Modelling And Simulation of Shunt Active Power Filter For Power Quality Improvement

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1.1 INTRODUCTION

Nowadays, power electronics devices are mostly used everywhere like domestic application, industry utilization and commercial application throughout the world [1-2]. Most of the power electronics devices are non-linear load such as variable frequency drives (VFD), personal computers, arc furnaces, switch mode power supplies (SMPS), converters and so on which led to power quality problems like voltage sag, voltage fluctuation, noises, flickering and so on [3-4]. When the current waveform does not follow the voltage waveform, it is referred as a non-linear load. Insulation failures, electrical device heating, power losses, interface problems in communication systems, and worst-case electrical power system failures are all caused by harmonic distortions on the distribution side. [5]. Therefore, eliminating the power quality issues are a big challenge for both utility and customer [6]. Furthermore, current-related power quality issues are mostly caused by harmonics, inadequate reactive power, and unbalanced loads [7]. SAPF is considered to be one of the most effective methods for achieving higher levels of power quality. By generating equal and opposite magnitude of harmonic current at PCC, SAPF is employed to inject compensating current and reduce the harmonics [8]. While performing the adopted approach, it should be noted that, the THD should not exceed 5%, as adopted by IEEE standard [9].

According to the review of recent literatures, different SAPF configurations, each with its own control strategy proposed by various researchers. Various control strategy of SAPF has been explored like SRF method, instantaneous active-reactive power (p-q) method etc. Among such control technique methods, SRF is the most well-known and widely applied [10]. Conventionally, we used passive series and shunt filter in distribution side for power quality improvement [11]. But there are some drawback of passive filters is such as its instability, inflexibility, resonance problem with load impedance [12]. But, nowadays active filters are used for harmonic compensation at PCC. Series active power filter is used for voltage related problems, whereas SAPFs are used for current related problems. SAPF is used with voltage source inverter (VSI) has replaced the passive filter to overcome the drawback of passive filters. SAPF has several advantages like fast dynamic response, filtering accuracy and flexibility [13].

The reactive power sensing method and current harmonics are the majorly determined by SAPF's harmonic mitigation capacity [14]. In this paper, harmonics are mitigated in the source side. The SRF approach is effective, however in this approach grid synchronization necessitates the application of the PLL method. The majority of the literature states that the implementation of SAPF is essentially based on three control techniques named as reference current generation technique, dc-bus capacitor voltage regulation and inverter switching pulse generation technique. The synchronous reference approach is used to create reference current in this paper because it is the most convenient and practical way. The DC-bus capacitor voltage is regulated by the PI controller or by the FLC. The PI-controller necessitates the creation of a precise linear mathematical model, which is extremely tough to accomplish in practice. FLC-controller smoothly adjusts the dc-link voltage and can tolerate non-linearity in this system. Still, most of the researchers have used PI-controller for dc-bus voltage regulation in SRF based SAPF for improving the PQ level of micro-grid which is connected with grid.

1.2 OBJECTIVES

The primary goal of this study is to design and implement a SAPF control strategy that will decrease the harmonic currents on the source side as a result of increased utilization of non-linear loads. The SAPF compensate the both current harmonics and reactive power. For current harmonics compensation, many strategies have been proposed in the literature. The objective of thesis work is:

Design a SAPF based on a VSI with sufficient current regulator bandwidth, highly efficient, and faster dynamic outcomes.
Determination of the best control methodology to obtain the reference current from distorted line values of current.
Choose an appropriate PWM-current controller technique which would generate switching pulse to regulate VSI.
Simulate the SAPF's performance in terms of harmonic and reactive-power correction.

1.3 SHUNT ACTIVE POWER FILTER (SAPF)

The harmonics, produced by the loads of non-linear types, is compensated using SAPF. This harmonic filter is made up of a power VSI and dc-link capacitor that regulates filter's harmonic injection. As a result, this device detects current harmonics and produces equal and opposite harmonic component to balance the source's unnecessary harmonics. It is clearly a

feedback mechanism in place, as the source generates clean waveforms for the load. The following are some of the advantages of employing a SAPF.
(a) Harmonics reduction
(b) Power factor improvement
(c) Reduces the resonance between filter and network impedance

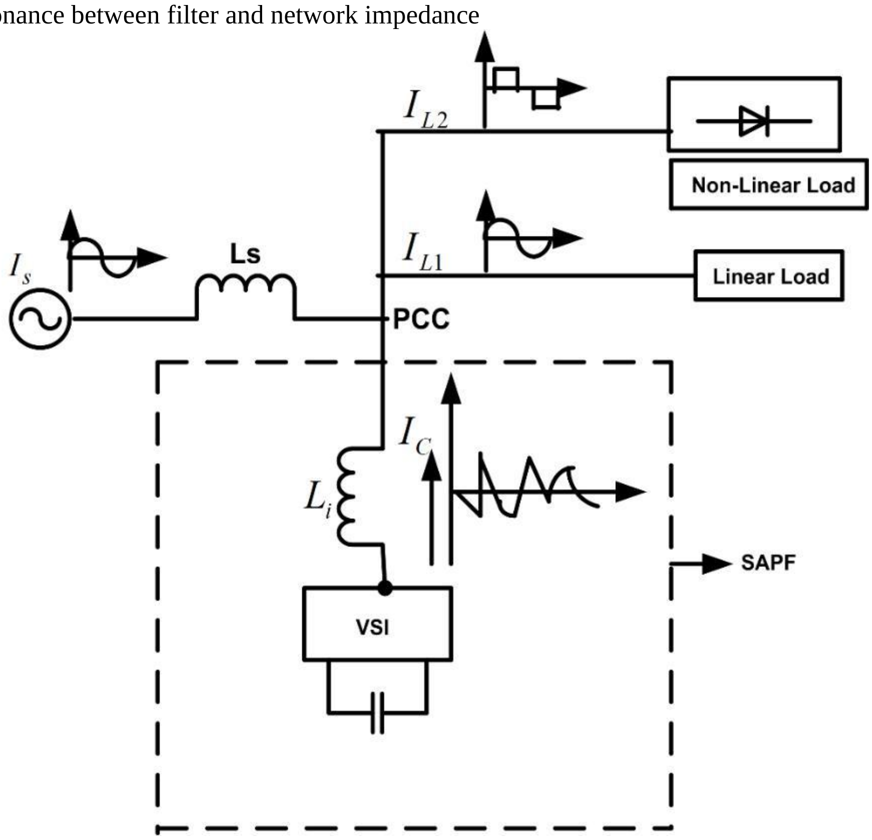


Figure 1.1: ***Basic structure of SAPF***

The SAPF configuration is chosen in this thesis. At the Point of Common Coupling (PCC), the SAPF is linked in parallel with the load being corrected. A two-level VSI based on PWM and operating in current control mode is used in this power circuit. For a faster response, the current compensation is done using a time domain approach. This SAPF is used to cancel out load current harmonics, the goal is inject to compensating current at the PCC to *is* become sinusoidal [15].
Fig. 1.1 shows the basic structure of SAPF. The DC side of a VSI has connection of an electrolytic capacitor, while the ac side of VSI has its connection through an interface inductor to an AC bus. As a result, the SAPF delivers the load current's harmonic components and allowing the grid to deliver only load current's harmonic fundamental component. An active power inverter and an interface inductor are used to create the current waveform for cancelling harmonics. By precisely regulating the switches in the VSI, the compensation filter current waveform can be obtained. The inverter's switching frequency and the available voltage across the interface inductor limit the control of current wave shape. This is significant because higher order harmonic components may necessitate somewhat high di/dt values to compensate. As a result, selecting an inductor is critical [16].
It is vital to note that the SAPF is necessary to deliver the compensating current at PCC in this arrangement. The SAPF should only be used to supply the load's reactive power in an ideal circumstance. As a result, it is critical to discuss the following concern in order to connect the SAPF at PCC:
Extract the suitable reference current Pulse generation for VSI
Maintain the dc-link voltage

1.4 LITERATURE REVIEW

The controller is the most important component of the SAPF system and different control schemes have been discussed in the literature recently. For the SAPF, there are primarily three types of controllers:
Generation of reference current from the distorted line current using the reference current extraction method.
The switching pulses to operate the inverter are generated using a PWM-VSI current control approach.
DC-bus voltage is regulated by effective controller

1.4.1 Reference Current Generation Technique

The reference current extracted from the distorted line currents, many control approaches have been proposed in the literature. Time domain and frequency domain technique can be used to classify according to reference current extraction approaches [17]. To extract the compensatory reference current, the time domain control approach is suitable for SAPF.

Both 1 and 3 systems can be benefitted from frequency domain techniques. Three-phase systems are typically studied using time domain methods. When compared to frequency-domain methods, the time-domain technique has a faster response [18]. Bhattacharya proposed calculating the d-q components of instantaneous 3 current. This technique generates reference currents from load currents by creating a SRF approach [19-20]. Salem Rahman demonstrated how to derive reference currents for a three-phase SAPF using a non-linear control technique. The approach compensates for reactive, unbalanced, and harmonic current components in the load [21].

1.4.2 PWM-Current Control Technique

For active filter applications, various PWM-VSI current control approaches are explored. The predictive controller is the most complicated and comprehensive piece of hardware, and it has the potential to limit the controller's dynamic response. The hysteresis controller with three independent controllers perform admirably. By providing zero voltages at appropriate periods, the switching frequency can be lowered Marian demonstrated two new PWM-VSI current-control methods. Both approaches rely on three-level hysteresis comparators, which use a switching electrically programmable read-only memory table to pick optimal voltage source inverter output voltage vectors [23]. Dixon simulated and assessed various current modulation algorithms for voltage source inverters. In comparison to previous approaches, the triangular-carrier controller claimed to have the lowest harmonic distortion and the lowest current ripple. However, the proportional gain approach introduced overshoot issues. With considerable time delays, the periodical- sampling controller improves and performs better when slow power switches are employed. Because of its ease of implementation, the hysteresis-band instantaneous current control PWM approach is widely utilised [24]. The hysteresis controller and SVM technique are both used in this technique. The controller uses an area detector to generate a set of space vectors and then applies a space vector chosen by the primary hysteresis controller. When compared to a two-level hysteresis current controller, this produces a significant reduction in the size and fluctuation of the switching frequency while also improving efficiency [25]. A SAPF was optimized using fuzzy hysteresis control and parametric optimization by B.Mazari. The PWM-switching inverter's pulses should match the load's harmonic needs while keeping a constant dc voltage. As a result, when the SAPF has a non-linear demand, it should only receive sinusoidal UPF balanced currents from the AC mains.

1.4.3 DC-Link Voltage Regulation Technique

The expected value of reference current for the PWM dc-link voltage regulation is investigated using PI and PID controllers [26]. DC-link voltage can be controlled by using PI-controllers, fuzzy logic controllers (FLCs) and other controller. But PI-controller is easy to implement. This type of controller requires accurate linear mathematical computation, which is complex to achieve in the face of parametric variations and load disruptions. Several artificial intelligence (FLC and GA etc.) control systems have been published in recent years to retrieve the reference current from the distorted line current [27]. To predict the quantity of reference current and keep the PWM-dc-voltage inverter's close to constant, the FLC is used. This method does not require a numeric calculation and can tolerate faulty data and non-linearity [28].

