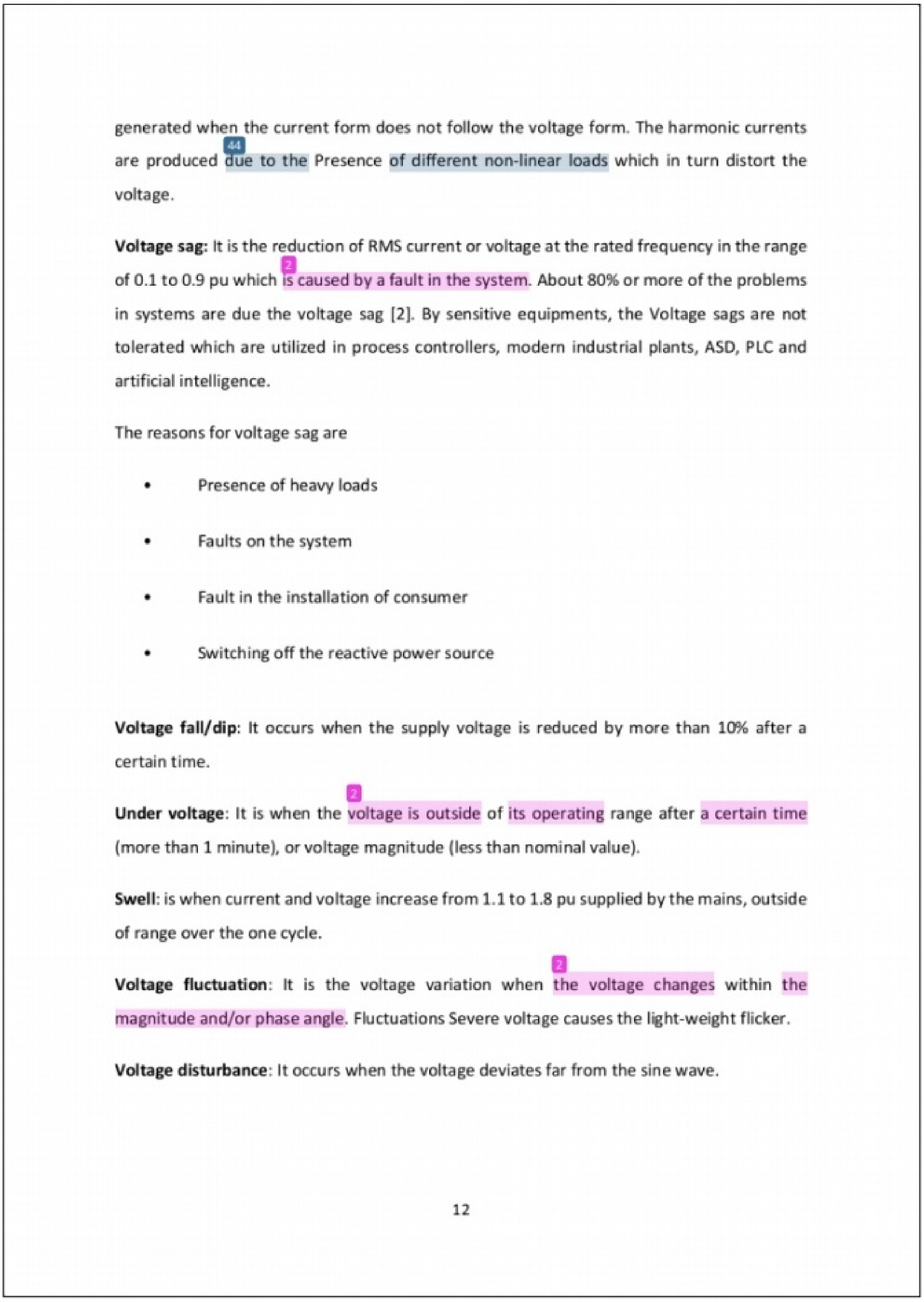
For different voltage levels regardless of the fluctuations of voltage, Power quality means maintaining the voltage at constant magnitude at PCC, maintaining the power factor close to unity, required power drawn from the source, preventing the current unbalance, reduction of current and voltage harmonics and neutral current suppression.

Conventionally, fixed compensating devices and passive LC filters with variation caused by thyristor-switched reactors and capacitors were used for power factor correction. The disadvantages of these types of devices are large in size and resonance ageing. Nowadays for solving power quality issues the equipment using power-switching devices, called active power filters is used. The devices STATCOM, Electric Spring etc. associated with the issues using various control methods.

1.3 Various Power Quality Problems

Nowadays the problems of Power quality are the most serious concern. The use of different power electronics devices (PLC, VSD etc.) led to a change in load nature. At the same time, these loads cause major issues. Due to nonlinear characteristics of the loads cause disturbances in the voltage waveform. These disturbances may disrupt the operation when the loads are sensitive and cause production loss. The various factors like short circuit faults, voltage sag in the system and electrical device energization have been discussed in [4]. These are discussed below.

Harmonic: It is the variation of a sine wave of the fundamental frequency (e.g., 150 Hz that is 3*50=150 if the fundamental frequency is 50 Hz). Using non-linear loads the harmonics are



generated when the current form does not follow the voltage form. The harmonic currents are produced due to the Presence of different non-linear loads which in turn distort the voltage.

Voltage sag: It is the reduction of RMS current or voltage at the rated frequency in the range of 0.1 to 0.9 pu which is caused by a fault in the system. About 80% or more of the problems in systems are due the voltage sag [2]. By sensitive equipments, the Voltage sags are not tolerated which are utilized in process controllers, modern industrial plants, ASD, PLC and artificial intelligence.

The reasons for voltage sag are

- Presence of heavy loads
- Faults on the system
- Fault in the installation of consumer
- Switching off the reactive power source

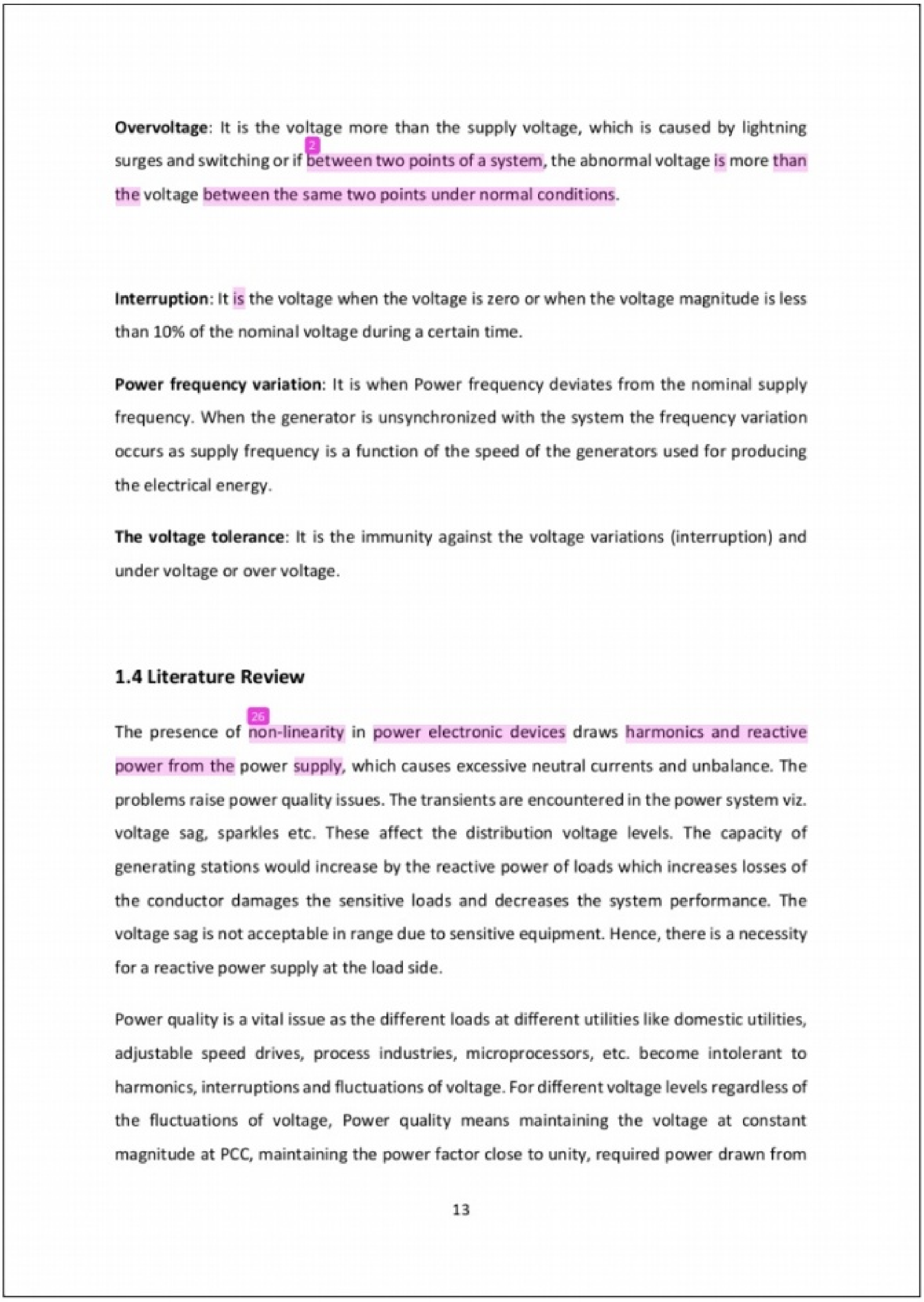
Voltage fall/dip: It occurs when the supply voltage is reduced by more than 10% after a certain time.

Under voltage: It is when the voltage is outside of its operating range after a certain time (more than 1 minute), or voltage magnitude (less than nominal value).

Swell: is when current and voltage increase from 1.1 to 1.8 pu supplied by the mains, outside of range over the one cycle.

Voltage fluctuation: It is the voltage variation when the voltage changes within the magnitude and/or phase angle. Fluctuations Severe voltage causes the light-weight flicker.

Voltage disturbance: It occurs when the voltage deviates far from the sine wave.



Overvoltage: It is the voltage more than the supply voltage, which is caused by lightning surges and switching or if [2] between two points of a system, the abnormal voltage is more than the voltage between the same two points under normal conditions.

Interruption: It is the voltage when the voltage is zero or when the voltage magnitude is less than 10% of the nominal voltage during a certain time.

Power frequency variation: It is when Power frequency deviates from the nominal supply frequency. When the generator is unsynchronized with the system the frequency variation occurs as supply frequency is a function of the speed of the generators used for producing the electrical energy.

The voltage tolerance: It is the immunity against the voltage variations (interruption) and under voltage or over voltage.

1.4 Literature Review

The presence of [26] non-linearity in power electronic devices draws harmonics and reactive power from the power supply, which causes excessive neutral currents and unbalance. The problems raise power quality issues. The transients are encountered in the power system viz. voltage sag, sparkles etc. These affect the distribution voltage levels. The capacity of generating stations would increase by the reactive power of loads which increases losses of the conductor damages the sensitive loads and decreases the system performance. The voltage sag is not acceptable in range due to sensitive equipment. Hence, there is a necessity for a reactive power supply at the load side.

Power quality is a vital issue as the different loads at different utilities like domestic utilities, adjustable speed drives, process industries, microprocessors, etc. become intolerant to harmonics, interruptions and fluctuations of voltage. For different voltage levels regardless of the fluctuations of voltage, Power quality means maintaining the voltage at constant magnitude at PCC, maintaining the power factor close to unity, required power drawn from the source, preventing the current unbalance, reduction of current and voltage harmonics and neutral current suppression.

Conventionally, fixed compensating devices and passive LC filters with variation caused by thyristor-switched reactors and capacitors were used for power factor correction. The disadvantages of this type of device are large in size, and resonance ageing. For solving power quality issues the equipment using power switching devices, called active power filters is used. Among these devices a promising device for such quality improvement is STATCOM.[1]

STATCOM can be renamed as DSTATCOM as a result of its application in the distribution system. It is used in the system for improving power factor and voltage regulation. It is based on the thyristor-based voltage source inverter and is used for harmonic control, voltage stabilization, correction of power factor, and several solutions to power quality issues.

Non-linear loads consume large power drawing the lagging power factor currents. Therefore it reduces the flow of active power to the system which increases the feeder losses and affects the voltage profile [2- 3].

The most significant power quality issue is the Voltage sag faced by several utilities.About 80% or more of the problems in systems are due the voltage sag [2]. By sensitive equipments, the Voltage sags are not tolerated which are utilized in process controllers, modern industrial plants, ASD, PLC and artificial intelligence [2-3].

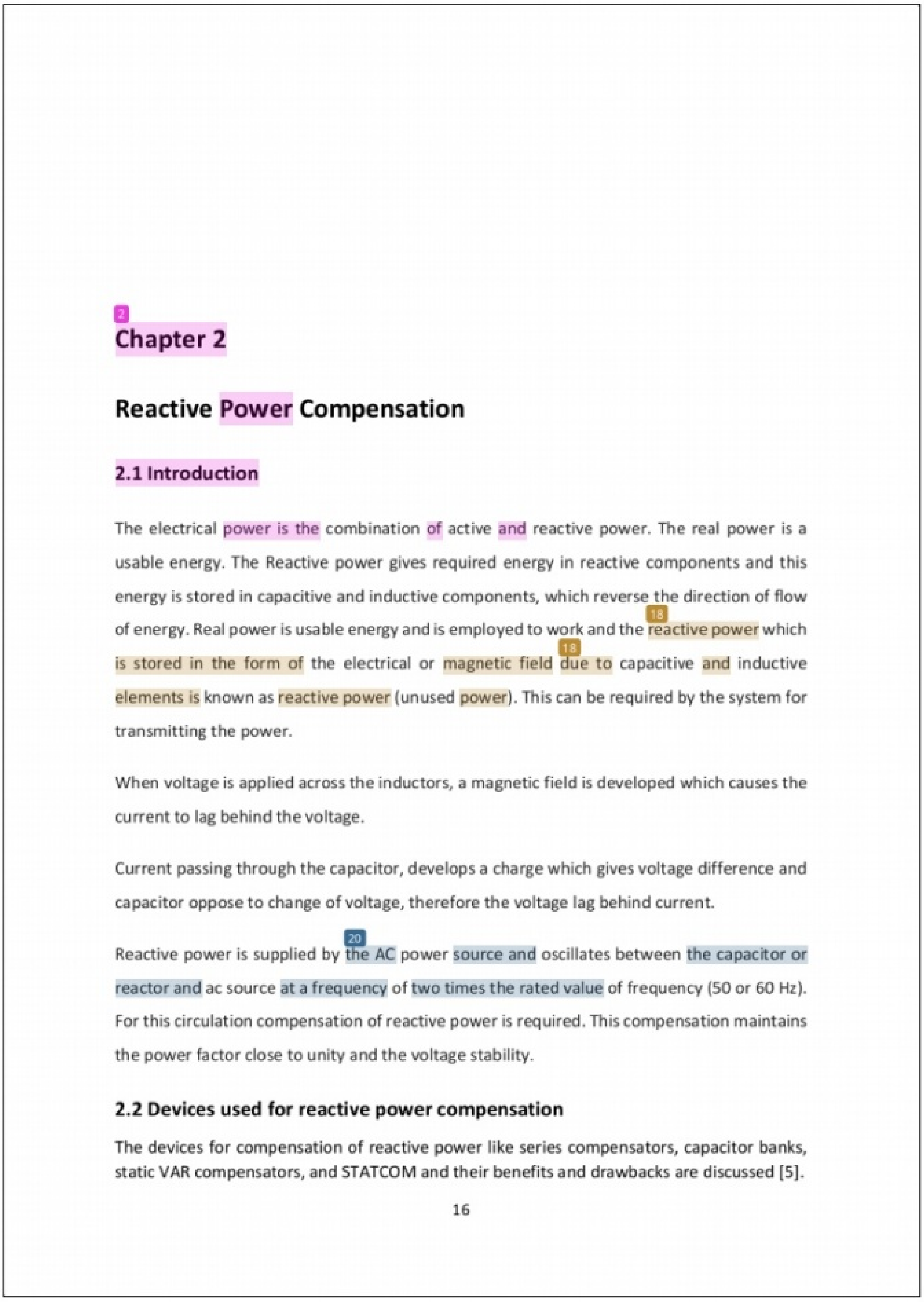
The various factors like short circuit faults, voltage sag in the system and electrical device energization have been discussed in [4]. The devices for compensation of reactive power like series compensators, capacitor banks, static VAR compensators, and STATCOM and their benefits and drawbacks are discussed [5]. A PWM-Based STATCOM with various Control methods and modelling has been explained in [6],[7],[8],[9]. The various control methods of the STATCOM and its simulation have been explained, and using traditional, control VSC-based STATCOM has been discussed in [10-11].

In a 3-phase distributed system the inverter interfacing with various types of filter design has been explained [12-13]. The control method of DSTATCOM using Current controller, Voltage controller, voltage source converter (VSC), DC link voltage control, PLL, SPWM and abc/dq and dq/abc transformation have been explained in [14-15]. The design of the DC link is explained [12]. This DC link technique enables DC link voltage [13]. Various types of filters like L, LC, LCL etc. are discussed in [16],[17],[18].

Electric spring (ES) has been used for compensation of power quality problems of critical loads [19] by using several control methods [20]. The performance of ES is investigated in [20] for harmonic mitigation and voltage regulation. ES with harmonic compensation function has been simulated. Results show that ES is capable of compensating harmonics of sensitive load voltage caused due to system voltage distortion. ES can regulate the sensitive load voltage by changing the power flow voltage through the non-sensitive load. To achieve this, injected voltage by ES which is quadrature with current of non-sensitive load provides the reactive power to the system reported in [19],[21].

The application of ESs in systems to improve power quality and regulate voltage has been demonstrated in [22, 23]. In [24, 25], the distribution losses in the systems are reduced using the controller. The ES can compensate the neutralize the negative and zero sequence current load imbalance issues [26].In ES operation for minimizing the active power output, several control methods are reported in [27, 28].