PQ PROBLEMS AND SOLUTIONS

2.1 INTRODUCTION

In this chapter PQ problems and solutions have been discussed as well as IEEE standard for PQ issue. PQ solutions method such as DVR, Filter, D-STATCOM and UPQC has been discussed briefly.

2.2 POWER QUALITY PROBLEMS

The use of sensitive electronic loads such as digital controllers and computers is the primary cause of power quality difficulties. Some of these devices have issues as a result of their closeness to other electrical equipment or power line disturbances because bigger power loads cause more disturbances.

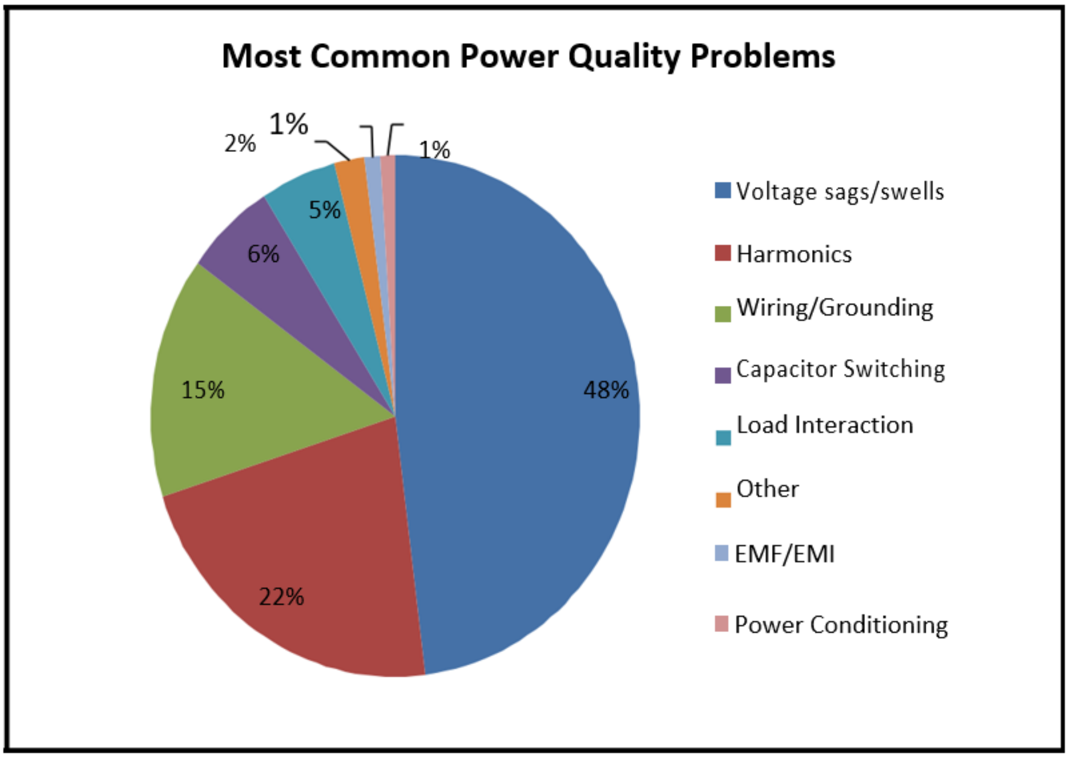


Figure 2.1: ***Most common power quality problems***

Poor power quality causes rapid wear and tear, overheating, inappropriate operation of electrical and electronic equipment and circuit breaker tripping, which can lead to dangerous situations. According to EPRI data, customers' premises account for 70% of all power quality concerns, while the network side accounts for 30%. The most common power quality issues among American consumers were voltage sags, voltage swells and harmonics caused by capacitor switching and harmonics, among other issues. Fig. 2.1 depicts the most prevalent power quality issues, which are discussed further below.

2.2.1 Voltage Sag

A voltage sag is defined as the decreases the voltage level between 0.1 to 0.9 pu for the duration of 0.5 cycle to 1 minute. Distribution and transmission system problems are the most common causes of voltage sags. Voltage sags can also be caused by defects in consumer-premises installations, transformer energization and the start of large motors. Fig 2.2 depicts the waveform of voltage sag. Because of its lower component ratings and lower cost, a series active power filter is superior to UPS for compensating for voltage sags from the AC supply.

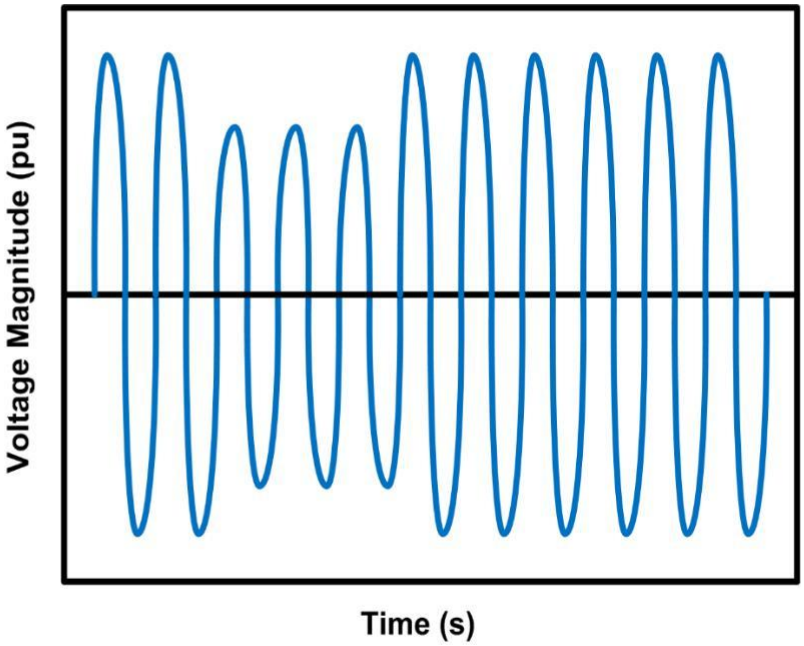


Figure 2.2: ***Waveform of voltage sag***

Table 2.1 Types of voltage sag

Sag	Time span	Voltage magnitude
Instantaneous	0.5-30 cycles	0.1 to 0.9 pu
Momentary	30 cycles to 3 sec	0.1 to 0.9 pu
Temporary	3 sec to 1 min	0.1 to 0.9 pu

2.2.2 Voltage Swell

When the supply voltage rises drastically in a short time period, this is known as a voltage swell. Fig. 2.3 depicts the waveform of voltage swell. Voltage swells are usually caused by capacitor switching. Surge suppressors are used for the problem related with voltage swell.

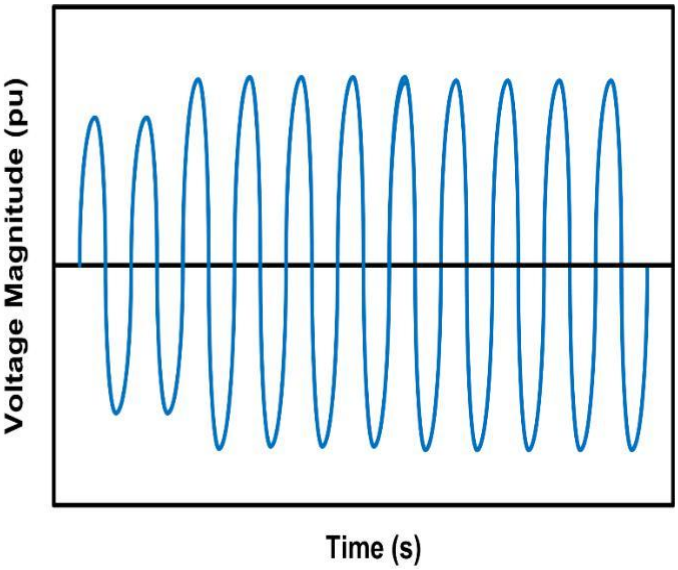


Figure 2.3: ***Waveform of voltage swell***

Table 2.2 Types of voltage swell

Swell	**Time span**	**Voltage magnitude**
Instantaneous	0.5-30 cycles	1.1 to 1.8 pu
Momentary	30 cycles to 3 sec	1.1 to 1.4 pu
Temporary	3 sec to 1 min	1.1 to 1.2 pu

2.2.3 Voltage Flicker

Voltage flicker also known as voltage fluctuations, refers to abrupt short-term changes in voltage levels induced by load switching or sudden shifts. Fig. 2.4 depicts the waveform of voltage flicker. Voltage flicker shorten the lifespan of electrical equipment and lighting as well as having a negative impact on human health by causing migraines and headaches owing to the strain placed on the eyes. In order to correct voltage fluctuations, voltage stabilisers and motor starters can be utilised.

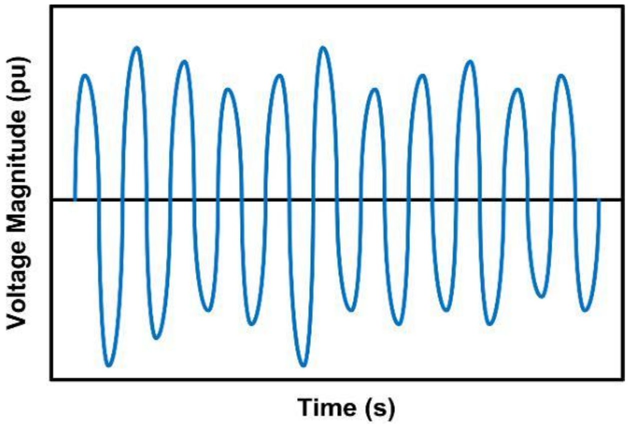


Figure 2.4: ***Waveform of voltage flicker***

2.2.4 Voltage Transient

Lightning or switching operations can cause a transient, which is a sudden change in frequency of the voltage in a steady state scenario.

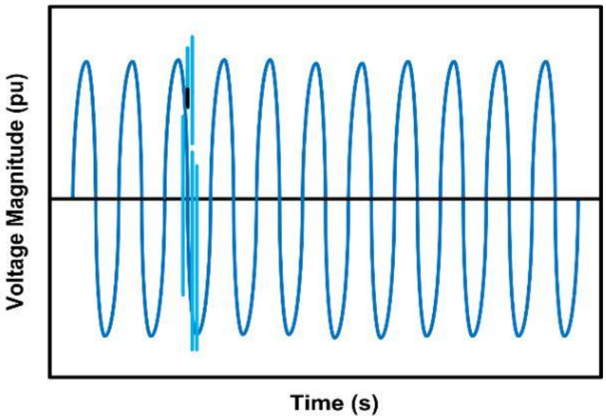


Figure 2.5: ***Waveform of impulsive transient***

Oscillatory transients may result from impulsive transients, which can damage power line insulators. Fig. 2.5 depicts the waveform of impulse voltage transient and oscillatory voltage transient. Surge arrester is commonly used to prevent impulsive transients.

2.2.5 Voltage Notching

During the regular operation of power electronic devices such as a rectifier, notching is a recurring PQ problem that happens during current commutation. Current waveform is the starting point for harmonic analysis, the IZ dips of harmonic currents can be used to derive voltage notching. Fig. 2.6 depicts the waveform of voltage notches. During the current commutation from one phase to another, a short circuit occurs between two phases.

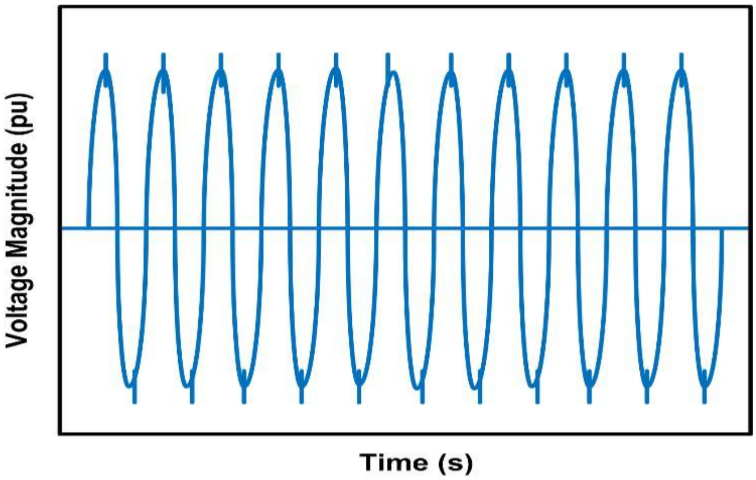


Figure 2.6: ***Waveform of voltage notches***

2.2.6 Interruption

A zero-voltage incident is referred to as a short interruption. Insulator flashover, lightning, faulty grounding, and insulation failure are the most common causes of system failure. Short power outages can result in data loss, protective device tripping, data processing equipment damage, and system failure. A long interruption is a condition in which the voltage is 0 for longer than two cycles. Fig. 2.7 depicts the waveform of interruption. Utility power failure and improper coordination or tripping of a circuit breaker are all possible causes of a blackout. Long power outages cause systems to completely shut down, lose data, and lose control. It could also cause electrical gadgets to be damaged. Generators can be utilized as power backups in the case of a power failure.

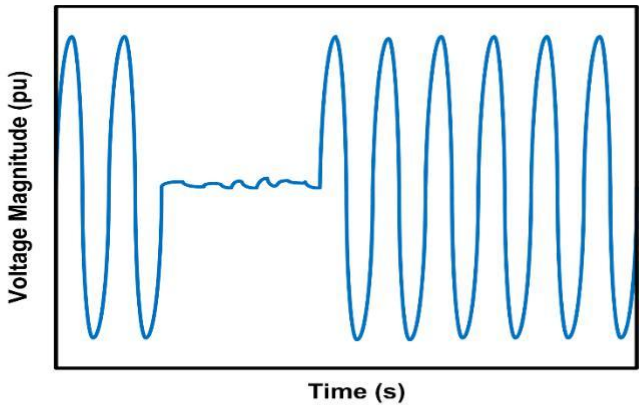


Figure 2.7: ***Waveform of interruption***

Table 2.3 Types of interruption

Interruption	Time Span	Voltage Magnitude
Instantaneous	0.5-30 cycles	< 0.1 pu
Momentary	30 cycles to 3 sec	< 0.1 pu
Temporary	3 sec to 1 min	1.1 to 1.2 pu

2.2.7 Electrical Noise

Electrical noise is a periodic, rhythmic distortion of the waveform with a frequency range up to 200 kHz. Fig. 2.8 depicts the waveform of electrical noise. Electromagnetic fields commonly generate electrical noise in networks, but poor grounding can also cause it.

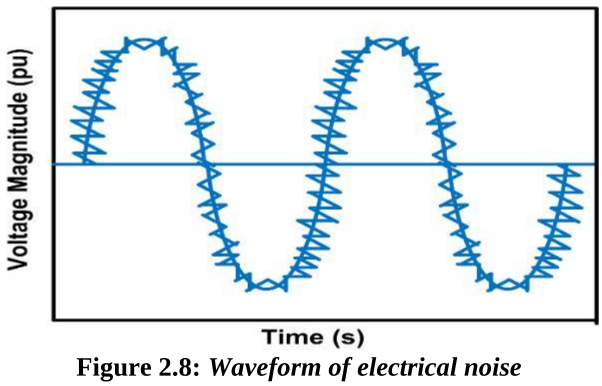


Figure 2.8: ***Waveform of electrical noise***

2.2.8 Harmonic Distortion

Variable speed drives and solid-state rectifiers, which are non-linear loads, create harmonic distortion, which is a common distortion of the sine wave pattern of the supply voltage or current. When the frequency of voltage or current is not an integer of the fundamental then it is termed as inter-harmonics. Transformer heating and increasing losses in the copper, core, and stray-flux may result in irregular tripping of thermal safeguards and relays as a result of harmonic distortion. Furthermore, it may result in cable losses, traffic control or ripple control system malfunctions, an increased likelihood of resonance, degeneration or failure of power factor correction capacitors, neutral conductor overload in three-phase systems and loss of efficiency in electric machines. Finally, harmonic currents, a low power factor, electromagnetic interference (EMI) and communication system interference may induce losses in the distribution network. Fig. 2.9 depicts the waveform of harmonic distortion. To compensate for harmonic load current, a shunt active power filter can be employed to inject an opposing and equal compensating harmonic current. A base sine waveform, its third harmonic and the distorted waveform, which is the sum of the base waveform and its third harmonics component.

$$THD \quad \frac{\sqrt{\sum_{n\,2} V^{2}_{n,rms}}}{V_{f,rms}}$$

Where and $V\,f$
rms is the rms voltage of nth harmonic frequency
is the rms voltage of fundamental frequency

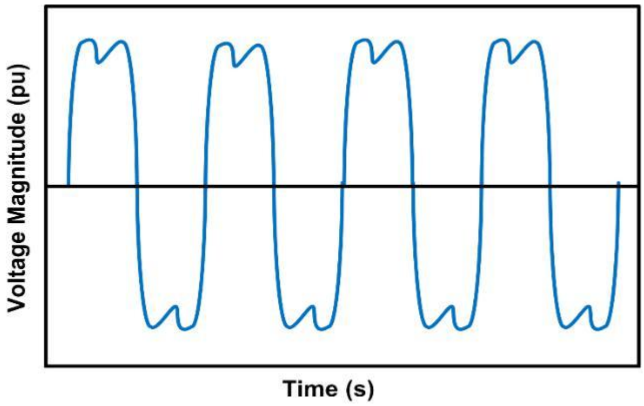


Figure 2.9: ***Waveform of harmonic distortion***

2.2.9 Overvoltage and Undervoltage

Undervoltage is defined as decrease in rms value of voltage up to 90% at power frequency for more than 1 minute. It happens due to load switching, incorrect tap setting of transformers. Overvoltage is defined as increase in the rms value voltage greater than 110% at power frequency for more than 1 minute. Fig. 2.10 and Fig. 2.11 depicts the waveform of under voltage and overvoltage respectively. It happens due to load switching, overloaded circuit and capacitor bank switch off.

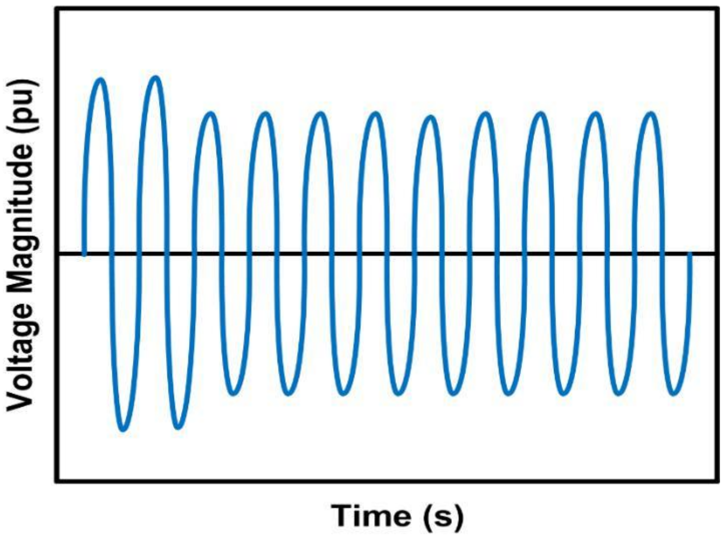


Figure 2.10: ***Waveform of undervoltage***

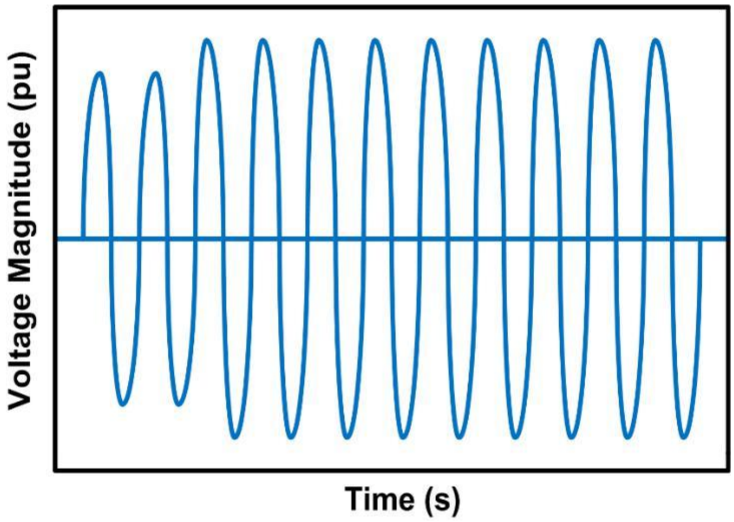


Figure 2.11: ***Waveform of overvoltage***

Table 2.4 Difference between overvoltage and undervoltage

Long duration variations	**Time span**	**Voltage magnitude**
Under-voltage	>1 min	0.8 to 0.9 pu
Overvoltage	>1 min	1.1 to 1.2 pu
Sustained interruption	>1 min	0.0 pu

2.2.10 Electromagnetic Interference (EMI)

EMI is a high-frequency phenomenon that occurs when magnetic and electric fields interact with sensitive electronic devices and circuits. Inductance is created on data-carrying systems as a result of EMI and RFI. Voltages above the functioning data levels can produce data that is opposite or different from that travelling in the data line. As a result, EMI and RFI bring noise into the system, which has an impact on power quality.

2.3 POWER QUALITY SOLUTIONS

D-STATCOM, Passive filter, Active filter, Dynamic voltage restorer (DVR), Unified power quality conditioner (UPQC) and others are the technologies available to address power quality issues.

2.3.1 Active and Passive Filter

An active filter is a type of filter device that deploys active elements like transistors or operational amplifiers, both of which require external power. A passive filter does not require an external power source and is made up of passive elements such as transformers, inductors, capacitors, and resistors, as well as nonlinear and complex linear elements such as transmission lines. Passive filter is a device that is composed entirely of passive parts and so requires external power to operate. Passive filters are primarily employed in the 100-500 kHz frequency range. Filters are categorized into five types based on the coefficients of the transfer function. Low pass, high pass, band pass, notch and all pass are the different types of filters.

Table 2.5 Difference between active filter and passive filter

Active filter	Passive filter
It requires an external power source.	It does not require an external power source.
It is made up of an active component.	It is made up of a passive component.
It has low output impedence and high input impedence.	It has high output impedence and low input impedence.
It has high oscillation and noises due to feedback loops for regulate the active component.	It has low oscillation and noises.
It does not consume the energy of signal.	It consumes energy of signal.
It has stable tuning, accuracy and high immunity to EMI.	It operates at a higher frequency.