The objective of this work is to improve the power quality in the system using hybrid DSTATCOM and Electric Spring by compensating the required amount of current to the system and maintaining the voltage to the nominal value. The operation of hybrid DSTATCOM and Electric Spring for harmonic mitigation with connected nonlinear loads in the distribution system has been discussed and demonstrated through simulation results.



Chapter 2

Reactive Power Compensation

2.1 Introduction

The electrical power is the combination of active and reactive power. The real power is a usable energy. The Reactive power gives required energy in reactive components and this energy is stored in capacitive and inductive components, which reverse the direction of flow of energy. Real power is usable energy and is employed to work and the reactive power which is stored in the form of the electrical or magnetic field due to capacitive and inductive elements is known as reactive power (unused power). This can be required by the system for transmitting the power.

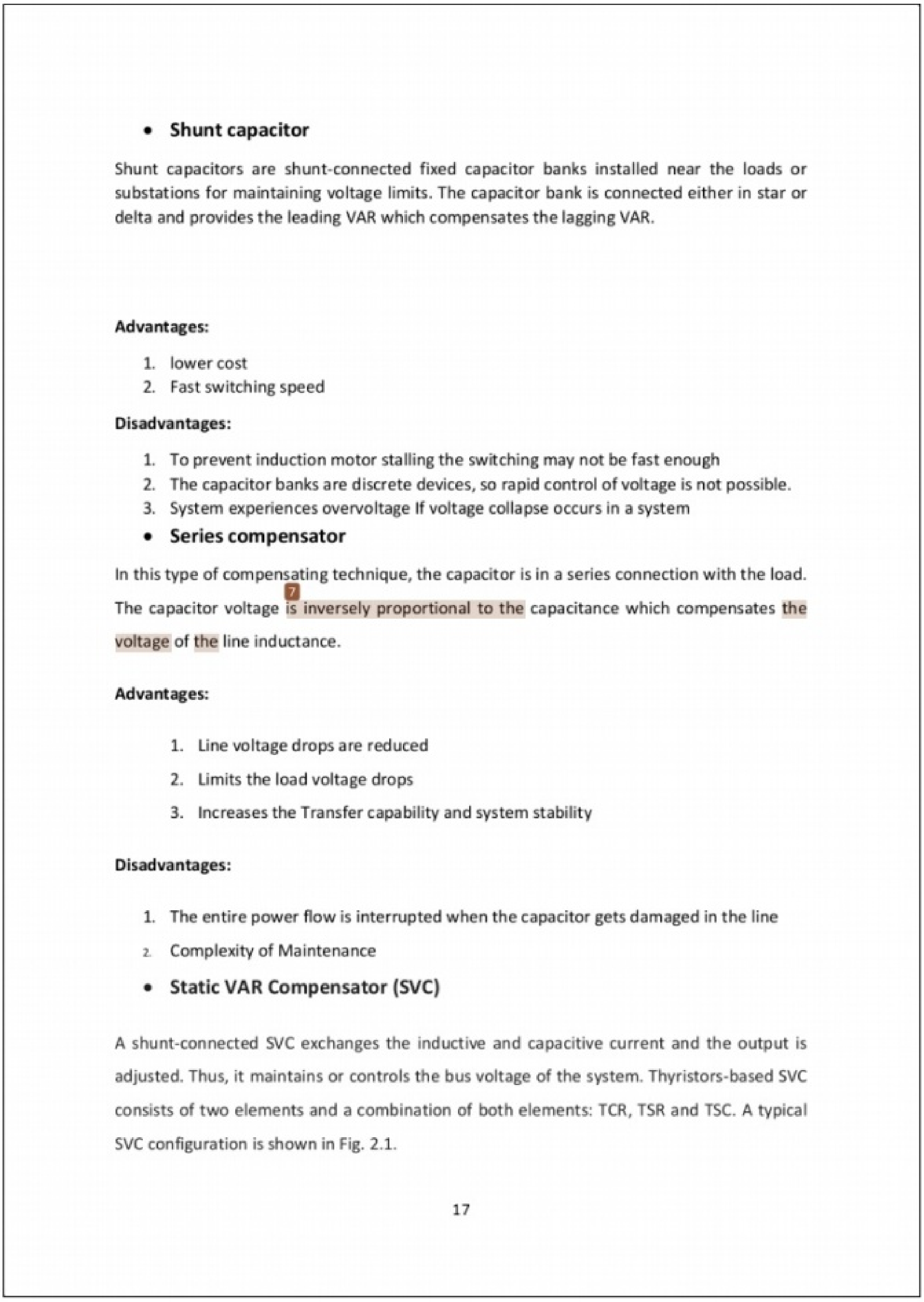
When voltage is applied across the inductors, a magnetic field is developed which causes the current to lag behind the voltage.

Current passing through the capacitor, develops a charge which gives voltage difference and capacitor oppose to change of voltage, therefore the voltage lag behind current.

Reactive power is supplied by the AC power source and oscillates between the capacitor or reactor and ac source at a frequency of two times the rated value of frequency (50 or 60 Hz). For this circulation compensation of reactive power is required. This compensation maintains the power factor close to unity and the voltage stability.

2.2 Devices used for reactive power compensation

The devices for compensation of reactive power like series compensators, capacitor banks, static VAR compensators, and STATCOM and their benefits and drawbacks are discussed [5].



- **Shunt capacitor**

Shunt capacitors are shunt-connected fixed capacitor banks installed near the loads or substations for maintaining voltage limits. The capacitor bank is connected either in star or delta and provides the leading VAR which compensates the lagging VAR.

Advantages:

1. lower cost
2. Fast switching speed

Disadvantages:

1. To prevent induction motor stalling the switching may not be fast enough
2. The capacitor banks are discrete devices, so rapid control of voltage is not possible.
3. System experiences overvoltage If voltage collapse occurs in a system

- **Series compensator**

In this type of compensating technique, the capacitor is in a series connection with the load. The capacitor voltage is inversely proportional to the capacitance which compensates the voltage of the line inductance.

Advantages:

1. Line voltage drops are reduced
2. Limits the load voltage drops
3. Increases the Transfer capability and system stability

Disadvantages:

1. The entire power flow is interrupted when the capacitor gets damaged in the line
2. Complexity of Maintenance

- **Static VAR Compensator (SVC)**

A shunt-connected SVC exchanges the inductive and capacitive current and the output is adjusted. Thus, it maintains or controls the bus voltage of the system. Thyristors-based SVC consists of two elements and a combination of both elements: TCR, TSR and TSC. A typical SVC configuration is shown in Fig. 2.1.

TCR and TSR are each composed of reverse-connected thyristors and shunt-connected reactors. With correct firing angle control TCR is controlled in a continuous manner, whereas without firing angle control TSR is controlled in a discontinuous manner. The operational mode of TSC same as TSR, only the capacitor is connected instead of the reactor. An SVC with a combination of TCR/TSR, TSC and fixed capacitors is used to absorb or supply reactive power from or to the line.

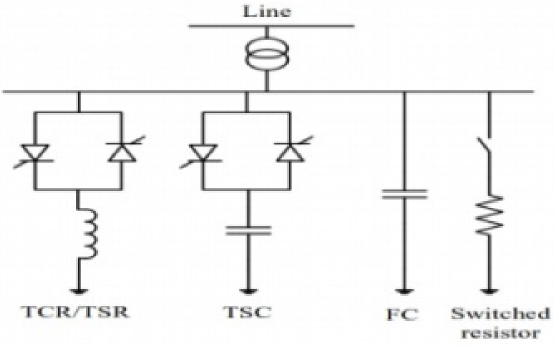


Fig. 2.1: Static VAR compensator (SVC)

- **Unified Power Quality Conditioner (UPQC)**

UPQC is a multifunctional device used to prevent the harmonic load current, compensate the voltage disturbances, and correct voltage fluctuations. It has shunt and series compensation capabilities for compensation of reactive power, harmonics mitigation, and power-flow control.

It performs the regulation of DC link voltage, compensating the reactive power and load current waveform distortions.

STATCOM:

It is a power shunt connected to electronic devices. It is composed of a three-phase inverter, DC capacitor, coupling transformer, ac filter and a control technique.

Advantages:

1. The voltage magnitude will not affect the maximum reactive current output. So it provides the constant current characteristics.

2. Improve the system stability

3. STATCOM is faster.

4. Lower harmonics emission.

5. It is compact.

Chapter 3

DSTATCOM Topology

3.1 DSTATCOM

It is a shunt-connected power device. [42] It is composed of a voltage source inverter (VSI) that gives the electrical phenomenon. Earlier, thyristor-based systems were used to mitigate the harmonics, compensate for [7] the reactive power and reduction of the voltage flicker. But there are some problems with thyristor-based systems, these are the possibility of occurrence of resonance, large in size and fixed compensation. To solve these problems DSTATCOM is used. It is used for solving the problems of harmonic distortions, voltage fall/dip, flickers, swell etc. It mitigates the harmonics by injecting harmonics compensation current in the system supplied.

Components and Configuration

It is connected to the systems near the load side at PCC. The components are shown in Fig [2] 3.1. It is composed of a three-phase inverter, DC capacitor, AC filter and a controller. The presence of a voltage-source convertor, in capacitive mode it [16] converts a DC voltage into an ac voltage and in inductive mode it converts AC voltage to DC voltage.

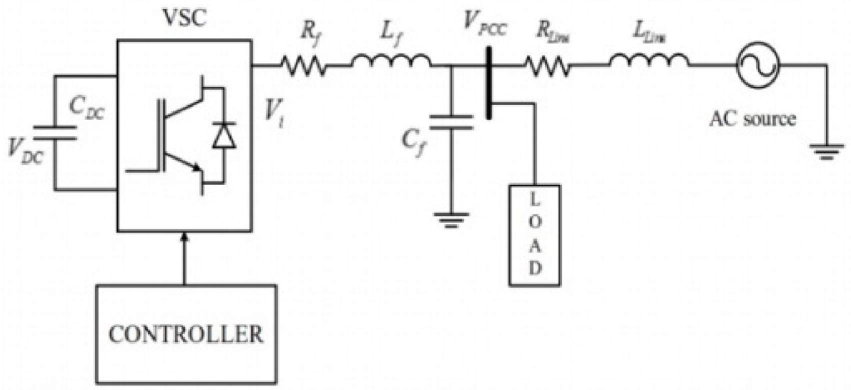


Fig. 3.1: the DSTATCOM

Working Principle:

Using an inverter, DSTATCOM converts voltage across the capacitor called DC link voltage V_{DC} to a voltage source. V_{DC} is the voltage across the VSI which is supplied by a DC-link capacitor. VSI is a conventional two-level voltage source converter whose reference is the three-phase voltages V_a ,V_b and V_c tracked from the source. These references are compared with the calculated three-phase voltages of the system to obtain error-free rectified output signals. Therefore, it can be seen as a voltage-controlled source.

Fig 3.1 shows the D-STATCOM, it injects the required amount of current for compensation of harmonic current such that the source draws sinusoidal current.

Control Algorithms:

The operation and performance of DSTATCOM are based on the control methodology i.e. how the reference signals are extracted. For this, various control schemes are reported in the literature and a few of those are SRF, IRP, MPC, ANFIS and SMC. It provides the compensation of reactive power in the load and as a result, the power factor of the supply current remains at unity. Since simply real power is being provided by the supply, load adjusting is accomplished by adjusting the supply reference current. A PWM-Based STATCOM with various Control methods and modelling has been explained in [6],[7],[8],[9]. The various control methods of the STATCOM and its simulation have been explained, and using traditional, control VSC-based STATCOM has been discussed in [10-11]. In a 3-phase distributed system the inverter interfacing with various types of filter design has been explained [12-13]. The control method of DSTATCOM using Current controller, Voltage controller, voltage source converter (VSC), DC link voltage control, PLL, SPWM and abc/dq and dq/abc transformation have been explained in [14-15]. The design of the DC link is explained [12]. This DC link technique enables DC link voltage [13]. Various types of filters like L, LC, LCL etc. are discussed in [16],[17],[18].

DSTATCOM Controllers

The controllers used in DSTATCOM are
- P controller
- PI Controller
- Hysteresis controller

3.2 Classification of DSTATCOM

The classification of DSTATCOM is based on the switching devices, use of transformers for neutral current compensation and isolation, types of converter, etc. are -phase 3-wire DSTATCOM and 3-phase 4-wire DSTATCOM.

3-Phase 3-Wire DSTATCOM

This topology shown in Fig. 3.2(a) is based on the 3-phase 3-wire with a capacitor and is used for the compensation of reactive power therefore improves the power quality. Due to fewer switching devices it is more advantageous. In figure the voltages v_{sa},v_{sb},, and v_{sc}, and currents i_{sa},i_{sb} and i_{sc} and connected to Nonlinear unbalanced load.

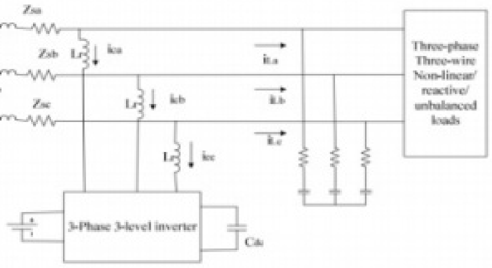


Fig. 3.2(a) 3-phase 3-wire DSTATCOM

3-Phase 4-Wire DSTATCOM

This topology is used to improve the power quality, and compensation in source current in three-phase four-wire distribution systems .In this topology, less number of power electronic switches are connected compared to 3-phase 3-wire DSTATCOM. In Fig. 3.2(b) shows 3 phase voltages v_{sa},v_{sb}, and v_{sc}, and currents i_{sa},i_{sb} and i_{sc} and reactive currents are i_{la},i_{lb} and i_{lc} . Based on the ripple current and switch frequency, the interfacing inductor is chosen.

Application of DSTATCOM

- regulation of voltage
- correction of power factor
- Balancing the unbalanced load
- Mitigation of harmonic

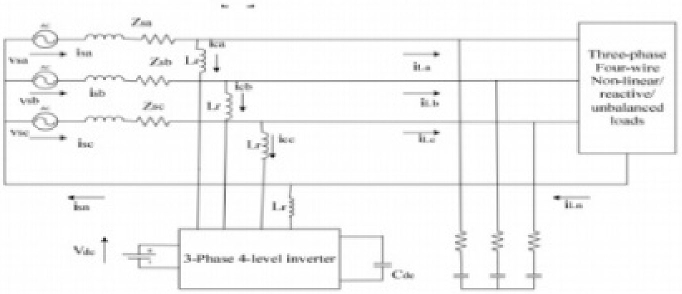


Fig 3.2(b) 3-phase 4-wire DSTATCOM

Advantages

- Power factor became unity
- compensation of Harmonic current
- Load balancing
- Regulation of line voltage
- Neutral current Compensation

Chapter 4

Electric Spring

An ES is used to solve the power quality issues of critical loads. It is connected in series with the non-critical loads called smart load that gives flexibility in consumption. When the critical load is connected to this load, its consumption is proportional to fluctuations caused by the system to make the regulation of critical load voltage.

ES can also solve problems viz. voltage balance, improving voltage regulation, harmonics mitigation, reducing neutral current, power factor correction and frequency control. Electric Spring (ES) has been used using various control methods. Electric Spring can mitigate the harmonic of CL loads. Electric Springs with improved control schemes can compensate for the harmonics.

4.1 Components and Principle of Operation

Fig. 4.1 shows ES . An ESs composed of a DC link, an inverter, and a LC filter which is in series connection with a NC load to convert it into a smart load.

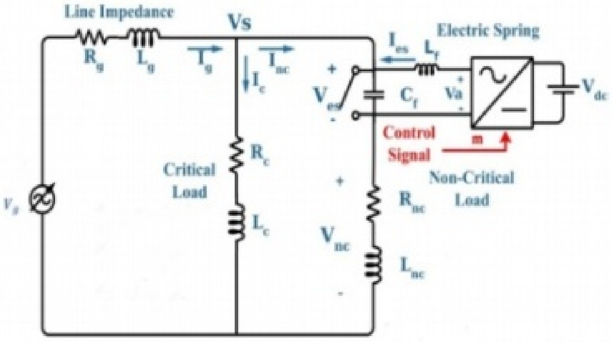


Fig. 4.1 Electric spring (ES)

The equations this circuit are obtained as follows:

$$V_s=V_{nc}+V_{es} \tag{4.1}$$

$$I_g=I_{nc}+I_C \tag{4.2}$$

V_g=mains voltage,

V_s=CL voltage

V_{nc}=NC load voltage

V_{es}=ES voltage

I_g=line current

I_{nc}=NC load current

I_c=CL current

And Z_g, Z_{nc}, and Z_c are impedance of line, NC load, and CL respectively.

Voltage Regulation

Due oscillating and non-linearity characteristics of the loads, can cause voltage fluctuations. The non-critical load connected to the mains when the switch is closed is shown in Fig 4.1. Therefore, the load side voltage fluctuates, which affects the critical loads. When the switch is open, the Electric Spring enters the circuit and regulates the voltage. For regulating the voltage by controlling the reactive power the voltage of Electric spring voltage should be perpendicular to the current.

In Undervoltage conditions, ES injects reactive power for compensation of CL voltage and operates in capacitive mode. In Undervoltage conditions, ES absorbs reactive power for regulation of the CL voltage and operates in inductive mode.

Harmonics Compensation

In the elements, the Presence of non-linearity connected to the system causes the harmonics in the system which can disturb the operation. Electric Spring produces an anti-harmonic voltage ($V_{es,h}$) which compensates for the harmonics of CL voltage ($V_{s,h}$) . As shown in Fig 4.2, by setting voltage harmonics of CL to zero, the harmonics of NC load current ($I_{nc,h}$) become equal to the harmonics of line current ($I_{g,h}$) and through the NC load, they close their path. Hence, the harmonics of CL load current ($I_{s,h}$) become equal to zero. The magnitude of harmonics NC load voltage ($V_{nc,h}$) should be the same as the anti-harmonic voltage of the ES,

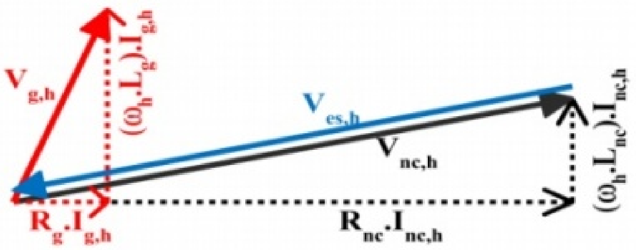


Fig. 4.2Harmonics compensation by ES.

4.2 Controller

Existing Control System

Fig 4.3(a) shows the control system. First measure the RMS voltage of the critical load and compare it with a reference value, the compared value is given to a (PI) controller to produce the amplitude of the modulation signal. For generating the phase angle of the modulation signal, PLL extracts the phase angle of the NC load current and adds it with $\frac{\pi}{2}$ or $\frac{\pi}{2}$ depending upon the Undervoltage or overvoltage conditions. So, by injecting or absorbing reactive power to regulate the voltage, the ES voltage should be perpendicular to its current.

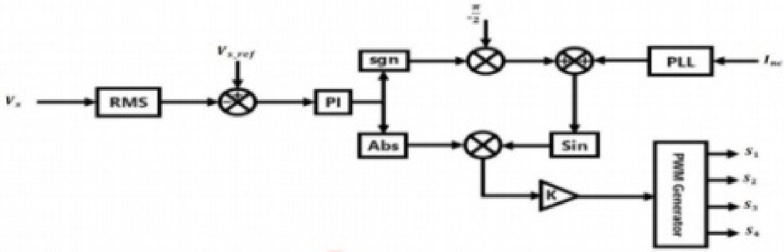


Fig. 4.3(a) Existing control system

Improved Control System

Fig 4.3(b) shows the control system which is the existing control system added with a harmonic compensation function. This compensates the harmonics of CL load voltage, regulating the RMS voltage critical load to maintain a nominal value. The harmonic compensation function separates its real and imaginary components with feedback from critical load voltage and transforms them into d and q components. The high-frequency components of real and imaginary components are removed using low-pass filters, leaving the fundamental components. Using the inverse d-q transformation, the fundamental real and imaginary components are extracted with the help of the PLL block. By subtracting the fundamental real value from the measured value of critical load voltage, harmonics of CL load voltage are extracted and compared with a reference value of zero is given to a P controller. Finally, this reference signal is converted into the switching pulses of the inverter using pulse-width modulation (PWM).

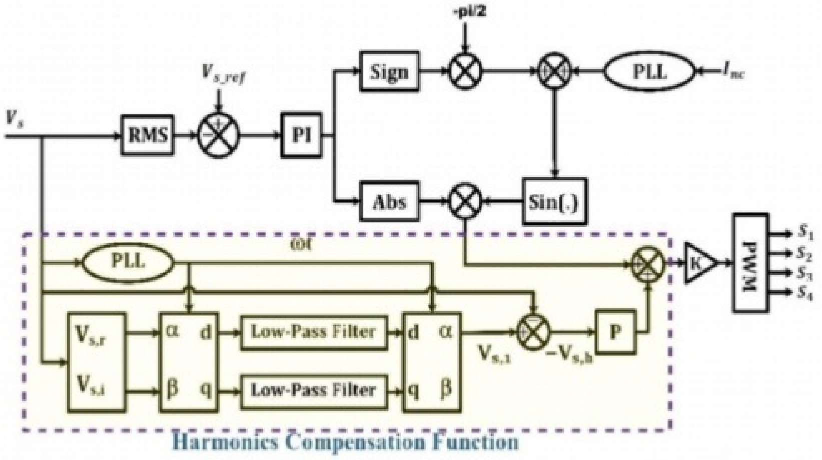


Fig. 4.3(b) Improved Control system

This system regulates the critical load voltage by providing the reactive power and also the harmonics CL load voltage therefore improving the power quality. In this control system, power quality has been improved because presence of a harmonic compensation function. Due to this, it compensates the higher and lower order harmonics.

Application

- Reactive power compensation
- Mitigating harmonics
- Reducing neutral current
- Power factor correction
- Voltage balancing
- Frequency control

The application of ESs in systems to improve power quality and regulate voltage has been demonstrated in [22, 23]. In [24, 25], the distribution losses in the systems are reduced using the controller. The ES can compensate the neutralize the negative and zero sequence current load imbalance issues [26].In ES operation for minimizing the active power output, several control methods are reported in [27, 28].

The ESs are used as a distributed harmonics compensation and voltage control. An ES is connected to the NC loads called a smart load, can compensate for the under voltages and the over voltages. This method is used in electric springs for regulating the critical load (CL) voltage such that it is equal to the nominal value and compensating for the harmonics of CL load voltage. The performance of ES for regulation of voltage magnitude and compensation of harmonic distortion are investigated using simulation.

An electric spring composed of an inverter, a low-pass LC filter a DC link, which is in series connection to a NC load called a smart load. This smart load have a wide range of tolerance of harmonic distortions and tolerable voltage fluctuations caused by the ES operation. This is in parallel connection to the CL load.

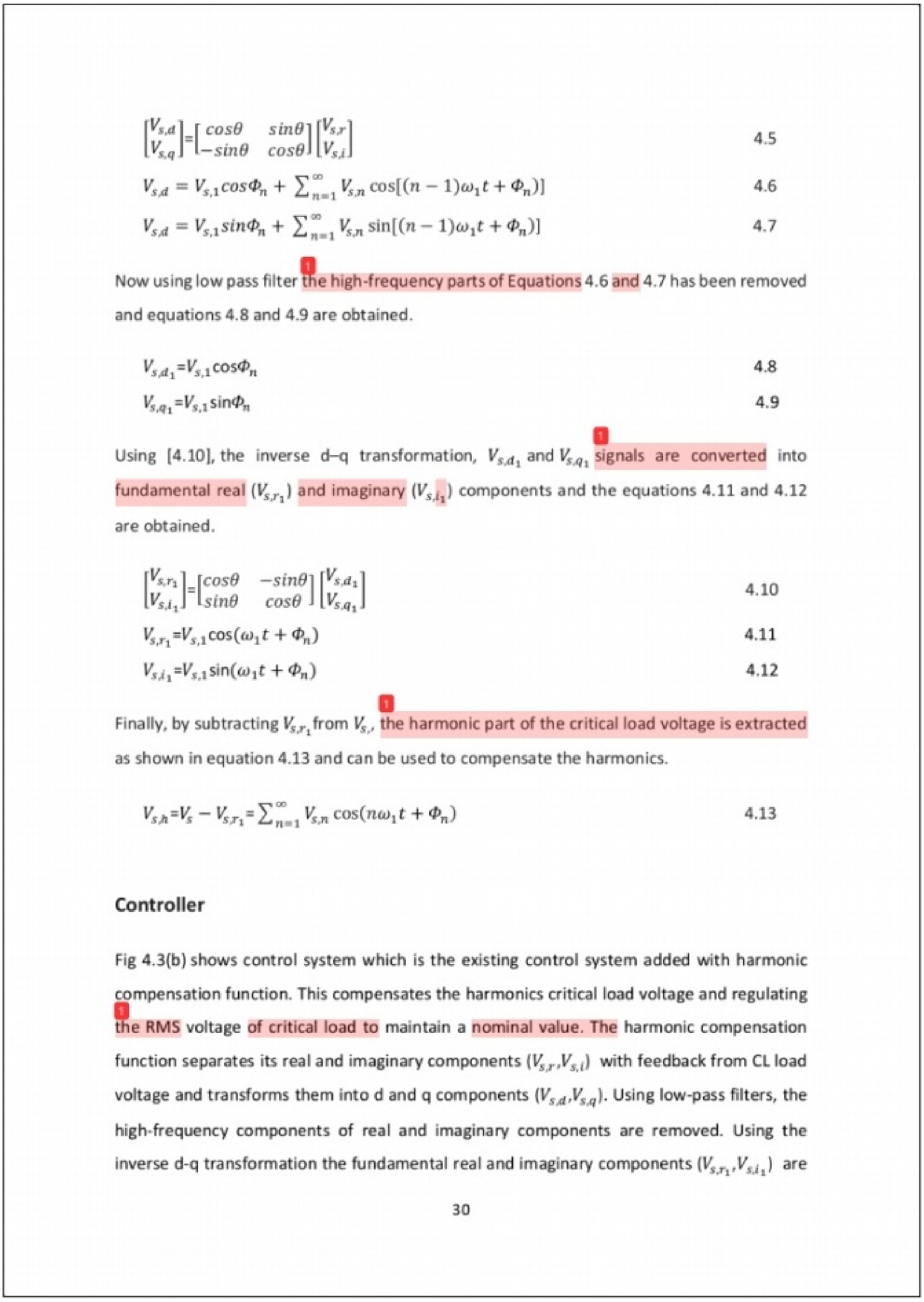
Due to non-linear characteristics of elements connected to the system causes harmonics in the system which can disturb the normal operation. Electric spring produces an anti-harmonic voltage ($V_{es,h}$) which compensates the harmonics of CL load voltage ($V_{s,h}$). As shown in Fig 4.2, by setting the harmonics of CL load voltage to zero, the harmonics of NC load current ($I_{nc,h}$) become equal to the harmonics of line current ($I_{g,h}$) and through the NC load they close their path. Hence, harmonics of CL load current ($I_{c,h}$) become zero. Magnitude of harmonics NC load voltage ($V_{nc,h}$) should be same as the anti-harmonic voltage of the ES,

The equations (4.3) and (4.4) are used for calculating harmonics of CL load voltage. Decomposed the CL load voltage into its real ($V_{s,r}$) component and imaginary ($V_{s,i}$) component and both are perpendicular to each other .

$$V_{s,r} = \sum_{n=1}^{\infty} V_{s,n} \cos(n\omega_1 t + \Phi_n) \qquad 4.3$$

$$V_{s,i} = \sum_{n=1}^{\infty} V_{s,n} \cos\left(n\omega_1 t + \Phi_n - \frac{\pi}{2}\right) \qquad 4.4$$

Where, $V_{s,n}$ is nth harmonic critical load voltage, and Φ_n is the phase angle nth harmonic CL load voltage. Next, $V_{s,r}$ and $V_{s,i}$ are converted into the horizontal ($V_{s,d}$) component and vertical ($V_{s,q}$) component, using [4.5], as shown in Equations 4.6 and 4.7.



$$\begin{bmatrix} V_{s,d} \\ V_{s,q} \end{bmatrix} = \begin{bmatrix} cos\theta & sin\theta \\ -sin\theta & cos\theta \end{bmatrix} \begin{bmatrix} V_{s,r} \\ V_{s,i} \end{bmatrix} \quad 4.5$$

$$V_{s,d} = V_{s,1} cos\Phi_n + \sum_{n=1}^{\infty} V_{s,n} \cos[(n-1)\omega_1 t + \Phi_n)] \quad 4.6$$

$$V_{s,d} = V_{s,1} sin\Phi_n + \sum_{n=1}^{\infty} V_{s,n} \sin[(n-1)\omega_1 t + \Phi_n)] \quad 4.7$$

Now using low pass filter the high-frequency parts of Equations 4.6 and 4.7 has been removed and equations 4.8 and 4.9 are obtained.

$$V_{s,d_1} = V_{s,1} \cos\Phi_n \quad 4.8$$

$$V_{s,q_1} = V_{s,1} \sin\Phi_n \quad 4.9$$

Using [4.10], the inverse d–q transformation, V_{s,d_1} and V_{s,q_1} signals are converted into fundamental real (V_{s,r_1}) and imaginary (V_{s,i_1}) components and the equations 4.11 and 4.12 are obtained.

$$\begin{bmatrix} V_{s,r_1} \\ V_{s,i_1} \end{bmatrix} = \begin{bmatrix} cos\theta & -sin\theta \\ sin\theta & cos\theta \end{bmatrix} \begin{bmatrix} V_{s,d_1} \\ V_{s,q_1} \end{bmatrix} \quad 4.10$$

$$V_{s,r_1} = V_{s,1} \cos(\omega_1 t + \Phi_n) \quad 4.11$$

$$V_{s,i_1} = V_{s,1} \sin(\omega_1 t + \Phi_n) \quad 4.12$$

Finally, by subtracting V_{s,r_1} from $V_{s,}$, the harmonic part of the critical load voltage is extracted as shown in equation 4.13 and can be used to compensate the harmonics.

$$V_{s,h} = V_s - V_{s,r_1} = \sum_{n=1}^{\infty} V_{s,n} \cos(n\omega_1 t + \Phi_n) \quad 4.13$$

Controller

Fig 4.3(b) shows control system which is the existing control system added with harmonic compensation function. This compensates the harmonics critical load voltage and regulating the RMS voltage of critical load to maintain a nominal value. The harmonic compensation function separates its real and imaginary components ($V_{s,r}$,$V_{s,i}$) with feedback from CL load voltage and transforms them into d and q components ($V_{s,d}$,$V_{s,q}$). Using low-pass filters, the high-frequency components of real and imaginary components are removed. Using the inverse d-q transformation the fundamental real and imaginary components (V_{s,r_1},V_{s,i_1}) are extracted with the help of PLL block. By subtracting fundamental real value V_{s,r_1} from the measured value of CL load voltage harmonics $(V_{s,h})$ are extracted and compare it with the reference value of zero and given to a P controller. Finally, this reference signal converted into the switching pulses of the inverter using pulse-width modulation (PWM). The performance of ES is investigated in [20] for harmonic mitigation and voltage regulation. ES with harmonic compensation function has been simulated. Results show that ES is capable of compensating harmonics of sensitive load voltage caused due to system voltage distortion. ES can regulate the sensitive load voltage by changing the power flow voltage through the non-sensitive load [19],[21].

Chapter 5

Hybrid DSTATCOM

A DSTATCOM topology addressed some problems such as compensation performance, filter size, power rating and power loss. An LCL filter which is connected at the front side of a VSI and it eliminates switching harmonics using a lower value of the inductor. The capacitor voltage of the LCL filter will be less which can reduce the power losses in resistor R_d called as damping resistor. Thus, this hybrid topology reduced the cost, weight, standing, and size with better current compensation capability.

However, the rating of VSI increases due to higher dc-link current which causes greater current rating of IGBT switches. The presence of a large inductor, for monitoring the reference power there is a low slew rate, and fosters a reasonable current flow through it, which, consequently, needs a greater worth of the electricity link current for compensation.So the large L- L-filter increases the price, size, and also power rating.

5.1 Hybrid DSTATCOM Topology

To improve the power quality, static capacitors and passive filters have been used But there are some problems using these such as fixed compensation and possible resonance [1]. To overcome these issues a DSTATCOM has been proposed [6]. To make the source currents balanced and sinusoidal in phase with the load voltages it injects the reactive power and harmonics component of load currents.

However, using an L-type filter the reduction in voltage is limited which makes bigger size of the filter bigger, for tracking it has a lower slew rate. To overcome these drawbacks LCL filter-based DSTATCOM topology has been proposed in the literature [7]. With the lower value of passive components, it gives better reference tracking performance which reduces the weight, cost, and size. However, the dc-link voltage is the same both for LCL filter and L-filter-based topology. therefore, the disadvantages of LCL filters are still present due to high dc-link voltage. To overcome this problem a series capacitor C_{se} is connected and improves reference tracking performance.

The performance of this topology is investigated using simulation. A three-phase four-wire system clamped with a VSI circuit of the hybrid topology is shown in Fig. 5.1. To provide the damping to the system a resistance R_d is connected in series with capacitor C. In traditional topology, VSI is connected through the inductor L_f and in hybrid DSTATCOM topology VSI is connected through LCL filter along with series capacitor C_{se}.

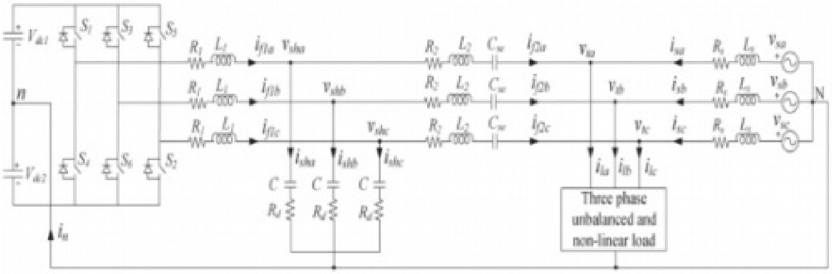


Fig. 5.1 Hybrid DSTATCOM topology in distribution system

5.2 DSTATCOM Control

Fig. 5.2 shows DSTATCOM controller

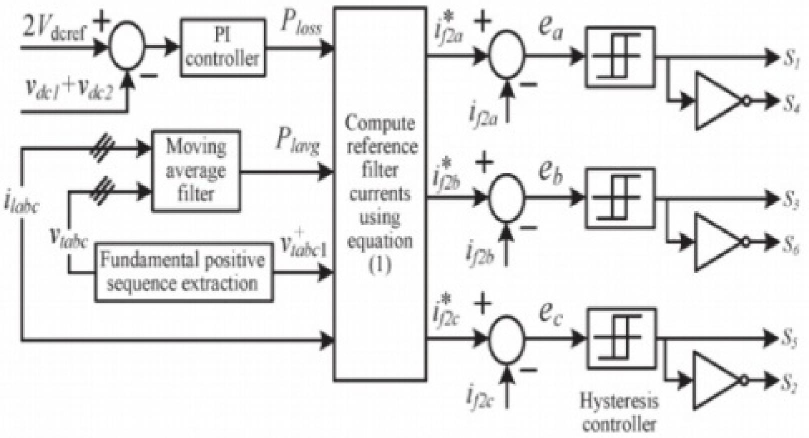


Fig 5.2 DSTATCOM controller

The fundamental positive sequence components of three phases are extracted to generate the reference filter currents (i^*_{f2a},i^*_{f2b},i^*_{f2c}) based on the instantaneous symmetrical component theory. These currents are calculated as follows:

$$i^*_{f2a} = i_{1a} - i^*_{sa} = i_{1a} - \frac{v^+_{ta1}}{\Delta^+_1}(P_{1avg} - P_{loss}) \qquad 5.1(a)$$

$$i^*_{f2b} = i_{1b} - i^*_{sb} = i_{1b} - \frac{v^+_{tb1}}{\Delta^+_1}(P_{1avg} - P_{loss}) \qquad 5.1(b)$$

$$i^*_{f2c} = i_{1c} - i^*_{sc} = i_{1c} - \frac{v^+_{tc1}}{\Delta^+_1}(P_{1avg} - P_{loss}) \qquad 5.1(c)$$

v^+_{ta1}, v^+_{tb1} and v^+_{tc1} are the fundamental positive sequence voltages

$$\Delta^+_1 = (v^+_{ta1})^2 + (v^+_{tb1})^2 + (v^+_{tc1})^2 \qquad 5.2$$

P_{1avg} and P_{loss} are the average load power and the total losses in the VSI. Using moving average filter The average load power is calculated during transients .