2.3.2 Distribution Static Compensator (D-STATCOM)

Current injected by a Distribution Static Compensator can improve low power factor, harmonic distortion, voltage swells and voltage sags. The D-STATCOM is a device that can be based on a VSC and is used to limit reactive power flow in a distribution system through compensation. A VSC may produce a sinusoidal voltage with any specified phase angle, frequency and magnitude. Fig. 2.11 depicts the block diagram of D-STATCOM. The VSC is powered by energy storage devices like capacitors, which provide a DC voltage that is subsequently utilized to switch the solid-state electronics devices. D-STATCOM is represented by a current source because it is working in a current control mode.

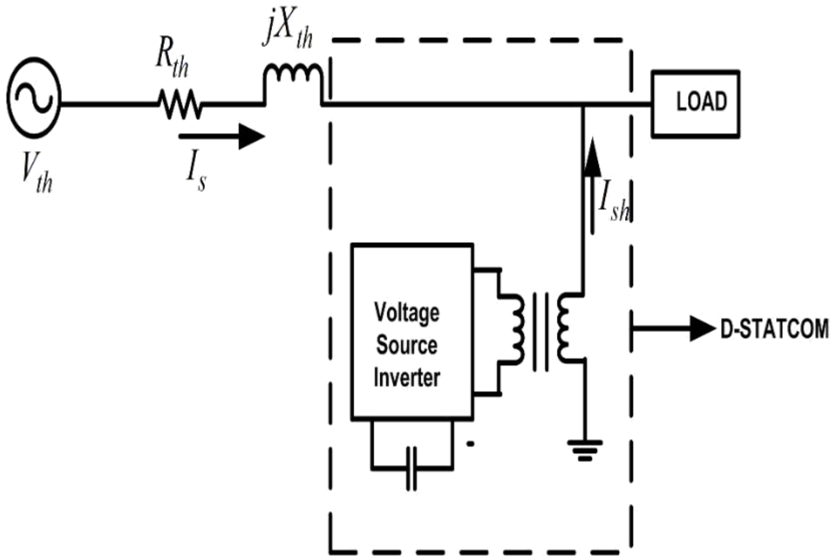


Figure 2.12: ***Block diagram of D-STATCOM***

2.3.3 Dynamic Voltage Restorer (DVR)

A DVR can protect against sensitive loads from voltage sags, surges. For protection of sensitive loads, a voltage source injecting a voltage can be utilized to simulate an ideal DVR. This device can be built to be able to supply or absorb real power or it can be built to be unable to do so. The DVR's voltage is controlled by regulating the dc-link voltage to any desired value and measure terminal voltage. Fig. 2.12 depicts the block diagram of DVR. At the time of steady state, if the DVR is unable to consume or deliver any actual power, it will do so during transients.

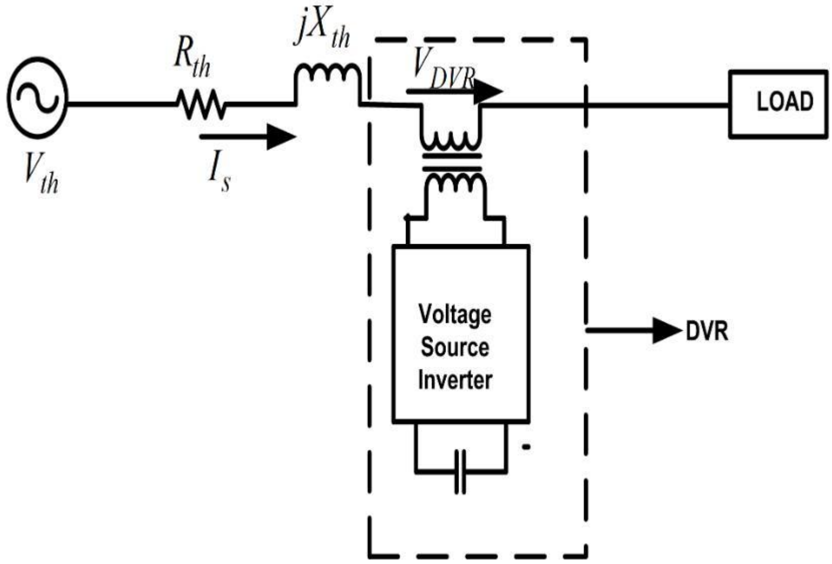


Figure 2.13: ***Block diagram of DVR***

2.3.4 Unified Power Quality Conditioner (UPQC)

UPQC is a combination of series DVR and shunt STATCOM compensators as a single solution for mitigating the both voltage and current related based power quality issue. Fig. 2.13 depicts the block diagram of UPQC. A custom power device (CPD) is known as UPQC is consider as the right choice for critical and sensitive load. When coupled to two voltage source inverters, a UPQC uses a shared capacitor for DC energy storage. The AC line is linked in shunt with one of the VSI, while the other is connected in series with the same AC line. Harmonics, reactive power, negative sequence current, voltage imbalance, and voltage flicker are all compensated with a UPQC. The series VSI, which injects a series voltage at the point of common connection, eliminates voltage imbalance and voltage flicker from the load terminal voltage. To reduce current harmonics, a series voltage proportionate to the line current injected into distribution side. In this device, shunt VSI is used to provide a conduit for active power flow and aid the VSI connected in series.

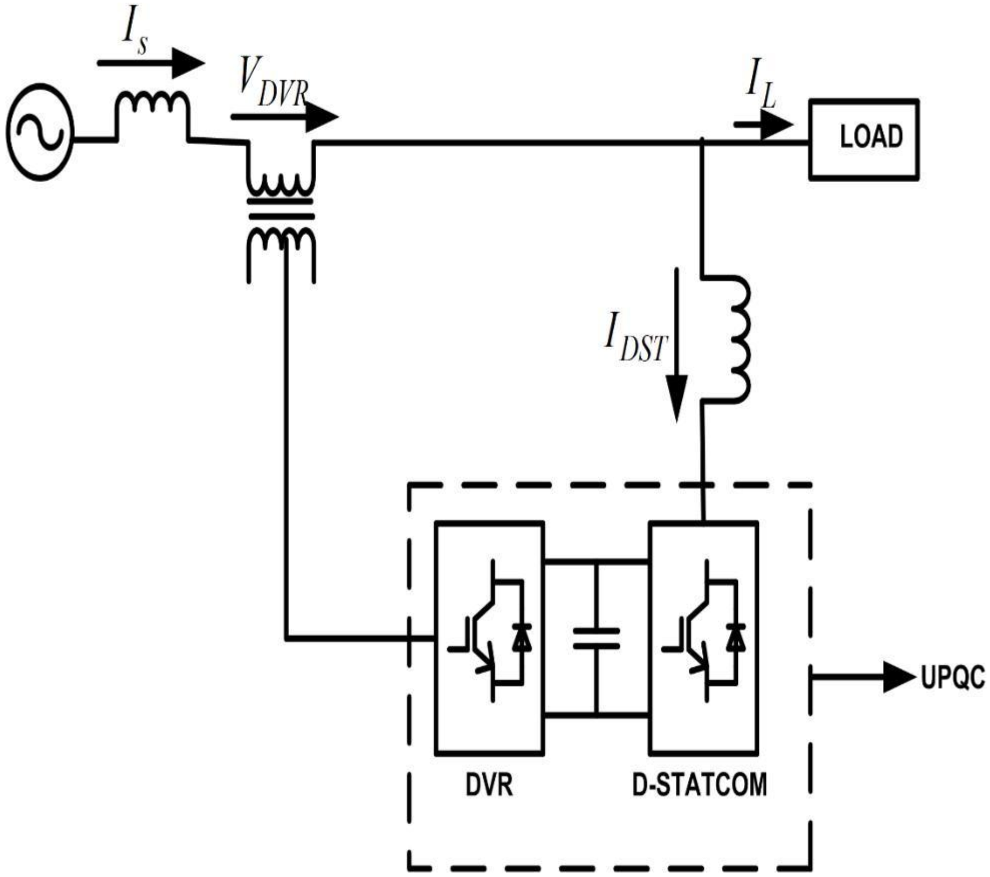


Figure 2.14: ***Block diagram of UPQC***

Table 2.6 Power quality issue standards

Power Quality issue	Standard
Harmonics	IEEE 519 and AS/NZS 61000 (for Australia and New Zealand)
Power and grounding	IEEE 1100
Monitoring and definition of electric power quality	IEEE 1159
Measurement of electrical quantities under different situations	IEEE 1459
Steady state voltage ratings	ANSI C84.1 (For America)
Electromagnetic compatibility	IEC 61000
Voltage disturbance	AS/NZS 61000
Voltage disturbance	EN 50160

MODELING OF SAPF

3.1 INTRODUCTION

The topology of a SAPF, system setup, system design and mathematical modelling are all covered in this chapter. The SAPF is typically used in ac power distribution systems for current harmonic correction. The power circuit and the control unit comprise the SAPF system. PWM-converters are commonly used in power circuits and topologies are classed as follows:
Current Source Inverter (CSI) Voltage Source Inverter (VSI)

3.2 SAPF TOPOLOGIES

Harmonic correction, reactive power as well as current phasor balance in ac power system are all addressed by the SAPF. PWM-based CSI or VSI are used to develop the SAPF. When it used as a current-controlled voltage source, VSI is more convenient for SAPF implementation.

3.2.1 Current Source Inverter (CSI)

Six controlled unidirectional switches make up CSI. It must carry the full current required by the load. The PCC is coupled to the current source active power filter via series transformers, which filter the carrier frequency components from the inverter currents. A massive dc-inductor in series is used to implement the dc-current supply. The inductor dc-current should be at least as high as the compensating current's highest value. Due to the unidirectional nature of the switches and the included short-circuit protection, the current source inverter offers distinct advantages such as direct output current control, high converter reliability and inbuilt short-circuit protection. It does, however, have a self-supporting dc-reactor that assures continuous dc-current circulation. Fig. 3.1 depicts the basic structure of CSI. To remove undesired current harmonics, it requires high values of parallel capacitor filters at the ac-terminals, which is bulkier and more expensive than VSI. This arrangement is not compatible with multilevel or cascaded harmonic correction in higher power levels.

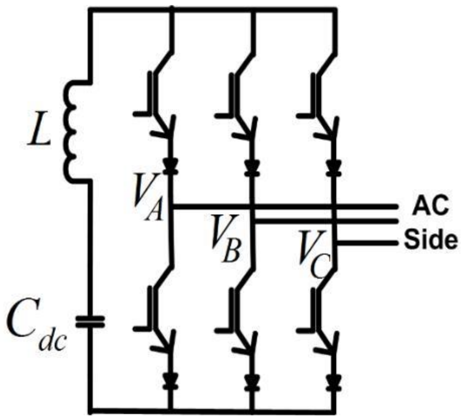


Figure 3.1: ***Basic structure of CSI***

3.2.2 Voltage Source Inverter (VSI)
PWM-VSI is one of the better options for SAPF applications due to light-weight and cheaper and better performance for high power rating. The PWM-VSI is more convenient for SAPF applications. As a current-controlled voltage source, the VSI works. Fig. 3.2 depicts the basic structure of VSI. Traditionally, a two-level voltage source inverter with an interface inductor (transformer) has been employed

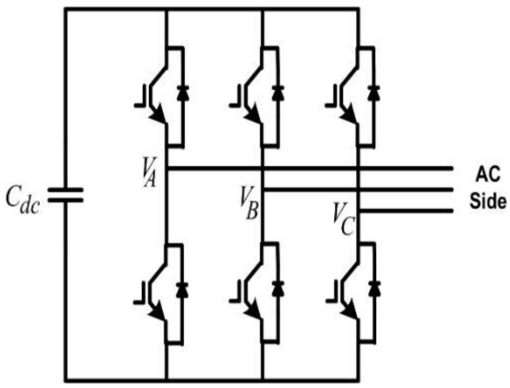


Figure 3.2: ***Basic structure of VSI***

Due to semiconductor rated value constraints, this arrangement is intended to counteract non-linear loads rated in the medium power application. However, multilayer or cascaded PWM-VSI SAPF for medium voltage and high rated power utilization have been created. Inverters are the power electronic circuit which converts DC voltage to AC voltage. They are two types of Inverters they are Voltage Source Inverter and second one is Current Source Inverter. The 1-phase VSI maintains voltage constant throughout whereas CSI maintains the current constant throughout. The active filters are used to reduce the harmonics and improve the power quality. There are two conduction modes of inverter i.e., 120-degree mode and 180-degree mode of conduction. For low power applications single phase system is fine but for high power ratings 3 phase inverters are used. Single phase VSI uses four switches two in each leg. The amplitude, frequency can be controlled by the PWM technique. The PWM technique will compare the triangular reference signal with the sinusoidal input signal and the difference in the signal produces the pulses. PWM technique can be used for the elimination of lower order harmonics in the circuit whereas the higher order current harmonics can be eliminated by using the active filters easily.
In a 180^0 mode, the gate signal is applied and removed from the thyristor, causing them to be ignited and commutated at the same time. This gives no time buffer for the commutation interval. A thyristor commutation time must always be turned off. Since there is no provision for this commutation interval in 180^0 mode inverters, there is always the danger of an abrupt short circuit of the dc source. The 120^0 mode inverter helps to mitigate this difficulty. In this inverter mode, a 60^0 is provided to allow commutation time, which is sufficient for safe conducting thyristor commutation.
In a 120^0 mode, it is determined at any throughout the cycle. When neither SCR is conducting, the potential of the third terminal of a particular leg is not well defined. Therefore, eliminating the power quality issues are a big challenge for both utility and customer. Furthermore, current-related power quality issues are mostly caused by harmonics, inadequate reactive power, and unbalanced loads. SAPF is considered to be one of the most effective methods for achieving higher levels of power quality. By generating equal and opposite magnitude of harmonic current at PCC, SAPF is employed to inject compensating current and reduce the harmonics.
As a consequence, the third terminal potential is determined by the type of load. As a consequence, analyzing the performance of a 120^0 mode inverter for a normal load circuit is difficult. However, the potential of all the three terminals a, band c for a balanced three phase load. Hence the three phase inverters are used as both inverter during loaded condition

and rectifier during braking condition by the power electronic switches like MOSFET and BJTs based on the application of the system.

3.3 SAPF CONFIGURATION

To fulfil the requirements for different types of nonlinear loads in supply systems, SAPF is divided into 1 and 3system topologies.

3.3.1 Single Phase System

SAPF is used to enhance the operation of distributed power systems due to harmonics in single customer equipment. Harmonic difficulties are caused by the extensive application of advanced technology such as computer, electronic devices, domestic application etc. which can be rectified by using a single-phase SAPF. As illustrated in Fig. 3.3, a voltage source inverter with 2-leg 4-switching power transistors and a DC-bus capacitor is used to create a single-phase SAPF.

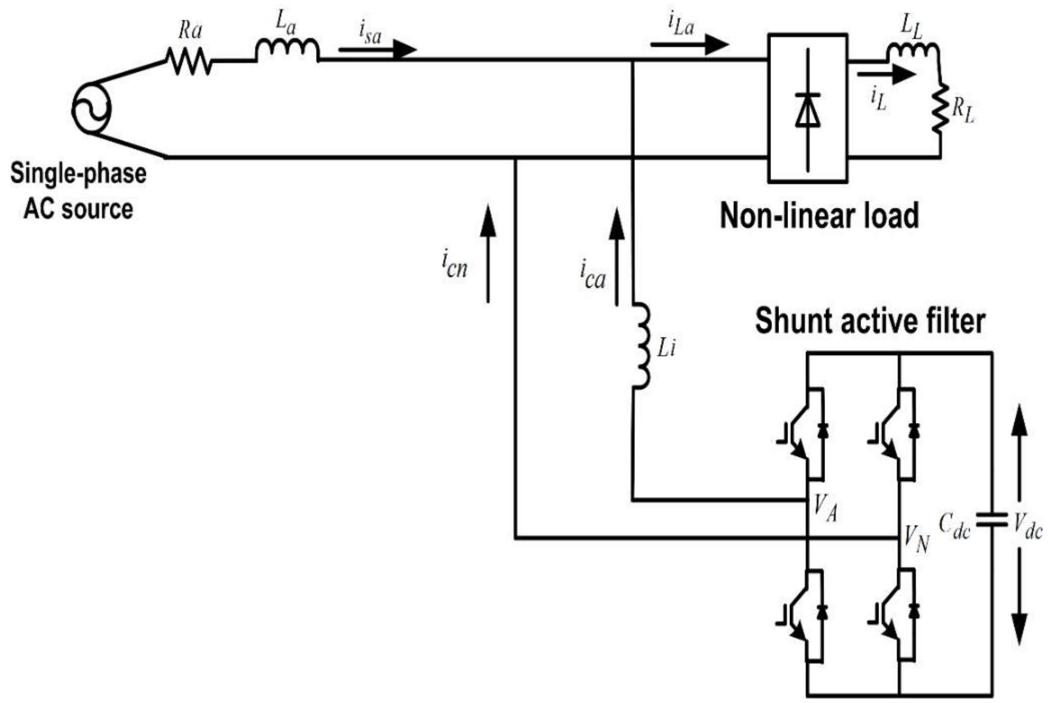


Figure 3.3: ***Single phase SAPF***

The inverter is connected to the PCC in parallel with the loads through an interface inductor. Single-phase SAPF compensates current harmonics by infusing equal and opposite harmonic compensation current.

3.3.2 Three-phase Three-Wire System

The two-level PWM-VSI shown in Fig. 3.4 incorporates a 3, 3 -wire SAPF. The PWM-VSI is composed of 6 power transistors, a DC-bus capacitor along with interface inductor that connects it to the PCC. Current harmonics are reduced by introducing equal and opposite of harmonic component at PCC, eliminating the harmonics and enhancing associated power system's PQ.

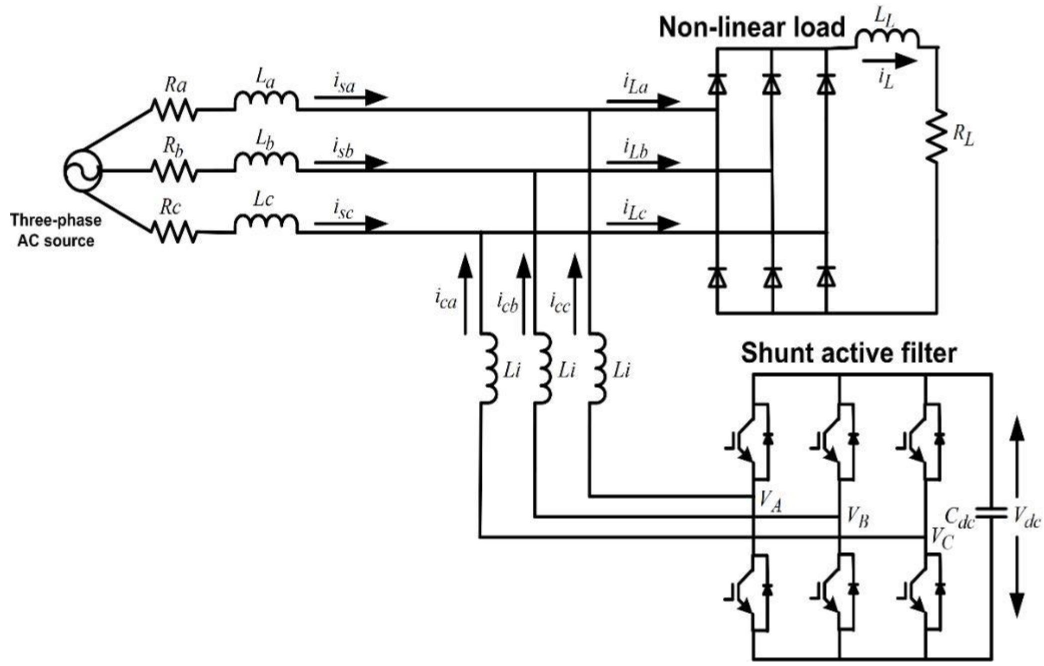


Figure 3.4: 3, 3-*wire SAPF system SAPF*

3.3.4 Three-Phase Four-Wire System

Two ways are used to configure a PWM-VSI 34-wire SAPF: (1) 4-leg inverter and neutral is delivered through 4th leg of the inverter (2) 3-leg inverter and neutral is provided through mid-point of the dc-bus. Fig. 3.5 shows a four-leg voltage source inverter with three legs for three-phase current compensation and a fourth leg for neutral current compensation.