For any time t_1 the average power can be calculated as

$$P_{1avg} = \frac{1}{\sqrt{T}}\int_{t_1-T}^{t_1}(v_{ta}\, i_{1a} + v_{tb} i_{1b} + v_{tc} i_{1c})dt \qquad 5.3$$

Total power is given by

$$P_{loss} = K_p e_{vdc} + K_i \int e_{vdc} dt \qquad 5.4$$

Now, the filter currents are subtracted from reference filter currents, then the current error e_{abc} is obtained and this is given to hysteresis controller and IGBT switching pulses are generated.

5.3 Design of DSTATCOM Parameters

The supply voltage of 230V, load of 10kVA rating, the ripple current of 1A (5% of rated current) and switching frequency of 10 kHz have been considered.

DC link voltage: The DC link voltage is the source of energy. Series capacitors and smaller value of filter inductor caused a significant reduction of DC link voltage. Here, for traditional topology, the DC link voltage of 520 V is selected and for hybrid DSTATCOM topology, 110 V is selected for better performance [29].

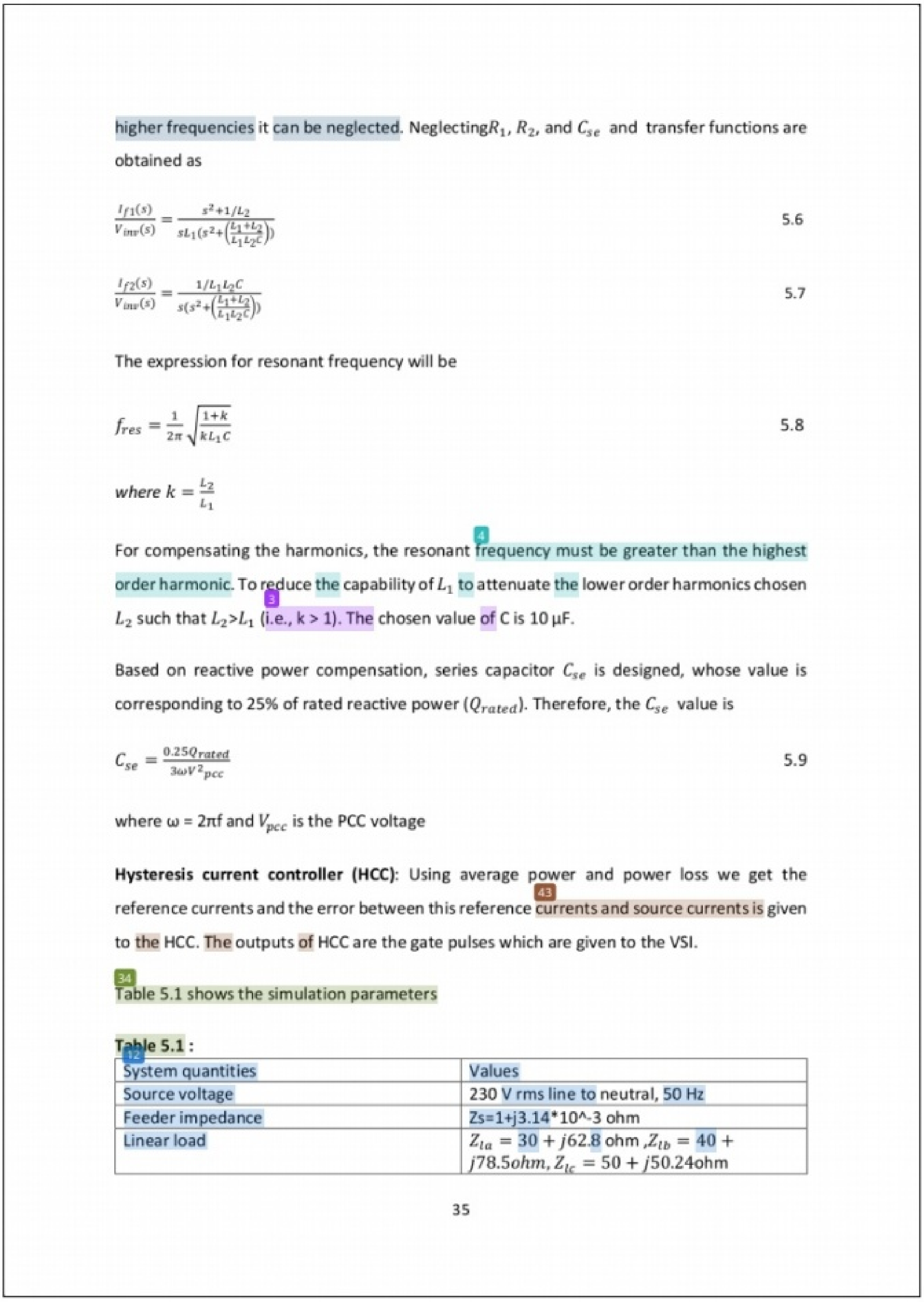
PI controller: For proper compensation, the DC link voltage of DSTATCOM is maintained at a sufficient value. PI controller is used to maintain it constant.

Filters: The chosen value of L_1 gives sufficient rate of change of the filter current and high switching frequency so that the VSI currents follow the reference currents and for attenuating lower order harmonics the L_1 is chosen. The inductor L_2 and capacitor C is chosen to eliminate higher order harmonics. Based on the reactive power compensation, Series capacitor designed.The value of L_1 is given by equation 5.5.

$$L_1 = \frac{V_{dcref}}{(2h_a)(2f_{max})} = \frac{V_{dcref}}{4h_a f_{max}} \qquad 5.5$$

Here, $2h_a$ is ripple in the current, and f_{max} is the maximum switching frequency.

To attenuate lower order harmonics once L_1 is chosen and L_2 and C need to be designed for elimination of higher order harmonics. C_{se} offers lower impedance than that of L_2 and at



higher frequencies it can be neglected. NeglectingR_1, R_2, and C_{se} and transfer functions are obtained as

$$\frac{I_{f1}(s)}{V_{inv}(s)} = \frac{s^2+1/L_2}{sL_1(s^2+\left(\frac{L_1+L_2}{L_1L_2C}\right))} \qquad 5.6$$

$$\frac{I_{f2}(s)}{V_{inv}(s)} = \frac{1/L_1L_2C}{s(s^2+\left(\frac{L_1+L_2}{L_1L_2C}\right))} \qquad 5.7$$

The expression for resonant frequency will be

$$f_{res} = \frac{1}{2\pi}\sqrt{\frac{1+k}{kL_1C}} \qquad 5.8$$

where $k = \frac{L_2}{L_1}$

For compensating the harmonics, the resonant frequency must be greater than the highest order harmonic. To reduce the capability of L_1 to attenuate the lower order harmonics chosen L_2 such that L_2>L_1 (i.e., k > 1). The chosen value of C is 10 µF.

Based on reactive power compensation, series capacitor C_{se} is designed, whose value is corresponding to 25% of rated reactive power (Q_{rated}). Therefore, the C_{se} value is

$$C_{se} = \frac{0.25Q_{rated}}{3\omega V^2{}_{pcc}} \qquad 5.9$$

where ω = 2πf and V_{pcc} is the PCC voltage

Hysteresis current controller (HCC): Using average power and power loss we get the reference currents and the error between this reference currents and source currents is given to the HCC. The outputs of HCC are the gate pulses which are given to the VSI.

Table 5.1 shows the simulation parameters

Table 5.1 :

System quantities	Values
Source voltage	230 V rms line to neutral, 50 Hz
Feeder impedance	Zs=1+j3.14*10^-3 ohm
Linear load	$Z_{la} = 30 + j62.8$ ohm ,$Z_{lb} = 40 + j78.5ohm, Z_{lc} = 50 + j50.24$ohm

RC type nonlinear load	R_l =50 ohm , C_l =1000μF
RL type nonlinear load	R_l =50 ohm , $L_l = 200\ mh$
VSI parameters Traditional topology	V_{dc} =520 V, C_{dc}=3000μF, L_f=26mh , R_f=0.1 ohm
VSI parameters LCL filter based	V_{dcref} =520 V, C_{dc}=3000μF, L_1=6.5mh , $L_2 = 1\ mh$, R_d=15 ohm , R_1=R_2 =0.05 ohm , C=10μF
VSI parameters Proposed topology	V_{dcref} = 110 V , C_{dc}=3000μF , L_1=1.5mh , $L_2 = 0.6\ mh$, R_d=15 ohm , R_1=R_2 =0.05 ohm , C=10μF , C_{se}=50μF
Hysteresis band(h)	±0.5

Chapter 6

SIMULATION RESULTS

This chapter presents the simulations results considering different types of nonlinear loads. The performance of the DSTATCOM and Electric Spring has been verified in MATLAB/ Simulink simulation environment. A comparative assessment has been carried out considering traditional and improved DSTATCOM topology and Electric Spring with focus on the THD improvement.

6.1 Simulation results with RL load

6.1.1 Simulation results without compensation:

Fig. 6.1(a) shows the waveforms of source currents before compensation. These currents are distorted and unbalanced due to nonlinear RL load. Therefore, source current contains harmonics. Fig. 1(b) shows different harmonic components present in the source current. Fig.6.1(c) shows the harmonic components when nonlinear load is delivering large amount of harmonic currents but up to 5th harmonic order only.

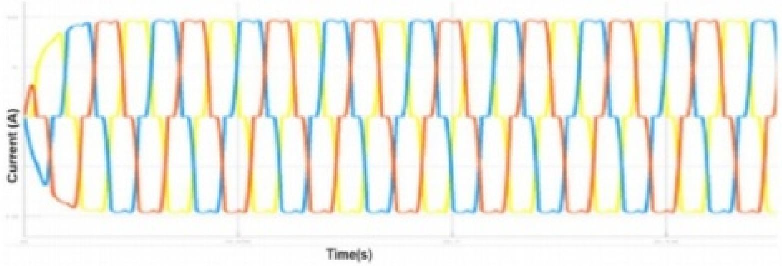


Fig 6.1 (a) Source current waveform without compensation and with nonlinear RL load

Fig. 6.1(d) shows waveform of the PCC voltages before compensation. These voltages are and distorted and unbalanced due to nonlinear load. Therefore, PCC voltage contains harmonics and the harmonic distribution is shown in Fig. 6.1 (e) which shows the THD of the PCC voltage is 22.24%. The harmonic distribution when nonlinear load contains harmonic load up to 5th order only is shown in Fig. 1(f) where the THD is 24.13%

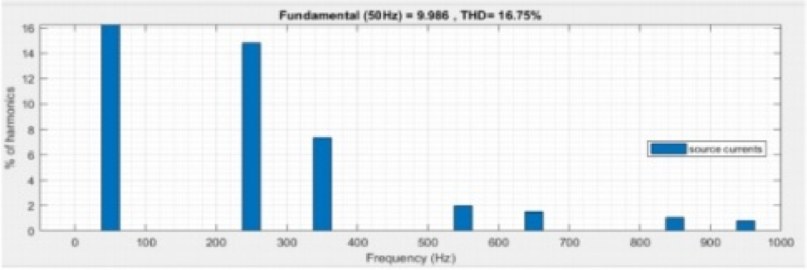


Fig. 6.1(b) Source currents harmonics without compensation and with nonlinear RL load

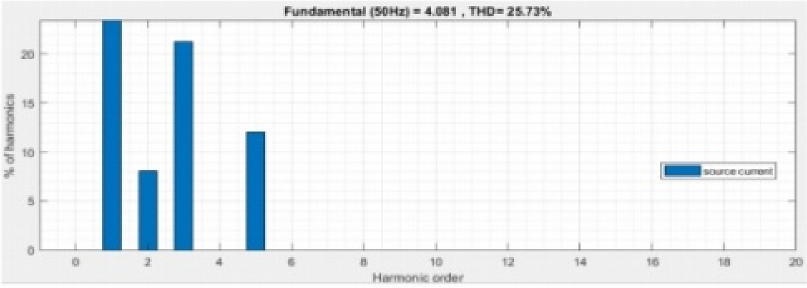


Fig. 6.1(c) Source current harmonics without compensation and with nonlinear RL load containing harmonics up to 5th order

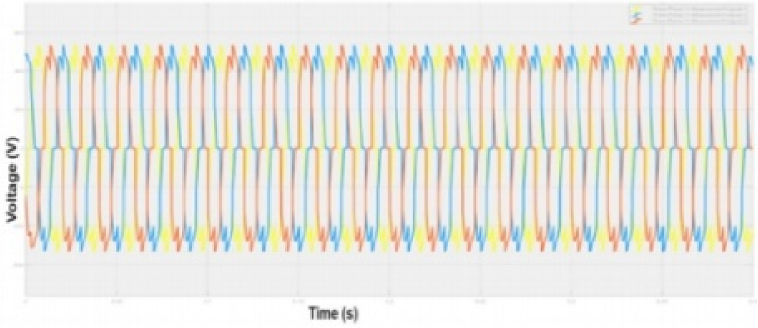


Fig. 6.1(d) PCC voltage waveform without compensation and with nonlinear RL load

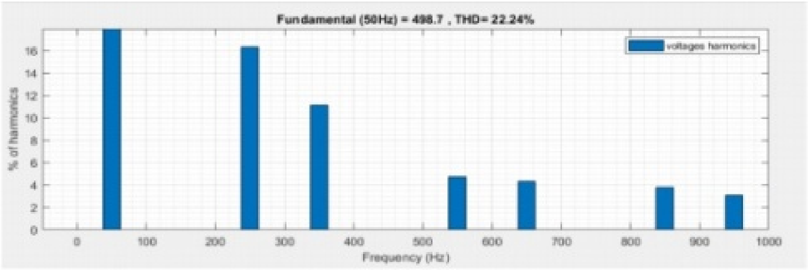


Fig. 6.1(e) PCC voltages harmonics without compensation and with nonlinear RL load

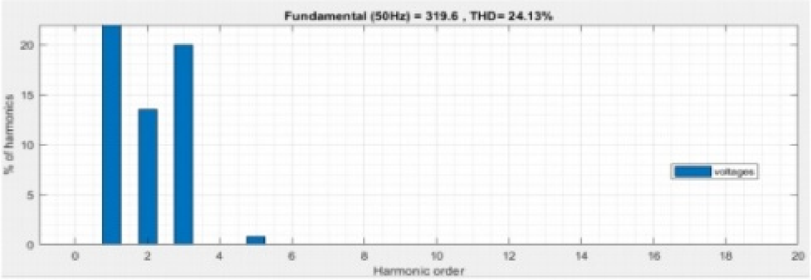


Fig. 6.1(f) PCC voltage harmonics without compensation and with nonlinear RL load containing harmonics up to 5th order

6.1.2 Simulation results with traditional DSTATCOM:

The simulation of the traditional DSTATCOM topology has been investigated in this section. The voltage across each capacitor connected across the VSI is 520 V and therefore, using PI controller total dc-link voltage for two capacitor is 1040 V.DC link voltage is very high because injected current here depends upon the dc link voltage due to the absence of series capacitor.

The waveform of three-phase source current is shown in Fig. 6.2(a) which contains switching frequency components of VSI and hence contains some harmonics. From Fig. 6.2(b) it has been observed that harmonic components have been reduced and THD has been hybrid to 2.93% whereas without compensation it was 16.75% as depicted in Fig. 6.1(c). Fig. 6.2(c) shows the harmonic components when the nonlinear load delivers harmonics up to 5th order only. It has been observed that THD has hybrid to 2.61% from 25.73% without compensation.

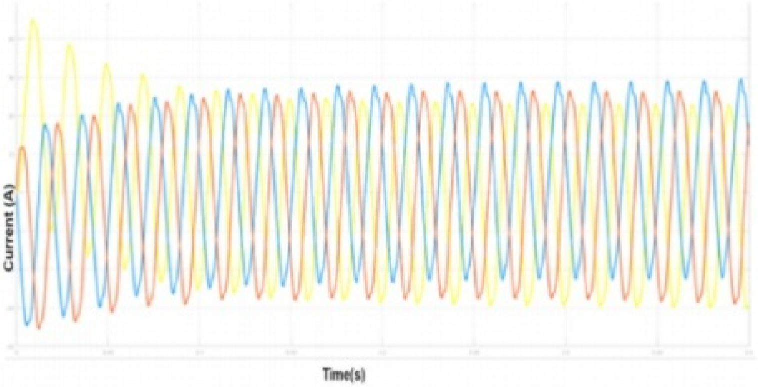


Fig. 6.2(a) Source current waveform with traditional topology and with nonlinear RL load

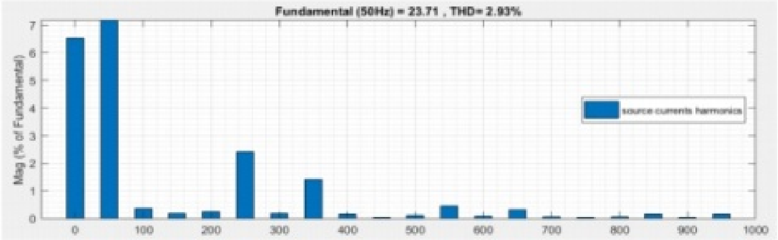


Fig. 6.2(b) Source current harmonics with traditional DSTATCOM topology and with nonlinear RL load

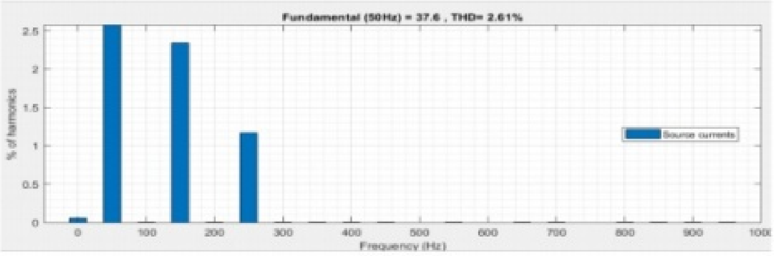


Fig. 6.2(c) Source current harmonics with traditional DSTATCOM topology and with nonlinear RL load containing harmonics up to 5th order

Fig. 6.2(d) shows the waveform of PCC voltages and the it contains the switching frequency components and hence, contain some harmonics. Fig. 6.2(e) shows the total harmonic distortions and Fig 6.2(f) shows the harmonic distribution in the PCC voltage when the load delivers up to 5th order harmonics. The THD value of the PCC voltage has improved to 16.39% and 1.41% from 22.24% and 24.13% respectively.

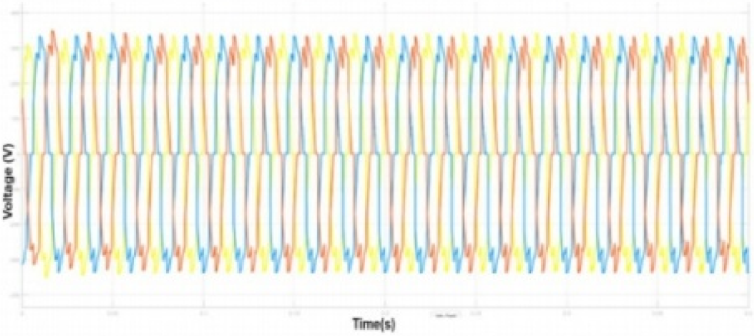


Fig. 6.2(d) PCC voltage waveform with traditional DSTATCOM topology and with nonlinear RL load

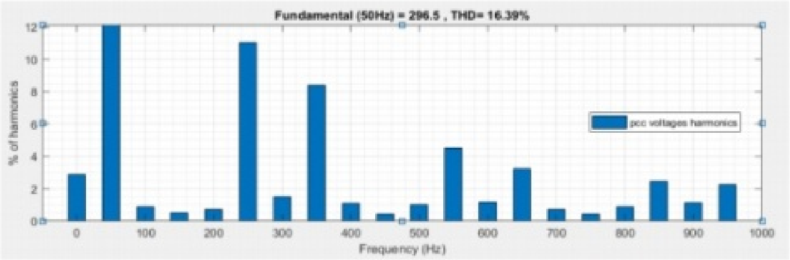


Fig. 6.2(e) PCC voltage harmonics with traditional DSATCOM topology and with nonlinear RL load

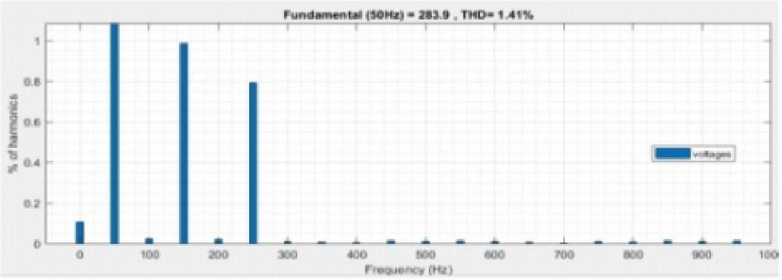


Fig. 6.2(f) PCC voltage harmonics with traditional DSATCOM topology and with nonlinear RL load containing harmonics up to 5th order

6.1.3 Simulation results with hybrid DSTATCOM:

The simulation of hybrid DSTATCOM topology is shown in this section. The voltage across each capacitor connected across the VSI is 110 V, whereas using the PI controller the total dc-link voltage across two capacitor is 220 V. In this topology dc link voltage is less compared to the traditional topology because there is reduction in the net impedance due to the presence of series capacitor in LCL filter. Hence, maximum current is injected and it requires less dc link voltage.

In Fig. 6.3(a), source current waveforms are shown, balanced, and have negligible switching ripples compared to the traditional topology due to the presence of LCL filter with series capacitor. Hence, the neutral current is nearly zero. Fig. 6.3(b) shows total harmonic distortion and Fig. 6.3(c) shows harmonic distortion when load is delivering harmonic up to 5th order only. Fig. 6.3(d) shows three phase PCC voltages which has less switching harmonics as compared traditional topology. Fig. 6.3(e) shows total harmonic distortions of the PCC voltage and Fig. 6.3(f) shows harmonic distortion when the load delivers harmonics up to 5th harmonic order only. It has been observed that though there is rise in the current THD value using hybrid DSTATCOM topology with respect to traditional topology, but considerable reduction in THD has been obtained for PCC voltage. The PCC voltage THD has been hybrid from 16.39% to 7.46% and from 1.41% to 0.36%.

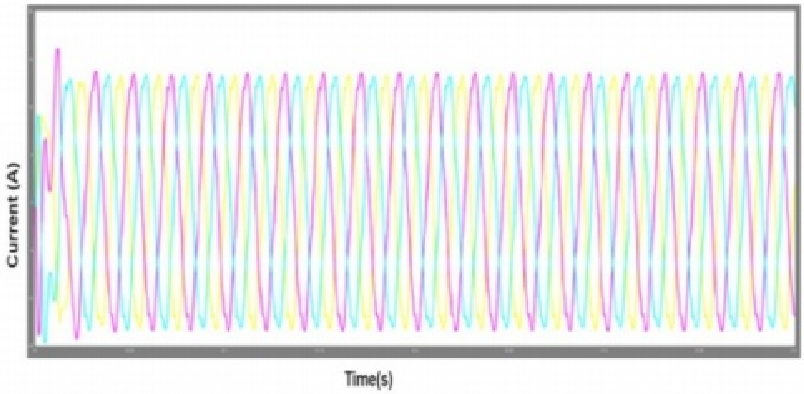


Fig. 6.3(a) Source currents waveform with improved DSTATCOM topology and with nonlinear RL load

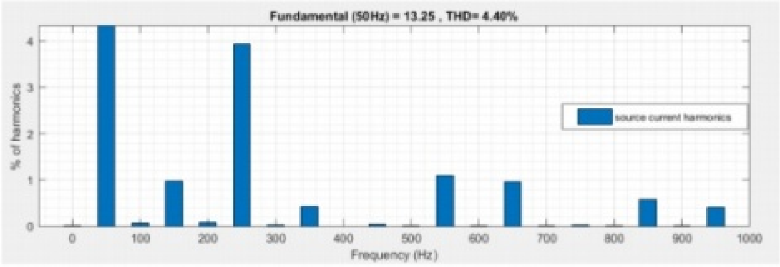


Fig. 6.3(b) Source current harmonics with improved DSTATCOM topology and with nonlinear RL load

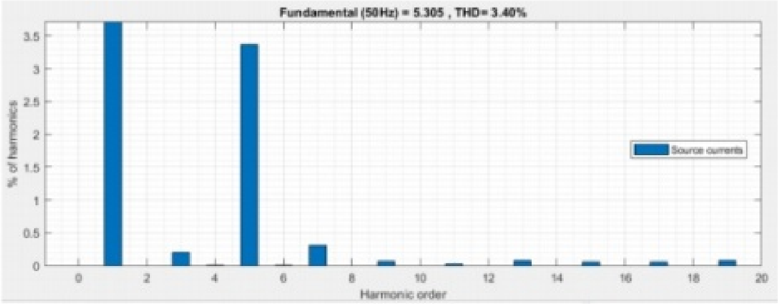


Fig. 6.3(c) Three phase current source harmonics with improved DSTATCOM topology and with nonlinear RL load containing harmonics up to 5th order

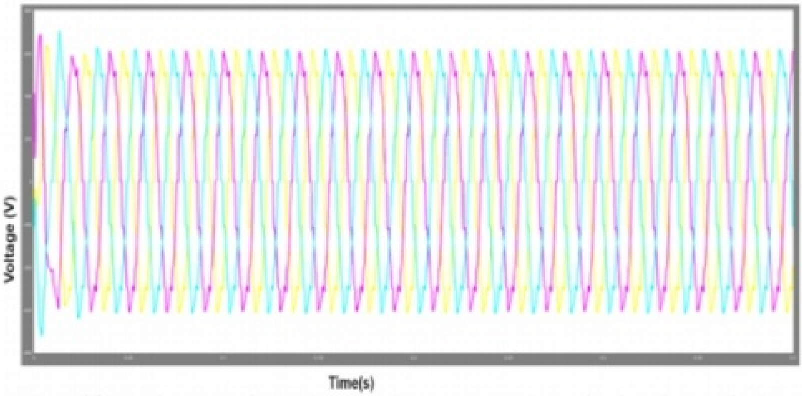


Fig. 6.3(d) PCC voltages waveform with improved DSTATCOM topology and with nonlinear RL load

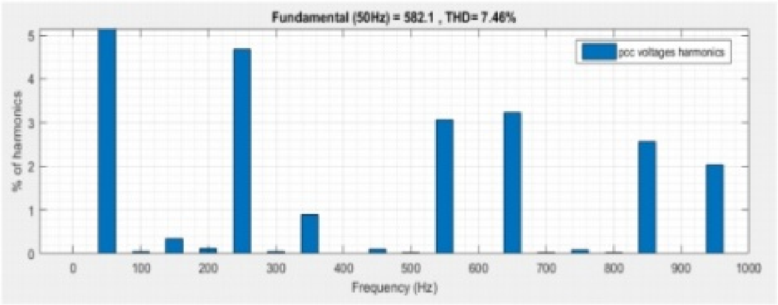


Fig. 6.3(e) PCC voltages harmonics with improved DSTATCOM topology and with nonlinear RL load

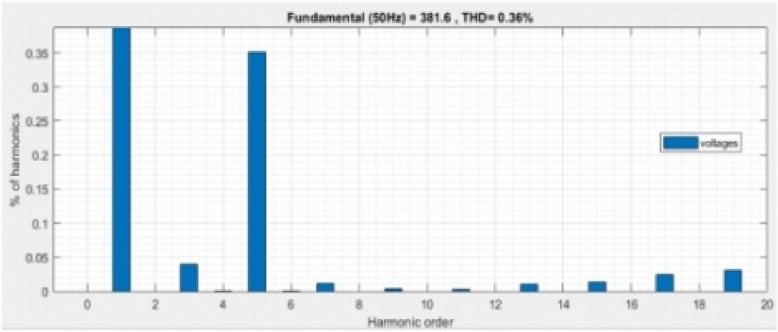


Fig. 6.3(f) PCC voltage harmonics with improved DSTATCOM topology and with nonlinear RL load containing harmonics up to 5th order

6.1.4 Simulation results with Electric Spring:

Electric Spring (ES) has been connected in place of DSTATCOM and the performance has been observed. The source currents are shown in Fig. 6.4(a). Here, the currents are almost sinusoidal because ES injects a current containing inverse harmonics into the system i.e., it injects non-sinusoidal currents in to the system to make the resultant current almost sinusoidal. Fig. 6.4(b) shows total harmonic distortions and Fig. 6.4(c) shows harmonic distortions when the load is delivering harmonics up to 5th order only.

Fig. 6.4(d) shows the PCC voltage which is also almost sinusoidal because ES injects non-sinusoidal currents and these non-sinusoidal currents generate non-sinusoidal voltages and therefore, suppress the harmonics in PCC voltages. Fig. 6.4(e) shows total harmonic distortions and Fig. 6.4(f) shows harmonic distortions when load contains harmonics up to 5th order only.

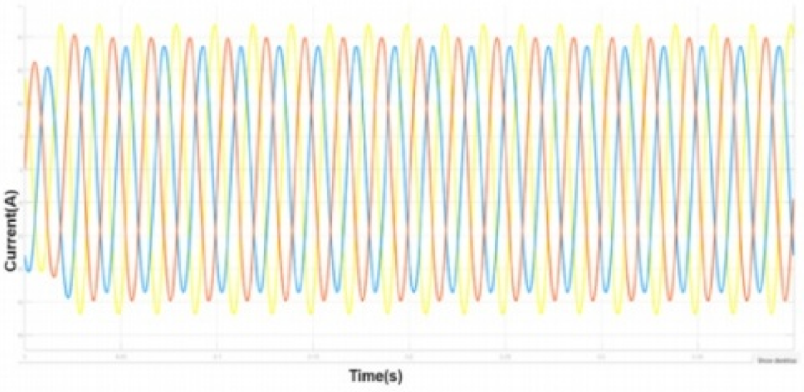


Fig. 6.4(a) Source current waveform with Electric Spring and with nonlinear RL load

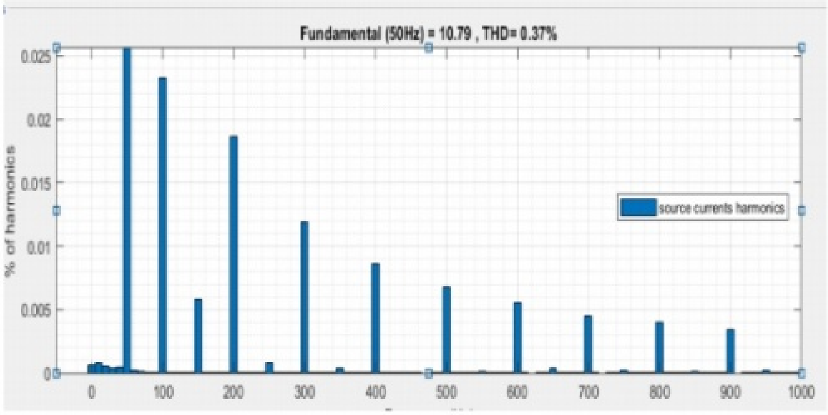


Fig. 6.4(b) Source current harmonics with Electric Spring and with nonlinear RL load

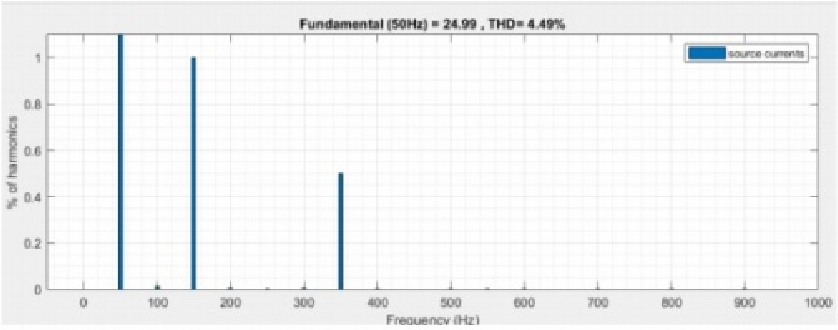


Fig. 6.4(c) Source current harmonics with Electric Spring and with nonlinear RL load

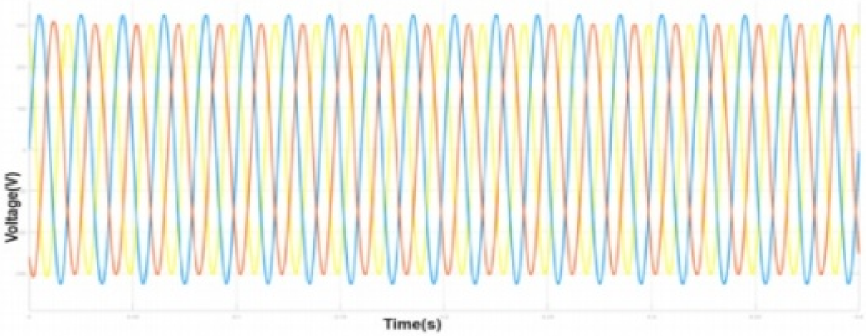


Fig. 6.4(d) PCC voltage waveform with Electric Spring and with nonlinear RL load

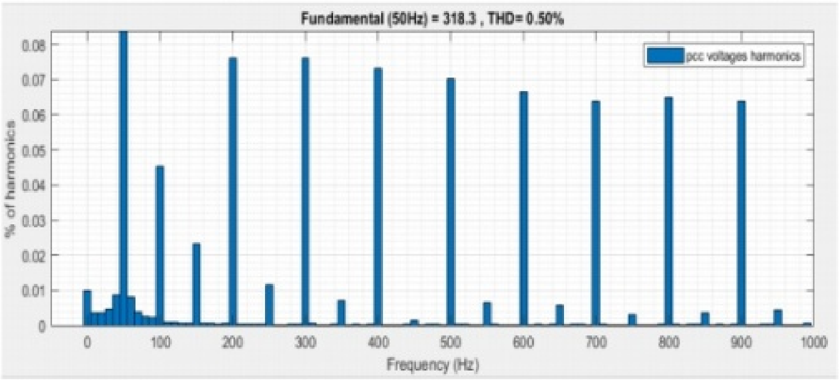


Fig. 6.4(e) PCC Voltages with Electric Spring and with nonlinear RL load

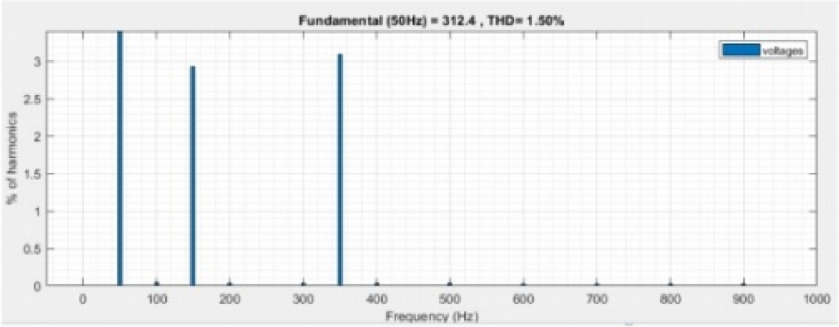


Fig. 6.4(f) PCC voltage harmonics with Electric Spring and with nonlinear RL load containing harmonic up to 5th order

Table 2 and 3 show the THD values with RL load for different case studies. It has been observed that the performance of the improved DSTATCOM is better than the traditional DSTATCOM as there has been considerable decrease of the THD in PCC voltage though there is slight increase in the current THD. It can be observed from both tables that Electric Spring provides better performance compared to DSTATCOM.