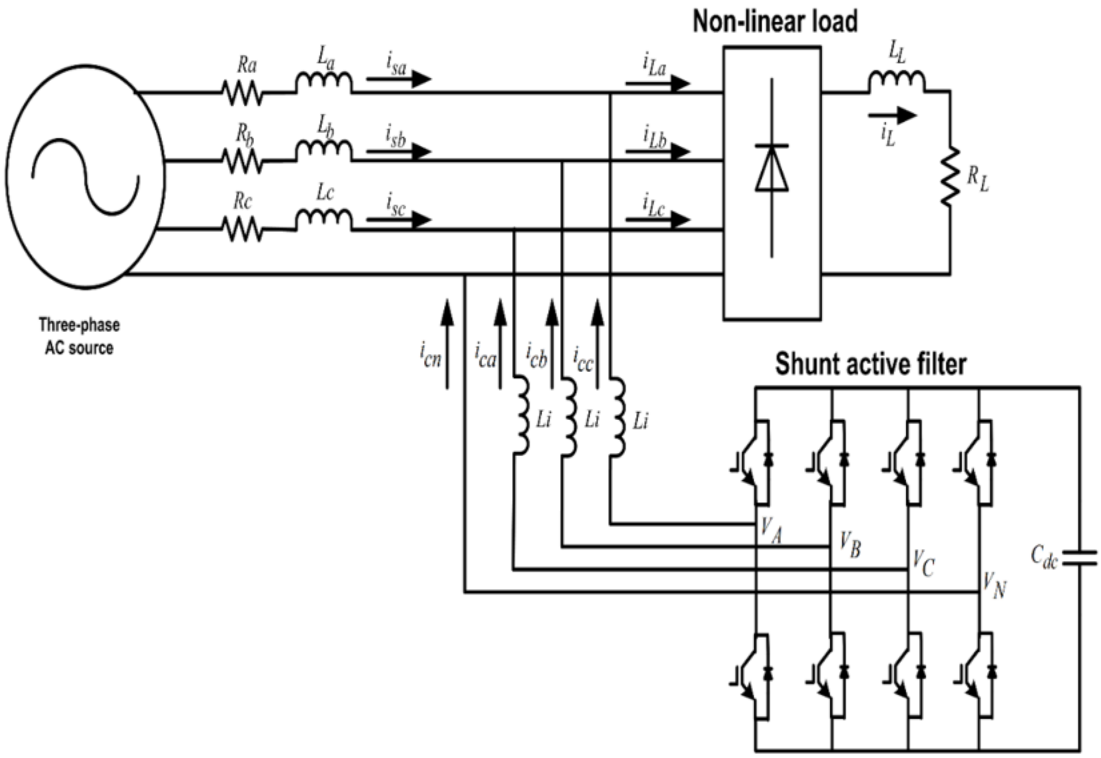


Figure 3.5: 3 *4-wire 4-leg SAPF*

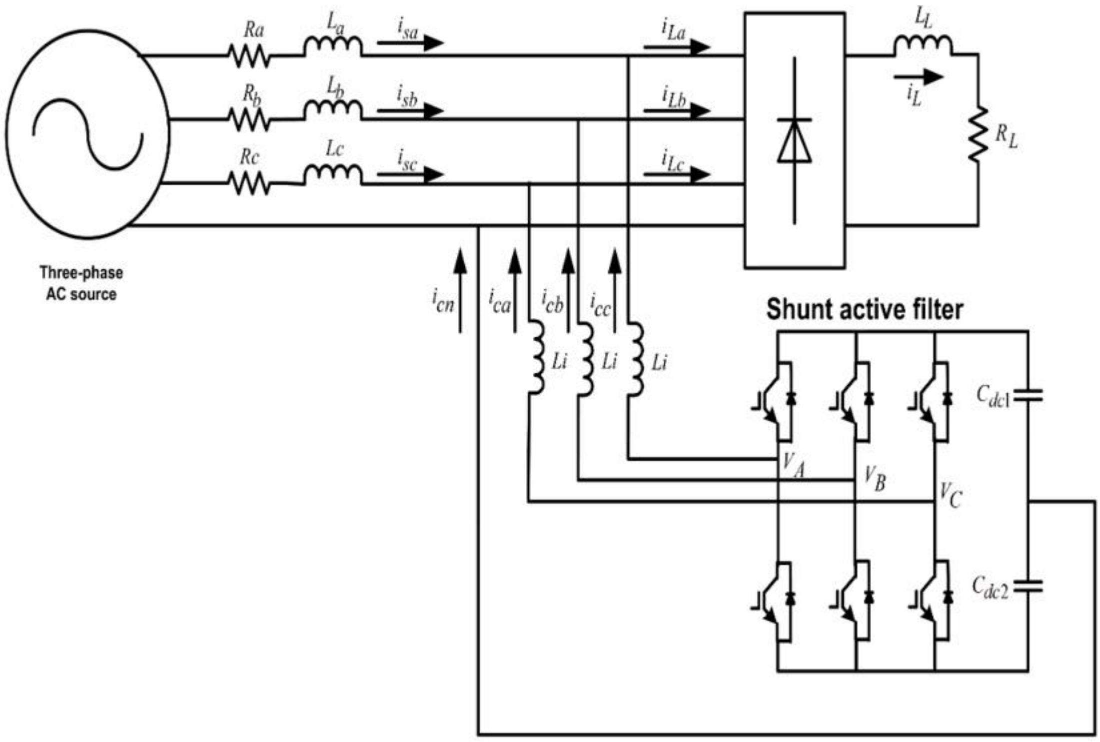


Figure 3.6: 3 *4-wire 3-leg SAPF*

The second method is both cost-effective and easy to implement. Fig 3.6 depicts the basic structure of 3 4-wire 4-leg SAPF. As illustrated in Fig. 3.6, it uses a normal 3-leg inverter with dc-bus capacitor which is divided into two parts and center point of capacitor is connected to the 4th wire of grid and 4th wire is offer the neutral current return path.

3.4 Principle of SAPF

Fig. 3.7 depicts the basic configuration of the SAPF, whereas Fig. 3.8 depicts the SAPF waveform. The SAPF comprises of two circuits named as the power circuit and the control circuit. The reference current or compensatory current is generated by the power circuit. The power circuit comprises of a VSI and a dc-bus capacitor with the capacitor storing energy and regulating voltage. A control circuit is used to continuously monitor the fluctuation of harmonic current for computing the instantaneous reference current compensation. The SAPF is generally connected at PCC for eliminating the source current harmonics.

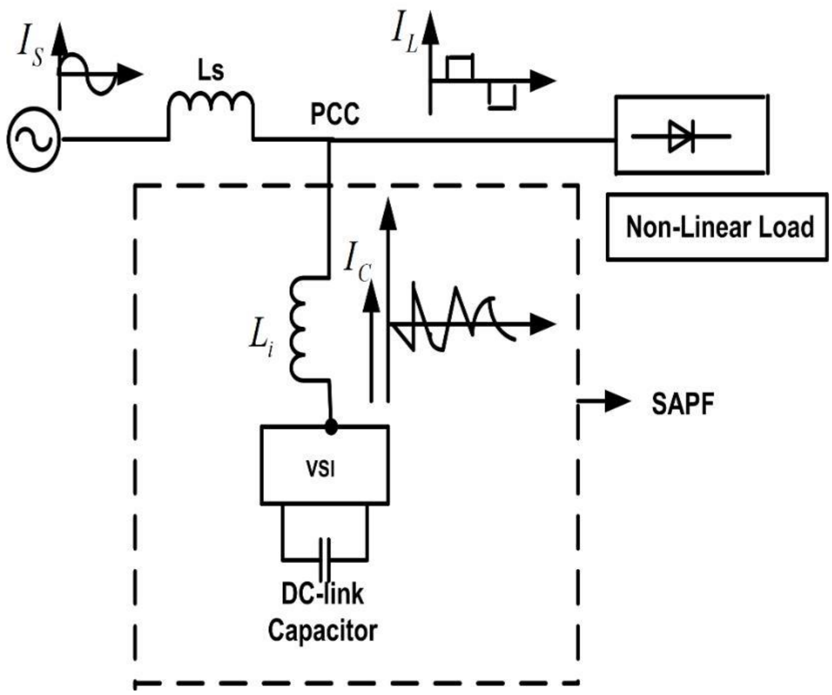


Figure 3.7: ***Schematic configuration of SAPF***

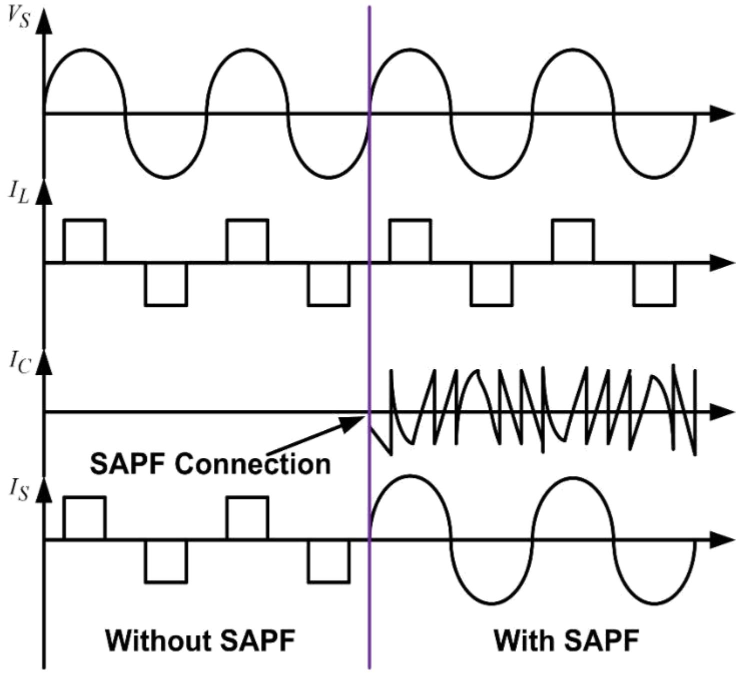


Figure 3.8: ***Schematic waveform of SAPF***

At PCC, SAPF generates a reference current that is equal to and in the opposite direction of the harmonic component of the load current. The interfacing inductor (Li) and voltage source inverter (VSI) are the key element of SAPF. The voltage across the interface inductor is determined by the maximum di/dt rating of VSI, which is necessary for compensating higher order harmonics. As a result of the SAPF's effect, harmonic current component in the *I* are cancelled and the I is sinusoidal and in *L S* phase with the *VS*. This technique can be applied to any nonlinear load that produces harmonic.

3.4.1 Characteristic of Harmonics

Both the voltage and current waveforms show harmonic distortion. Electronic or non- linear loads cause the majority of current distortion. 1 or 3 non-linear load is possible. +ve and –ve sequence harmonic currents as well as zero-sequence harmonic current are generated by electrical loads. The Fourier series is a useful tool for studying and analyzing harmonic distortion. The instantaneous source voltage (t) and instantaneous source current $i_s(t)$ of the SAPF is expressed as:

(t) = (t)- (t) (3.1)

28

(t) =sin (3.2)

The load current expression for non-linear load using Fourier transform is

(t)= sin(+ø) + Σ sin(+ø) (3.3)

The instantaneous load power expression is expressed as

(t) = (t)+ (t)

= sin²ωt*cos ø + sin * Σ sin(+ø) (3.4)

= (t)+ (t)+ (t) (3.5)

Where, (t) is fundamental active power, (t) is total reactive power and (t) is total harmonic power. Fundamental active power expression is

(t) = (t)* (t) = sin²ωt*cos ø (3.6)

(t)= (t) / = cos ø₁ * sin= sin (3.7)

where cos ø₁ .

There is some switching losses in PWM technique due to switches in VSI, As a result, in addition to providing active power to the load, the utility must also provide switching losses. Source current expression before connecting the SAPF is:

= = + (3.8)

where, denotes the source current, denotes the load current, denotes the harmonic component of load current and denotes the fundamental component of load current. When SAPF is connected to PCC, then source current expressed as:

= + + = + (3.9)

where, represents the generating compensating current which is equal to and opposite to the harmonic component of load current and represents the dc-link current.

CONTROL TECHNIQUE FOR SAPF

4.1 INTRODUCTION

According to the review of recent literatures, different SAPF configurations, each with its own control strategy proposed by various researchers. Various control strategy of SAPF has been explored like SRF method, instantaneous active-reactive power (p-q) method etc. Among such control technique methods, SRF is the most well-known and widely applied. Conventionally, we used passive series and shunt filter in distribution side for power quality improvement. But there are some drawback of passive filters is such as its instability, inflexibility, resonance problem with load impedance. But, nowadays active filters are used for harmonic compensation at PCC. Series APF is used for voltage related problems, whereas SAPFs are used for current related problems. SAPF is used with voltage source inverter (VSI) has replaced the passive filter to overcome the drawback of passive filters. SAPF has several advantages like fast dynamic response, filtering accuracy and flexibility.