Table 6.1: Percentage THD in source currents and PCC voltages for nonlinear RL type load

System configuration	i_{sa} (%)	i_{sb} (%)	i_{sc} (%)	v_{ta} (%)	v_{tb} (%)	v_{tc} (%)
Without compensation	17.92	17.96	17.94	20.39	20.64	20.56
Traditional DSTATCOM topology	3.32	3.33	3.24	15.44	15.80	15.28
Improved DSTATCOM topology	4.40	4.50	4.29	7.46	7.49	7.52
Electric Spring	0.37	0.16	0.09	0.50	0.66	0.63

Table 6.2: Percentage THD in source currents and PCC voltages for nonlinear RL type load containing up to 5th order harmonics

System configuration	i_{sa} (%)	i_{sb} (%)	i_{sc} (%)	v_{ta} (%)	v_{tb} (%)	v_{tc} (%)
Without compensation	25.73	25.73	25.64	24.13	24.10	24.10
Traditional DSTATCOM topology	2.61	2.61	2.61	1.49	1.41	1.32
Improved DSTATCOM topology	3.38	3.40	3.70	036	0.36	0.36
Electric Spring	4.49	4.47	4.49	1.42	1.50	1.55

6.2 Simulation results with RC load

6.2.1 Simulation results without compensation

This section presents simulation results when nonlinear RC load is connected in the circuit. Fig. 6.5(a) shows harmonic distribution of source currents without compensation. These currents are distorted and unbalanced due to nonlinear RC load and therefore, source current contains harmonics. Fig. 6.5(b) shows harmonic distribution without compensation when nonlinear RC load delivers harmonics up to 5th order only. It has been observed that THD is quite high i.e. 20.92% and 15.99% respectively. Similarly, Fig. 6.5(c) depicts total harmonic distortion of three phase PCC voltages before compensation. These voltages are distorted and unbalanced due to nonlinear RC load.Therefore, PCC voltage contains harmonics and THD is 3.8%. THD for PCC voltage when nonlinear load delivering harmonics up to 5th order only is 7.34% as observed from Fig. 6.5(d).

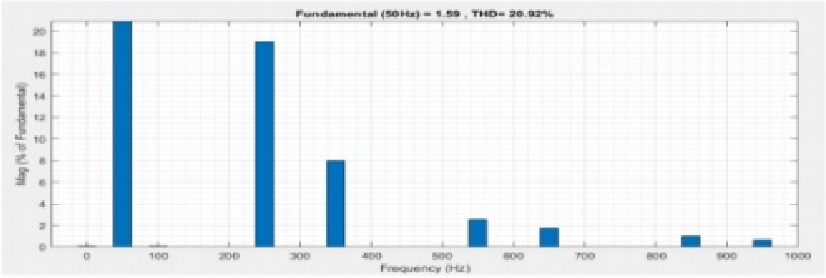


Fig .6.5(a) Source current harmonics without compensation and with nonlinear RC load

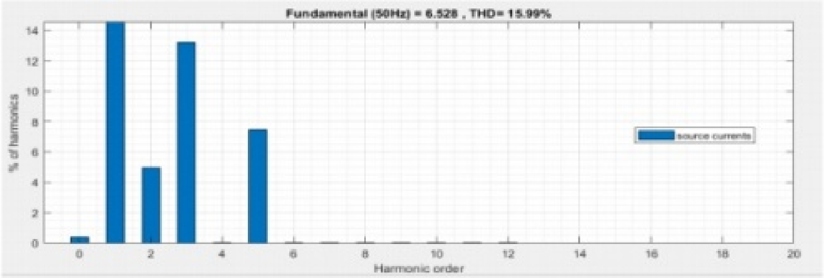


Fig. 6.5(b) Source current harmonics without compensation and with nonlinear RC load containing harmonics up to 5th order

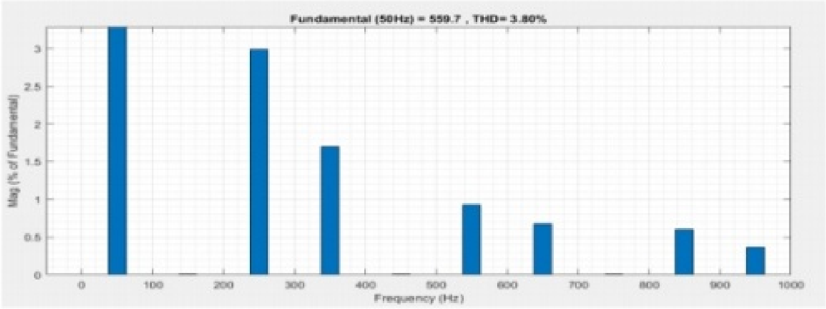


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Fig. 6.5(c) PCC voltage harmonics without compensation and with nonlinear RC load

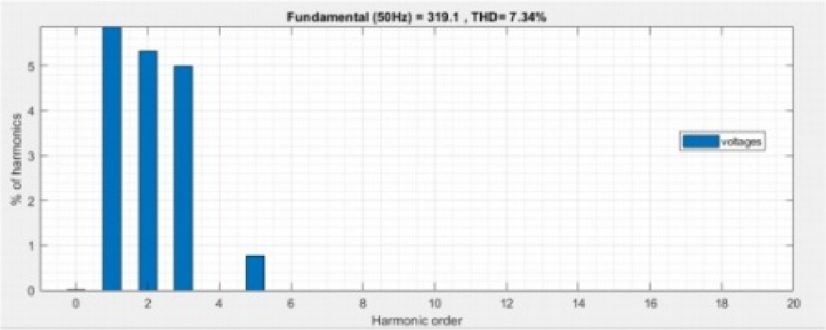


Fig. 6.5(d) PCC voltage harmonics without compensation and with nonlinear RC load containing harmonics up to 5th order

6.2.2 Simulation results with traditional DSTATCOM

Fig. 6.6(a) shows total harmonic distribution of source currents when traditional DSTATCOM is connected and the load is nonlinear RC load. Fig. 6.6(b) shows harmonic distribution in three phase source currents when nonlinear RC load delivering up to 5th harmonic current is connected. It has been observed that current THD has improved from 20.92% to 0.34% and from 15.99% to 2.78% with circuit is compensated with traditional DSTATCOM topology. Similarly, Fig. 6.6(c) and 6.6(d) present PCC voltage harmonic distribution for the two types of nonlinear RC loads with traditional DSTATCOM topology. It has been observed that PCC voltage THD has improved from 3.8% to 0.34% and from 7.34% to 2.78% when traditional DSTATCOM is connected.

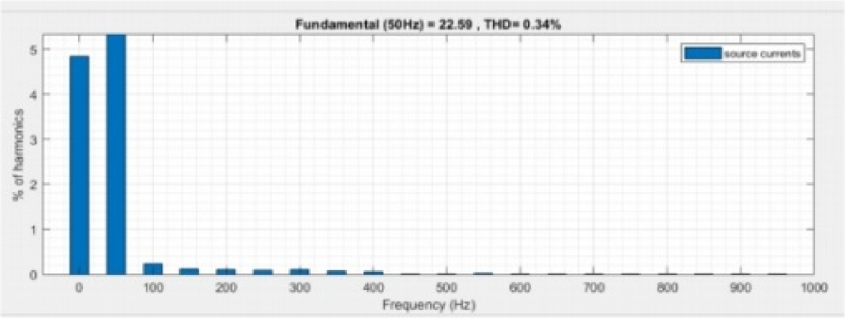


Fig. 6.6(a) Source current harmonics with traditional DSTATCOM topology and with nonlinear RC load

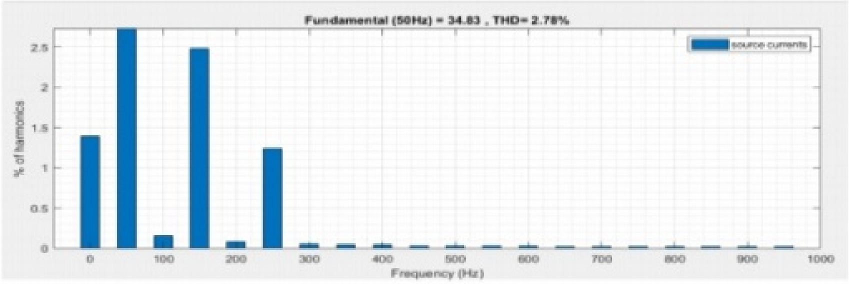


Fig. 6.6(b) Source current harmonics with traditional DSTATCOM topology and with nonlinear RC load containing harmonics up to 5th order

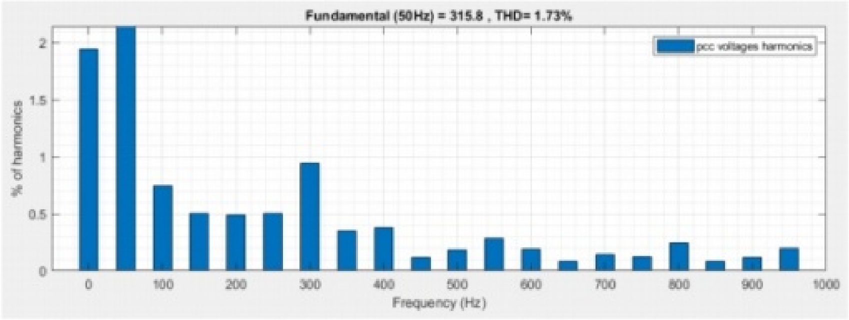


Fig. 6.6(c) PCC voltage harmonics with traditional DSATCOM topology and with nonlinear RC load

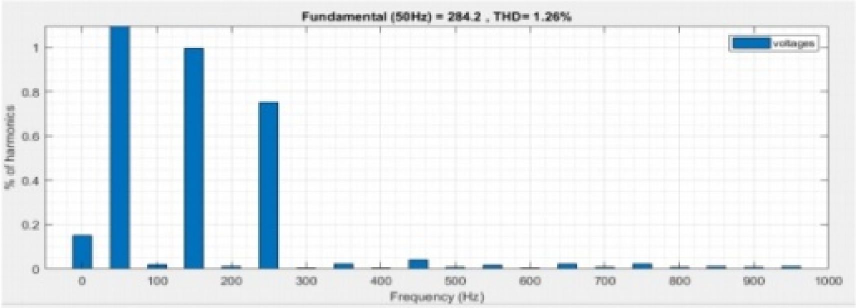


Fig. 6.6(d) PCC voltage harmonics with traditional DSATCOM topology and with nonlinear RC load containing harmonic up to 5th order

6.2.3 Simulation results with hybrid DSTATCOM

Fig. 6.7(a) and 6.7(b) depict the harmonic distribution in source current in the presence of hybrid DSTATCOM with two types of nonlinear RC connected load. Similarly, Fig. 6.7(c) and 6.7(d) depict the harmonic distribution in PCC voltage in the presence of hybrid DSTATCOM with same two types of nonlinear loads. It has been observed though current THD with hybrid topology is more than the traditional topology, but there has been considerable decrease in the value of voltage THD with hybrid DSTATCOM topology.

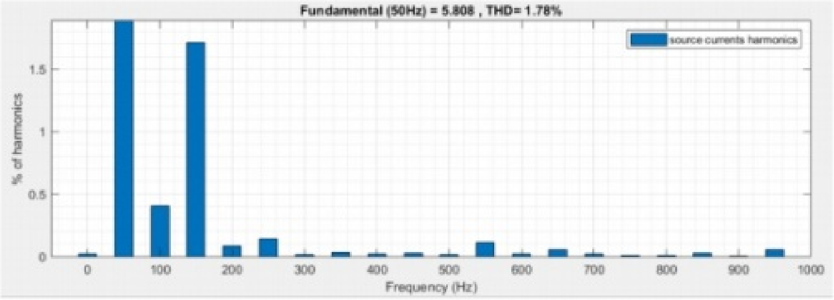


Fig. 6.7(a) Source current harmonics with improved DSATATCOM topology and with nonlinear RC load

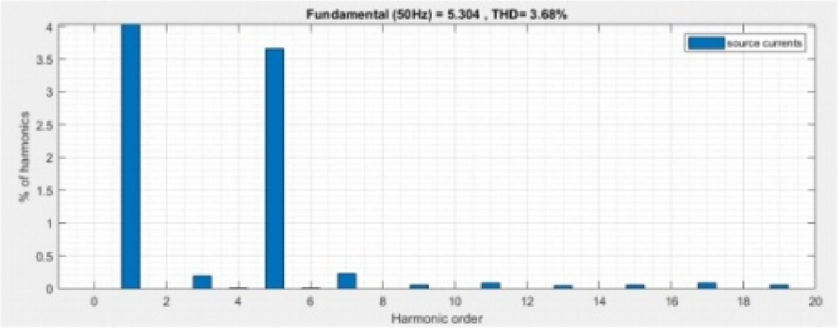


Fig. 6.7(b) Source current harmonics with improved DSTATCOM topology and with nonlinear RC load

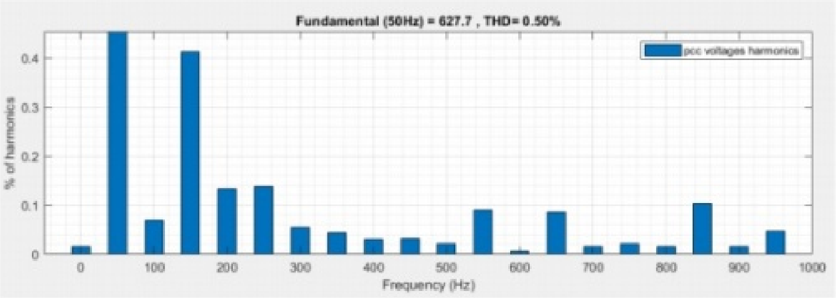


Fig. 6.7(c) PCC voltage harmonics with improved DSTATCOM topology and with nonlinear RC load

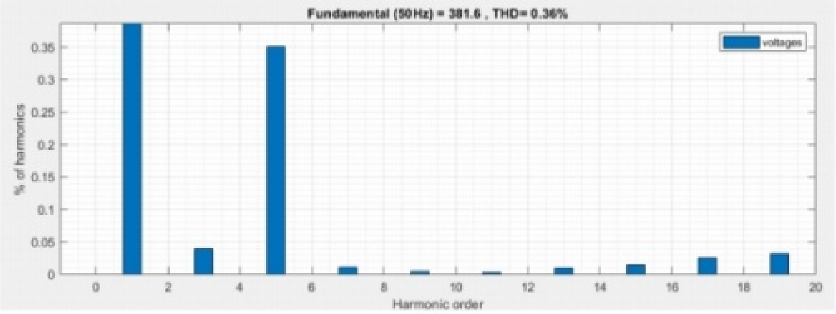


Fig. 6.7(d) PCC voltage harmonics with improved DSTATCOM topology and with nonlinear RC load containing harmonic up to 5th order

6.2.4 Simulation results with Electric Spring

The simulation results for Electric Spring with two types of nonlinear loads have been presented in this section. Fig. 6.8(a) and 6.8(b) shows the current harmonic distribution while Fig. 6.8(c) and 6.8(d) show voltage harmonic distribution. It can be observed that THD values are considerable less than the THD values without compensation and hence, it can be concluded that Electric Spring can efficiently mitigate harmonics.

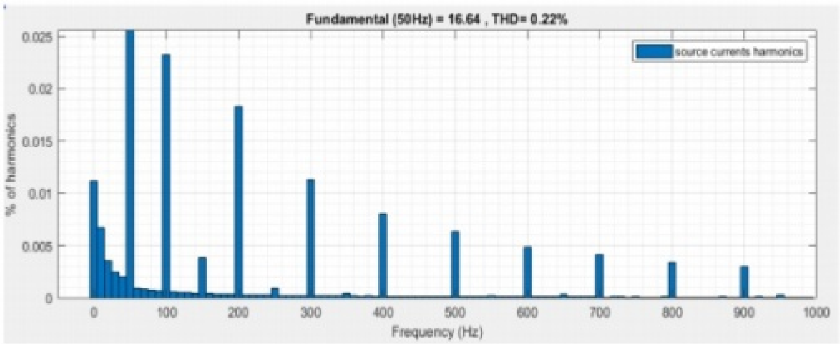


Fig. 6.8(a) Source current harmonics with Electric Spring and with nonlinear RC load

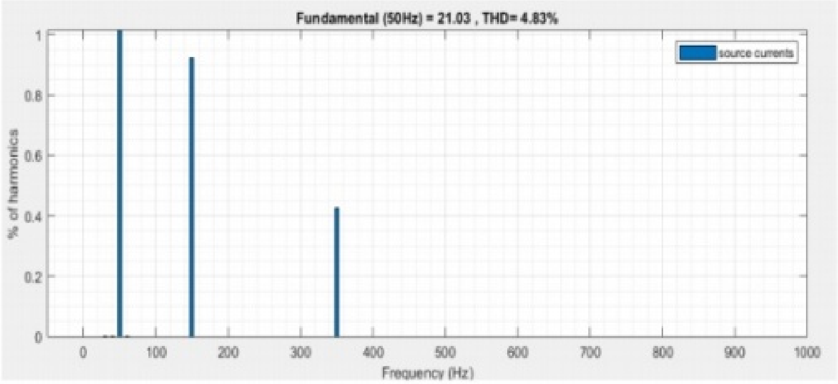


Fig. 6.8(b) Source current harmonics with Electric Spring and with nonlinear RC load containing harmonic up to 5th order

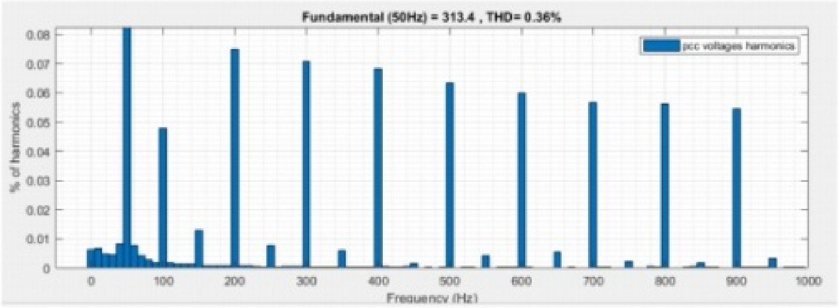


Fig. 6.8(c) PCC voltage harmonics with Electric Spring and with nonlinear RC load

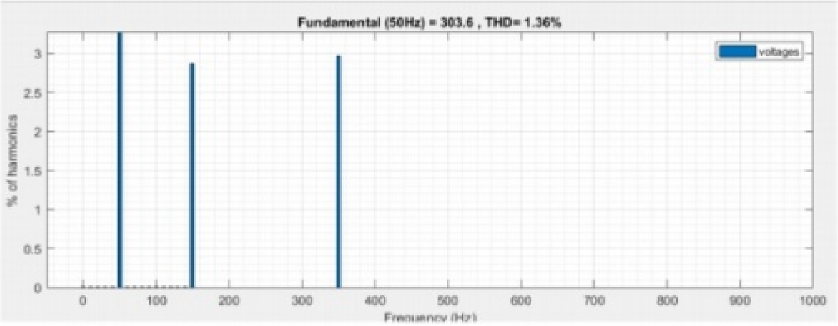


Fig. 6.8(d) PCC voltage harmonics with Electric Spring and with nonlinear RC load containing harmonic up to 5th order

Table 6.3 and 6.4 show the THD values in the source line currents of the three phases and the voltages of the three phases without compensation and with different types of compensators for the two types of nonlinear RC load.

Table 6.3: Percentage THD in source currents and PCC voltages for nonlinear RC type load

System configuration	i_{sa} (%)	i_{sb} (%)	i_{sc} (%)	v_{ta} (%)	v_{tb} (%)	v_{tc} (%)
Without compensation	20.92	20.94	21.0	3.79	3.81	3.80
Traditional DSTATCOM topology	0.34	0.53	0.46	1.18	2.04	1.42
Improved DSTATCOM topology	1.78	1.54	1.15	0.54	0.47	0.53
Electric Spring	0.22	0.11	0.06	0.36	0.48	0.45

Table 6.4: Percentage THD in source current and PCC voltage for nonlinear RC type load containing harmonic up to 5th order

System configuration	i_{sa} (%)	i_{sb} (%)	i_{sc} (%)	v_{ta} (%)	v_{tb} (%)	v_{tc} (%)
Without compensation	15.99	16.05	16.10	7.80	6.70	7.34
Traditional DSTATCOM topology	2.78	2.76	2.63	1.26	1.26	1.27
Improved DSTATCOM topology	3.39	3.68	3.76	0.36	0.38	0.36
Electric Spring	4.83	4.73	4.88	1.36	1.38	1.36

6.3 Simulation results with RL and RC load

6.3.1 Simulation results without compensation

This section presents simulation results when nonlinear RL and RC load is connected in the circuit. Fig. 6.9(a) shows harmonic distribution of source currents without compensation. These currents are distorted and unbalanced due to nonlinear RL and RC load and therefore, source current contains harmonics. Fig. 6.9(b) shows harmonic distribution without compensation when nonlinear RL and RC load delivers harmonics up to 5th order only. It has been observed that THD is quite high i.e. 17.14% and 11.14% respectively. Similarly, Fig. 6.9(c) depicts total harmonic distortion of three phase PCC voltages before compensation. These voltages are distorted and unbalanced due to nonlinear load. Therefore, PCC voltage contains harmonics and THD is 22.37 %. THD for PCC voltage when nonlinear load delivering harmonics up to 5th order only is 6.66% as observed from Fig. 6.9(d).

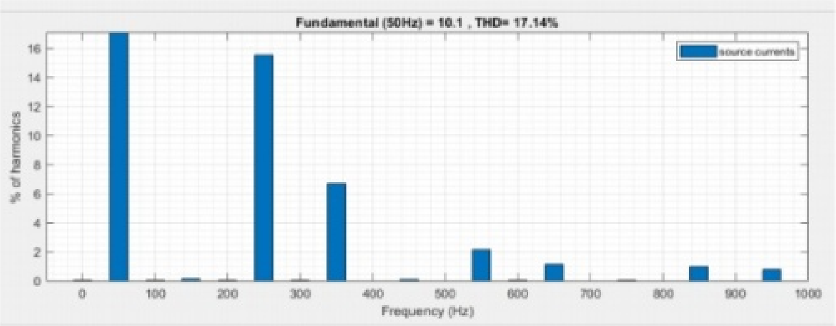


Fig. 6.9(a) Source current harmonics without compensation and with nonlinear RL and RC load

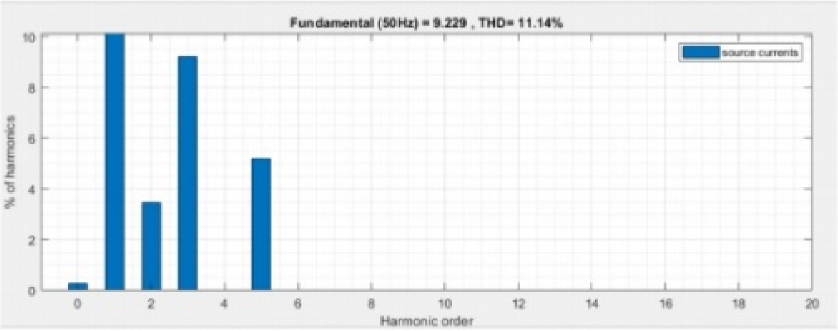


Fig. 6.9(b) Source current harmonics without compensation with nonlinear RL and RC load containing harmonic up to 5th order only

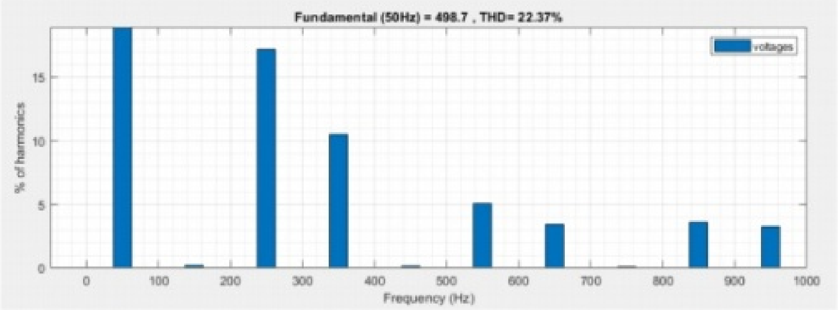


Fig. 6.9(c) PCC voltage harmonics without compensation and with nonlinear RL and RC load

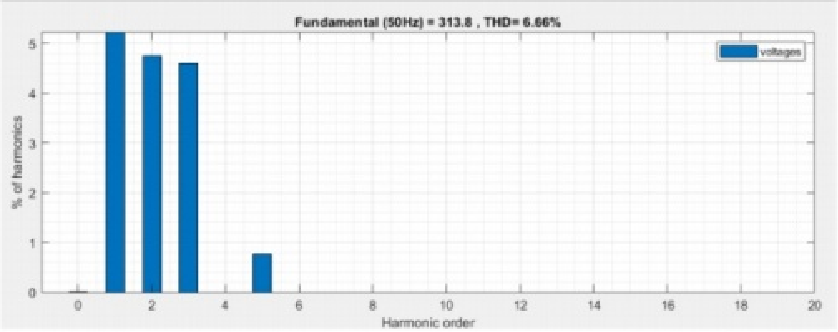


Fig. 6.9(d) PCC voltage harmonics without compensation and with nonlinear RL and RC load containing harmonic up to 5th order

6.3.2 Simulation results with traditional DSTATCOM

Fig. 6.10(a) shows total harmonic distribution of source currents when traditional DSTATCOM is connected and the loads nonlinear RL and RC loads. Fig. 6.10(b) shows harmonic distribution in three phase source currents when nonlinear RC load delivering up to 5th harmonic current is connected. It has been observed that current THD has improved from 17.14% to 2.99% and from 11.14% to 2.55% with circuit is compensated with traditional DSTATCOM topology. Similarly, Fig. 6.10(c) and 6.10(d) present PCC voltage harmonic distribution for the two types of nonlinear RL and RC loads with traditional DSTATCOM topology. It has been observed that PCC voltage THD has improved from 22.37% to 16.34% and from 6.66% to 1.26% when traditional DSTATCOM is connected.

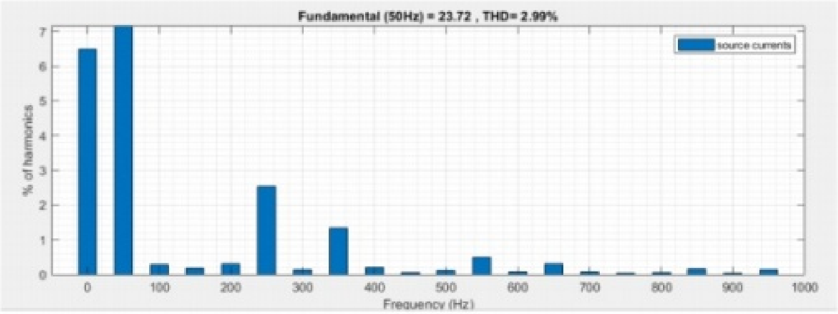


Fig. 6.10(a) Source current harmonics with traditional DSTATCOM topology and with nonlinear RL and RC load

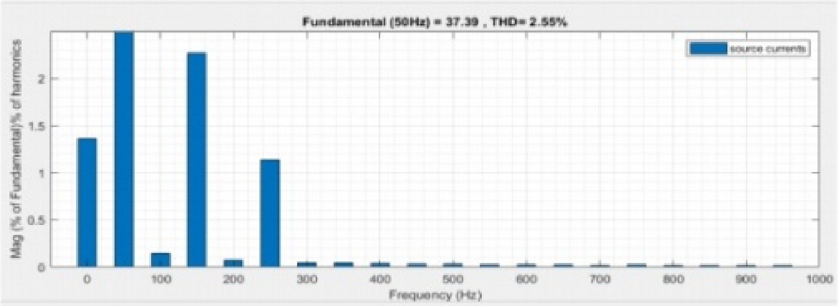


Fig. 6.10(b) Source current harmonics with traditional DSTATCOM topology and with nonlinear RL and RC load containing harmonic up to 5th order

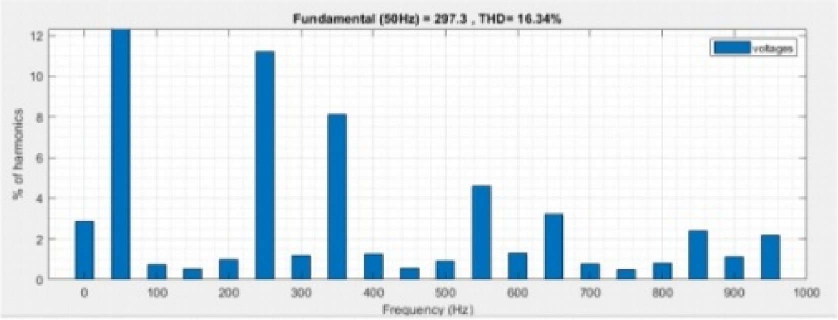


Fig. 6.10(c) PCC voltage harmonics with traditional DSTATCOM topology and with nonlinear RL and RC load

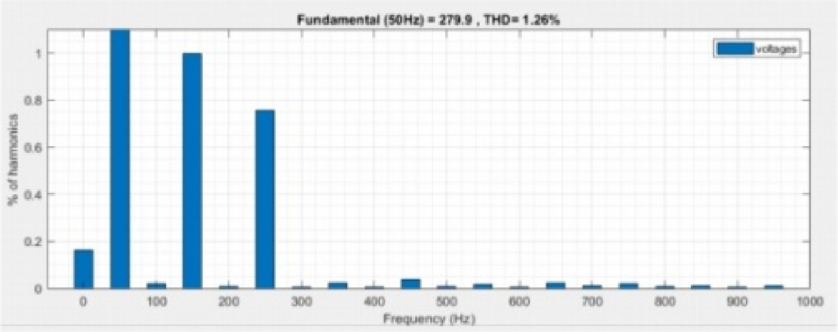


Fig. 6.10(d) PCC voltage harmonics with traditional DSTATCOM topology and with nonlinear RL and RC load containing harmonics up to 5th order

6.3.3 Simulation results with hybrid DSTATCOM

Fig. 6.11(a) and 6.11(b) depict the harmonic distribution in source current in the presence of hybrid DSTATCOM with two types of nonlinear RL and RC connected load. Similarly, Fig. 6.11(c) and 6.11(d) depict the harmonic distribution in PCC voltage in the presence of hybrid DSTATCOM with same two types of nonlinear loads. It has been observed though current THD with improved topology is more than the traditional topology, but there has been considerable decrease in the value of voltage THD with hybrid DSTATCOM topology.

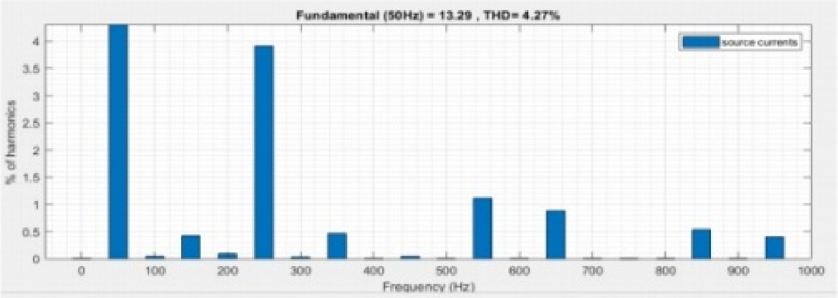


Fig. 6.11(a) Source current harmonics with improved DSTATCOM topology and with nonlinear RL and RC load

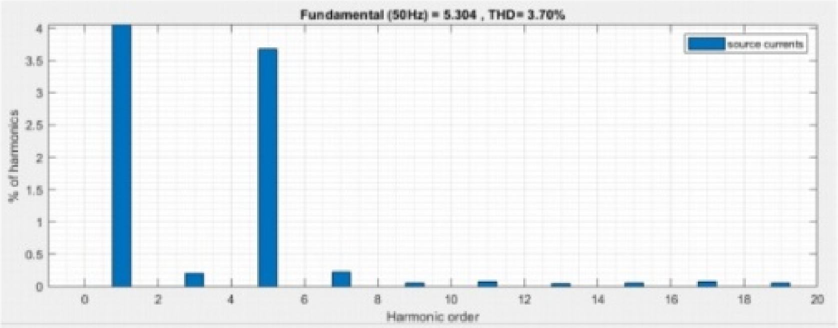


Fig. 6.11(b) Source current harmonics with improved DSATCOM topology and with nonlinear RL and RC load containing harmonic up to 5th order

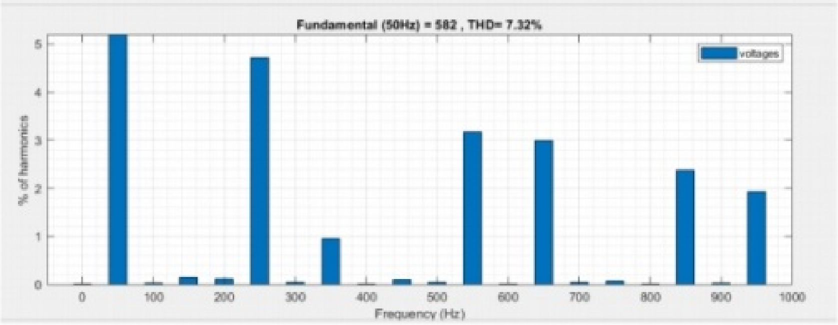


Fig. 6.11(c) PCC voltage harmonics with improved DSATCOM topology and with nonlinear RL and RC load

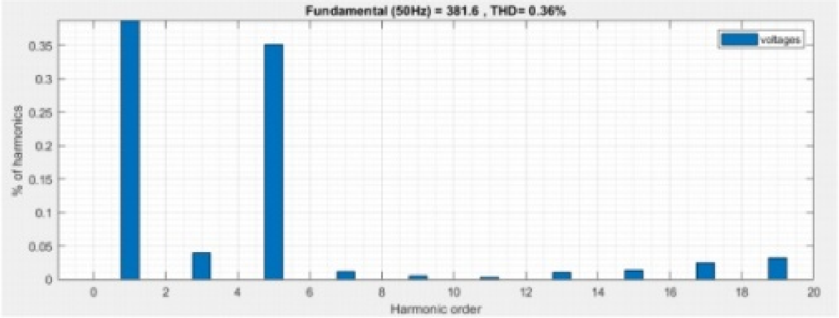


Fig. 6.11(d) PCC voltage harmonics with improved DSATCOM topology and with nonlinear RL and RC load containing harmonic up to 5th order

6.3.4 Simulation results with Electric Spring

The simulation results for Electric Spring with two types of nonlinear loads RL and RC have been presented in this section. Fig. 6.12(a) and 6.12(b) shows the current harmonic distribution while Fig. 6.12(c) and 6.12(d) show voltage harmonic distribution. It can be observed that THD values are considerably less than the THD values without compensation and hence, it can be concluded that Electric Spring can efficiently mitigate harmonics.