The reactive power sensing method and current harmonics are the majorly determined by SAPF's harmonic mitigation capacity. In this paper, harmonics are mitigated in the source side. The SRF approach is effective, however in this approach grid synchronization necessitates the application of the PLL method. The majority of the literature states that the implementation of SAPF is essentially based on three control techniques named as reference current generation technique, dc-bus capacitor voltage regulation and inverter switching pulse generation technique.

4.2 REFERENCE CURRENT GENERATION TECHNIQUE

Time-domain and frequency-domain approaches are the two types of reference current extraction methods. In comparison to frequency-domain methods, the time-domain technique has a faster response. For the SAPF, the time-domain approaches listed below are used. As described in, there are several strategies accessible in the literature.

Instantaneous active-reactive power theory SRF theory

This chapter discussed the SRF theory for extracting the required reference or fundamental current components in SAPF.

4.2.1 SRF Theory for Reference Current Generation Technique

To extract the reference current from the distorted line current, the time domain based synchronous reference frame theory is used. The SRF control technique perfectly controls the SAPF in real-time and in both steady-state and dynamic-state applications. Another key feature of SRF theory is the simplicity with the calculations are performed, it just require algebraic calculations. The reference current is generated using the SRF technique. We employ Clarke transformation and Park transformation in this way to $(d - q - 0)$. Fig 4.1 depicts the SRF approach. In this figure, first instantaneous load current i_{la}, i_{lb}, i_{lc} is converted into i_{lo}, i_{ld}, i_{lq} by using Park transformation. It is expressed as:

$$[\;] = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \sin & \sin(\;-120) & \sin(\;+120) \\ \cos & \cos(\;-120) & \cos(\;+120) \end{bmatrix} \quad (4.1)$$

The instantaneous load current is now sent via a LPF that permits only whereas the q-axis and zero-axis components become 0, and it is then passed via a comparator that is supplied by the PI-controller. By comparing the reference dc-link voltage (V_{dc}^*) to the actual dc-link voltage (Vdc), the PI-controller increases the steady state accuracy. The output of a PI-controller (Imax) is considered a loss component of a VSI because of the high switching frequency and considerable switching losses. The 3 AC source or an external source compensates these losses. The instantaneous load current (, , $_0$) is then converted into reference source current (*, *, *) using the inverse park transformation, which is expressed as:

$$[\;^*] = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \sin & 0 \\ \frac{1}{\sqrt{2}} & \sin(\;-120) & \cos(\;-120) \\ \frac{1}{\sqrt{2}} & \sin(\;-120) & \cos(\;+120) \end{bmatrix} [\;] \quad (4.2)$$

Finally, the pulses for VSI is generated by comparing the reference source current with actual source currents using a HCC. PLL circuit generates an angle (θ), which affects the instantaneous load current.

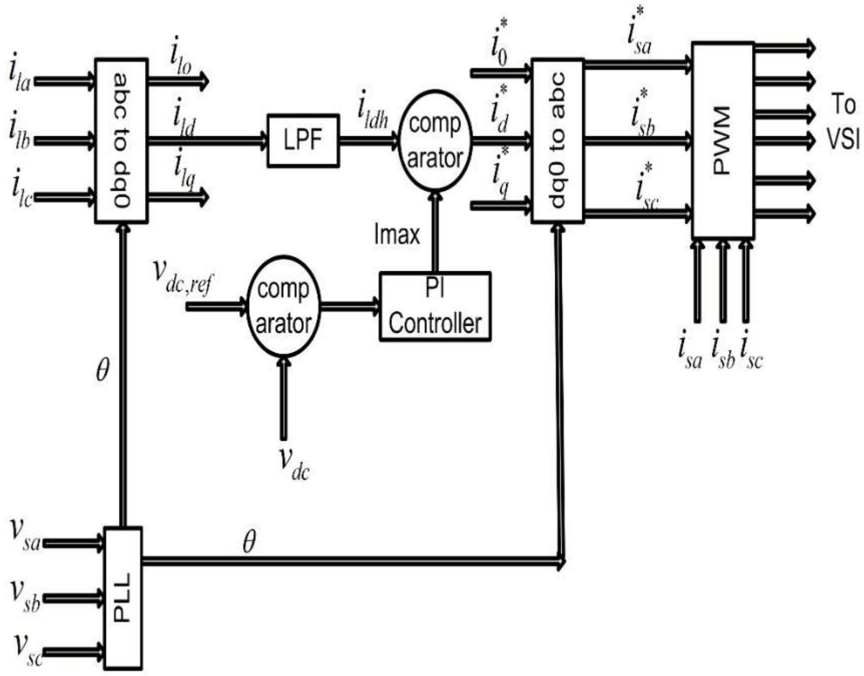


Figure 4.1: ***Reference current generation by SRF method***

The source voltage and source current are transformed into (0- −) using Clarke transformation and is expressed as:

$$\begin{bmatrix} 0 \\ \\ \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} \\ \\ \end{bmatrix} \qquad (4.3)$$

$$\begin{bmatrix} 0 \\ \\ \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 1 & \frac{-1}{2} & \frac{-1}{2} \\ 0 & \frac{\sqrt{3}}{2} & \frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} \\ \\ \end{bmatrix} \qquad (4.4)$$

4.3 PULSE GENERATION TECHNIQUE FOR VSI

In SAPF, most current control strategies are based on a PWM-current control strategy. For SAPF applications, many PWM-current control methods are used. In most real applications, however, high current-control performance is a challenging task since the inverter load is unidentified and variable. As a result, for the SAPF to perform efficiently, existing control mechanisms should adhere to the criteria listed below:

Improved VSI for high current in non-linear loads.

Low current-control problems for both static and dynamic VSI switches with lower switching losses.

Simple to use and takes less time to compute.

The 3error signals produced by measuring the difference between reference current values and sensing actual current value.

4.3.1 Direct Current Control Technique

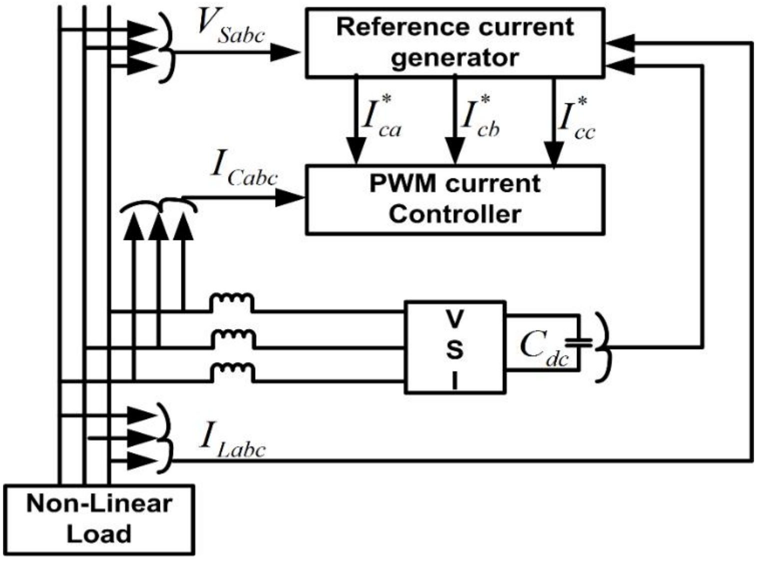


Figure 4.2: ***Structural diagram of direct current controller***

Seven analogue signals and three compensating currents are sensed and computed to perform the direct current control technique. Fig. 4.2 depicts the structural diagram of direct current controller. The reference current sensing control approach is used to generate the reference signals. The PWM switching pulses are calculated by comparing the sensed three-phase SAPF currents and reference currents.

4.3.2 Indirect Current Control Technique

The four analogue signals along with actual source current phasor values are measured and calculated in this technique. PWM-switching pulses are derived using this technique by comparing sensed three-phase actual currents to their reference current produced by reference current extraction methods. The gate driver circuit processes the PWM-switching pulses for isolation and amplification. Fig. 4.2 depicts the structural diagram of indirect current controller. SAPF system's reaction in the steady state circumstance indicated that the direct control technique delivers a delayed response. Indirect current control method provides immediate reaction with no delay.

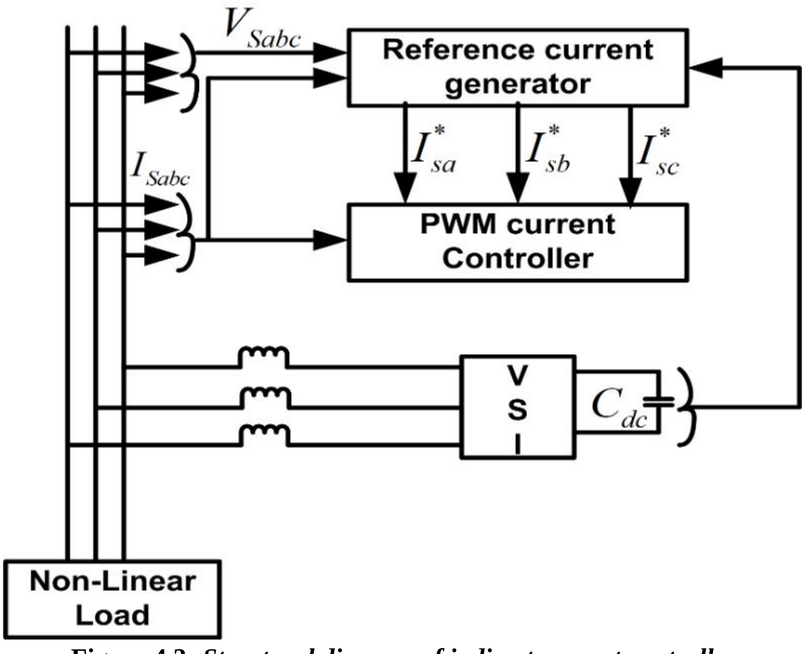


Figure 4.3: ***Structural diagram of indirect current controller***

4.4 HYSTERESIS CURRENT CONTROLLER (HCC)

According to a literature review, there are various types of current control techniques such as Selective harmonic elimination (SHE) based PWM, Sinusoidal PWM, Space vector modulation (SVM) based PWM, hysteresis current controller (HCC) based PWM and other current control techniques. HCC-based PWM was employed in this paper because of its simplicity and accuracy, quick response, and unconditional stability.