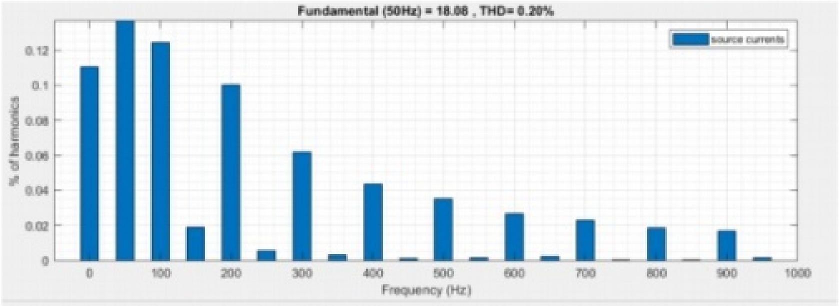


Fig. 6.12(a) Source current harmonics with Electric Spring and with nonlinear RL and RC load

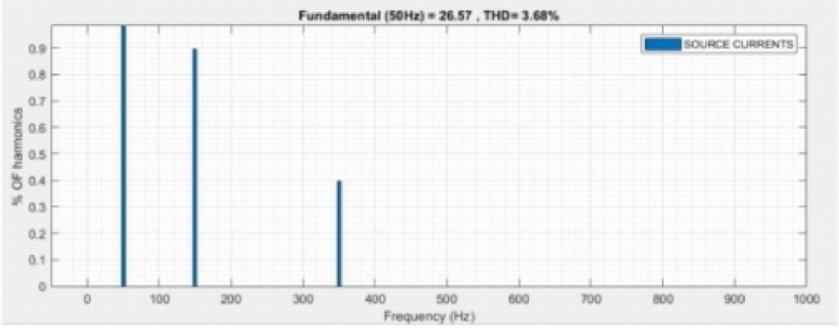


Fig. 6.12(b) Source current harmonics with Electric Spring and with nonlinear RL and RC load containing harmonic up to 5th order

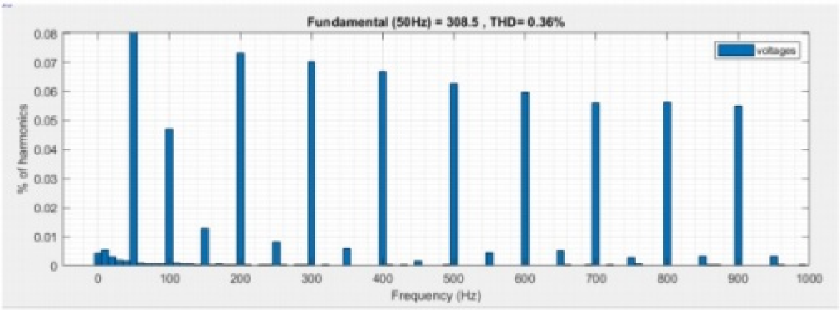


Fig. 6.12(c) PCC voltage harmonics with Electric Spring and with nonlinear RL and RC load

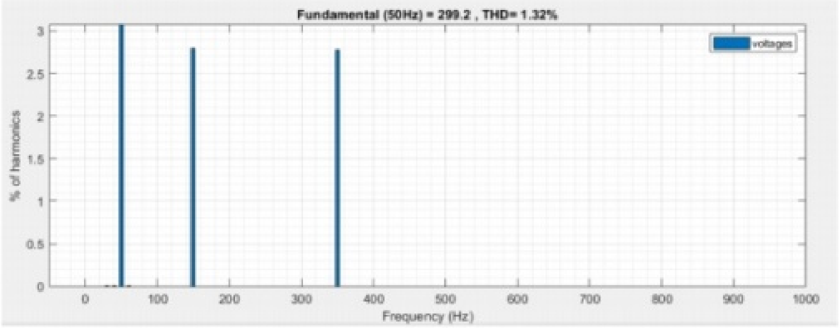


Fig. 6.12(d) PCC voltage harmonics with Electric Spring and with nonlinear RL and RC load containing harmonic up to 5th order

Table 6.5 and 6.6 show the THD values in the source line currents of the three phases and the voltages of the three phases without compensation and with different types of compensators for the two types of nonlinear RL and RC loads. It has been observed that the performance of Electric Spring is superior than DSTATCOM for mitigation of current and voltage harmonics.

Table 6.5: Percentage THD in source currents and PCC voltages for nonlinear RL and RC type load

System configuration	i_{sa} (%)	i_{sb} (%)	i_{sc} (%)	v_{ta} (%)	v_{tb} (%)	v_{tc} (%)
Without compensation	17.4	17.14	17.25	22.39	22.48	22.62
Traditional DSTATCOM topology	2.99	2.99	3.04	16.31	16.45	16.50
Improved DSTATCOM topology	4.27	4.31	4.24	7.31	7.36	7.37
Electric Spring	0.20	0.10	0.06	0.36	0.49	0.46

Table 6.6: Percentage harmonic in source currents and PCC voltages for RL and RC type load containing harmonic up to 5th order

System configuration	i_{sa} (%)	i_{sb} (%)	i_{sc} (%)	v_{ta} (%)	v_{tb} (%)	v_{tc} (%)
Without compensation	11.14	11.18	9.41	7.05	6.04	6.66
Traditional DSTATCOM topology	2.55	2.54	2.41	1.26	1.26	1.27
Improved DSTATCOM topology	3.39	3.69	3.70	0.36	0.38	0.36
Electric Spring	3.67	3.68	3.66	1.32	1.35	1.36

Chapter 7

Conclusions

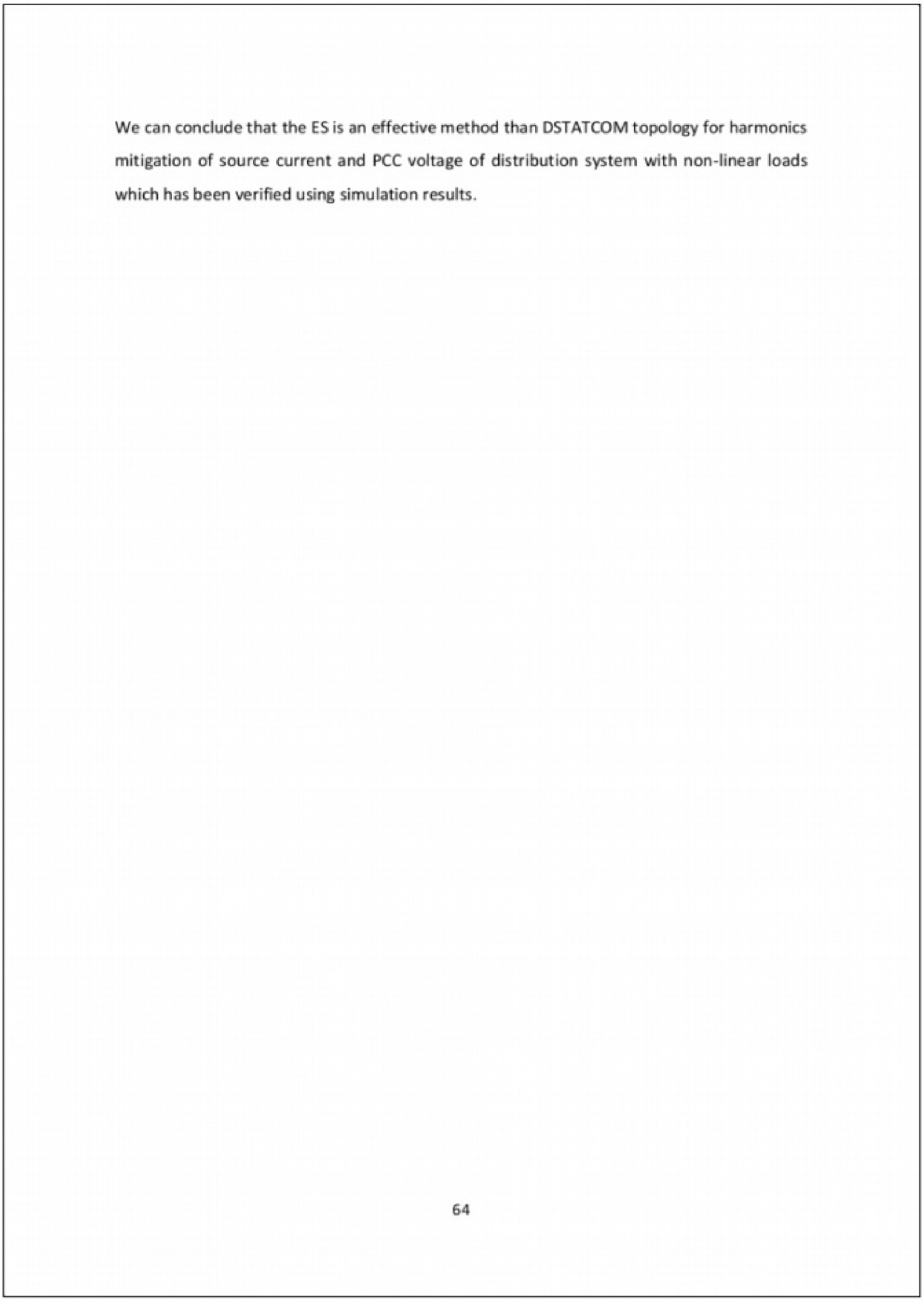
The performance of traditional DSTATCOM, hybrid DSTATCOM and Electric Spring has been studied for compensation of source current harmonics and PCC voltage harmonics in the distribution system with non-linear loads. In hybrid DSTATCOM, an LCL filter with a series capacitor called a hybrid interfacing filter is used. With this filter, hybrid topology gives improved the [4]load current compensation capabilities and with reduced dc-link voltage compared to traditional DSTATCOM. Moreover, as compared to traditional DSTATCOM topology, the current across the shunt capacitor is reduced, causing a reduction of cost, size, power rating and weight.

Compared to the traditional method, the value of coupling inductance is less, and therefore, reduced the voltage drop. Sufficient [46]dc-link voltage is maintained so that the voltage stress across switches is reduced which reduces the switching losses.

The simulation results demonstrate that in hybrid topology, the THDs [13]in three-phase source current are a little more than traditional but THDs in [13]PCC voltage are less in the hybrid topology compared to traditional topology. Therefore, overall losses in hybrid DSTATCOM topology are less compared to traditional DSTATCOM topology.

Electric Spring with inbuilt harmonic compensation function takes feedback from critical load voltage which compensates [25]the source current and the PCC voltage harmonics and minimizes the source current and PCC voltage. The harmonic compensation function in an electric spring produces anti-harmonic voltage and current.

The simulation results show that THDs in [3]source current and PCC voltage are less for Electric Spring compared to hybrid DSTATCOM topology and traditional DSTATCOM topology.Therefore the overall losses in Electric Spring are less compared to hybrid DSTATCOM reduces system's demand for energy storage. This makes ES a promising technology for power quality problems.



We can conclude that the ES is an effective method than DSTATCOM topology for harmonics mitigation of source current and PCC voltage of distribution system with non-linear loads which has been verified using simulation results.

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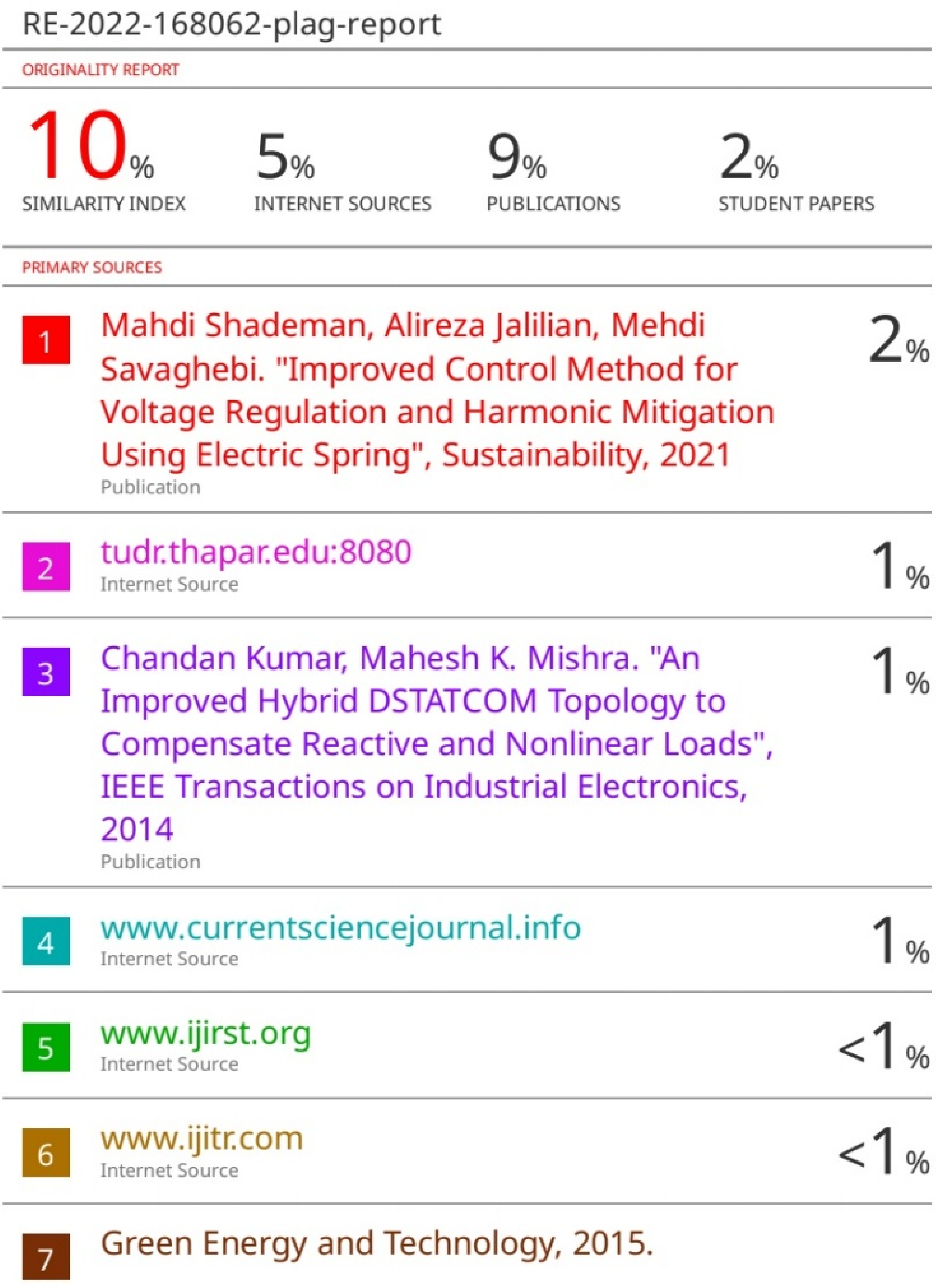

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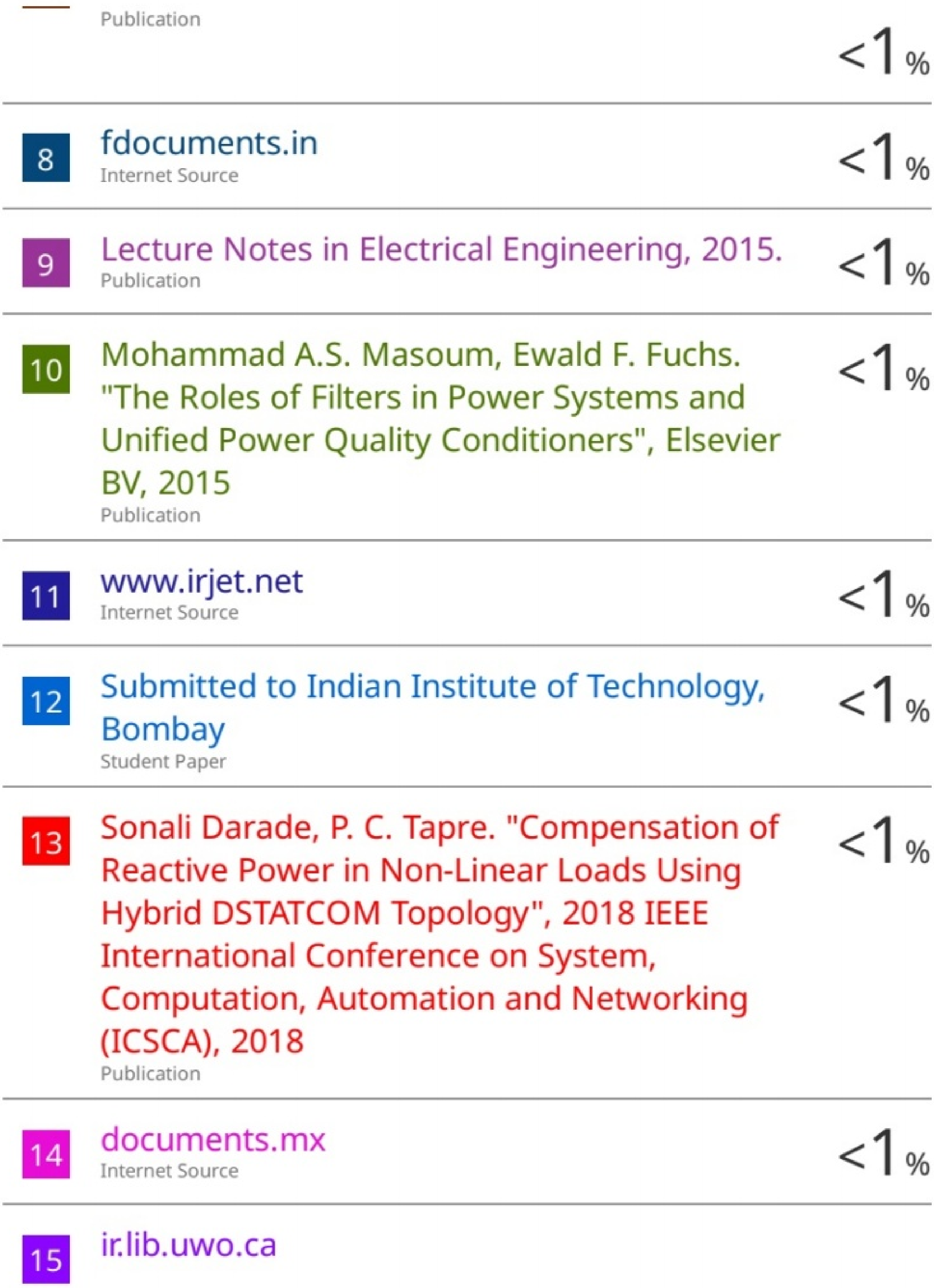

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