The HCC based configuration is shown in Fig. 4.4 which is accountable for determining the operation of switching state of VSI. By comparing the reference source current which is generated by SRF method and actual source current and passed through a current regulator, it generates the error signal. Working principle of hysteresis controller is that when the error signal exceeds the higher hysteresis band, the upper switch is turned off and the lower switch is turned on and when the error signal exceeds the lower hysteresis band, the upper switch is turned on and the lower switch is turned off and so on. Phase-A switching presentation is:
S = OFF if (t) > * ( )+hb S = ON if (t) < * ( )-hb

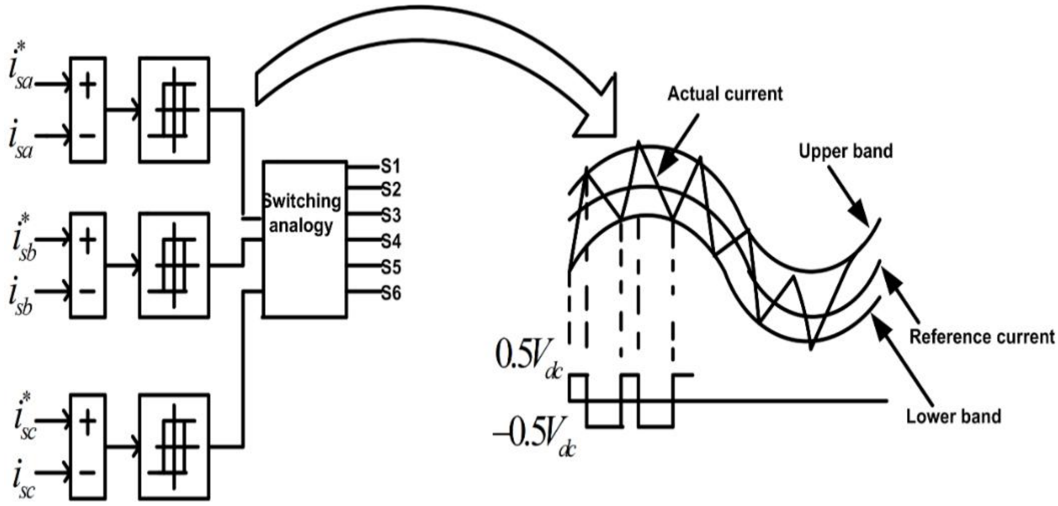


Figure 4.4: ***Current control technique by HCC***

Likewise, hysteresis- bandwidth (hb) can be used to calculate the switching effectiveness of phase-B and phase-C components. Two-level modulation's harmonic performance is well known to be inferior to three-level modulations. Around the switching frequency, the two-level modulation produces substantial sideband harmonics.

4.5 DC-LINK VOLTAGE CONTROL

The dc-link voltage can be controlled by using PI-controllers, fuzzy logic controllers (FLCs) and other controller. However, in this work, the dc-link voltage is controlled by a PI-controller. Fig. 4.5 is showing the block diagram of PI-controller. is obtained using a voltage measuring device and compared to a , . It is then send via a LPF and higher order harmonics are filtered and passes the lower order harmonics and which minimizes the steady state error to zero. The loss component Imax is produced by the PI-controller and supplied by the 3 AC source. The dc-link capacitor serves two roles here: the first is to control the dc-link voltage and the second is to store the energy with no actual power exchange between the SAPF and the AC supply, the dc-link capacitor should ideally stay constant. Practically, the VSI uses the little fraction of real power for VSI switching component.
The dc-voltage regulation enables effective current management at the SAPF's input.

Imax is represented as:max = (+) (4.5)

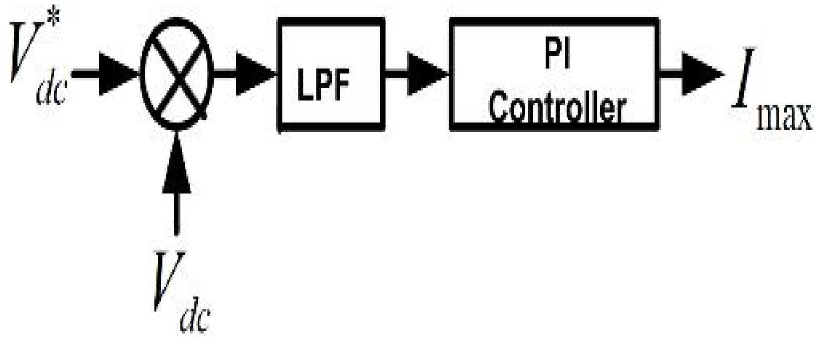


Figure 4.5: ***PI-controller***

where, denotes the proportional gain controller and denotes the integral gain controller. The value of and can be found by hit and trial method which are 28 and 0.8 respectively.
PI controller's transfer function is: + —

SIMULATION AND RESULT
5.1 INTRODUCTION
The realisation of SAPF is investigated in this chapter using the SRF method of SAPF control approaches. The SAPF controller includes reference current generation technique, switching pulse generation by HCC and dc-link voltage regulation PI-controller. The PI-controller, indirect PWM-VSI current control approaches and reference current generation method are all described in Chapter 4. The SAPF is based on a VSI comprises of six power transistors and coupled to the PCC through an interface inductor. Table 5.1 depicts the system parameter. This chapter is focused on simulation result and examine of the 3 SAPF system.

Table 5.1 System Parameters

Parameters	**Values**
Source voltage(v_s)	230 V (rms)
Supply frequency(f)	50 Hz
Source resistance( )	0.1 Ω
Source inductance(L_S)	0.5 mH
Interfacing inductor( )	2 mH
DC-link capacitor(C_{DC})	2200 μF
DC-link reference voltage($V_{DC,ref}$)	700 V
Switching frequency(f_{sw})	25 kHz
K_P	0.8
K_I	28

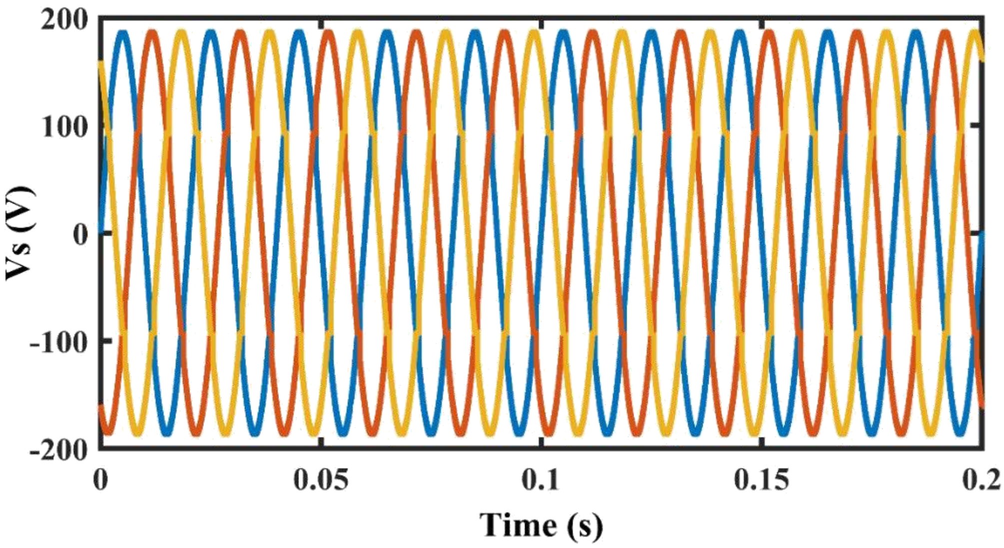


Figure 5.1: ***before SAPF connection***

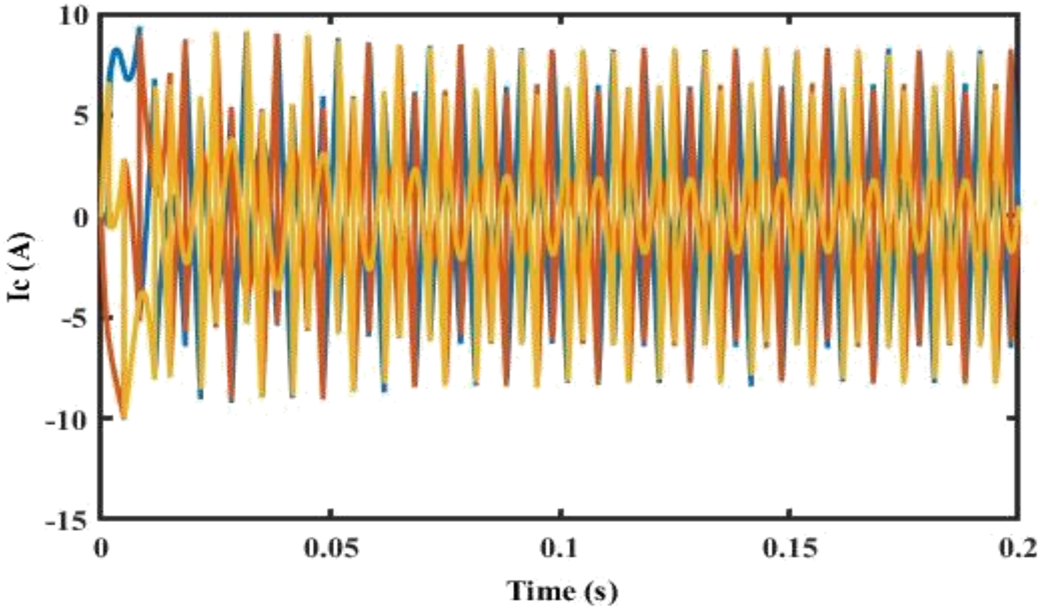
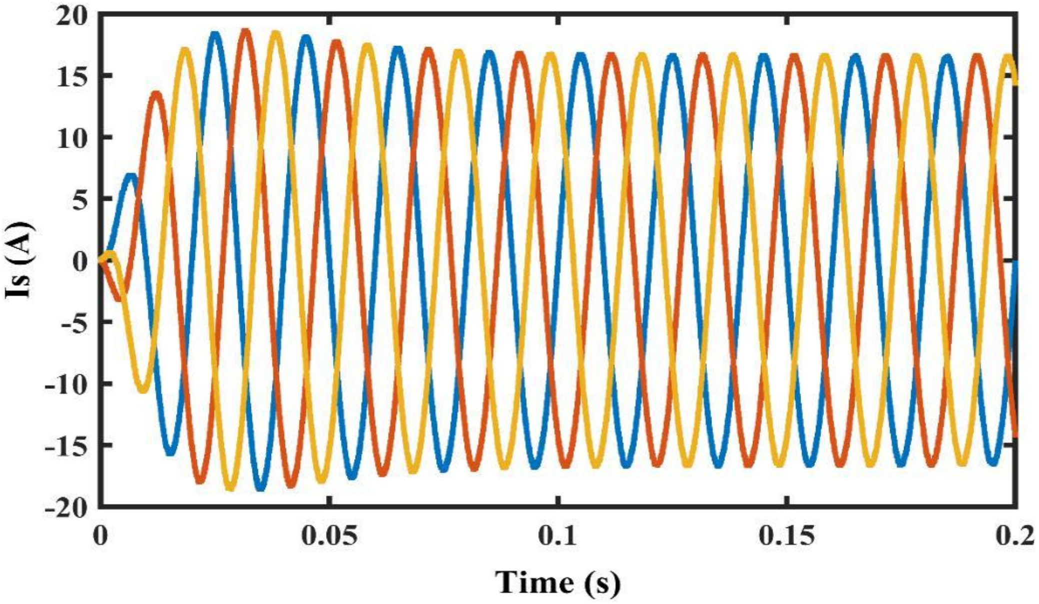


Figure 5.2:before SAPF connection

The before compensation under a non-linear load as shown in Fig. 5.2. Because of the non-linear load, the includes fundamental and harmonic components. The switching pulses that drive the SAPF inverter is generated by fixed-HCC. As demonstrated in Fig. 5.3, the inverter produces the appropriate compensatory current to compensate for the harmonic current. Equal and opposite harmonic components are injected to produce harmonic correction.

Figure 5.3: ***Compensating current generated by SRF based designed SAPF***



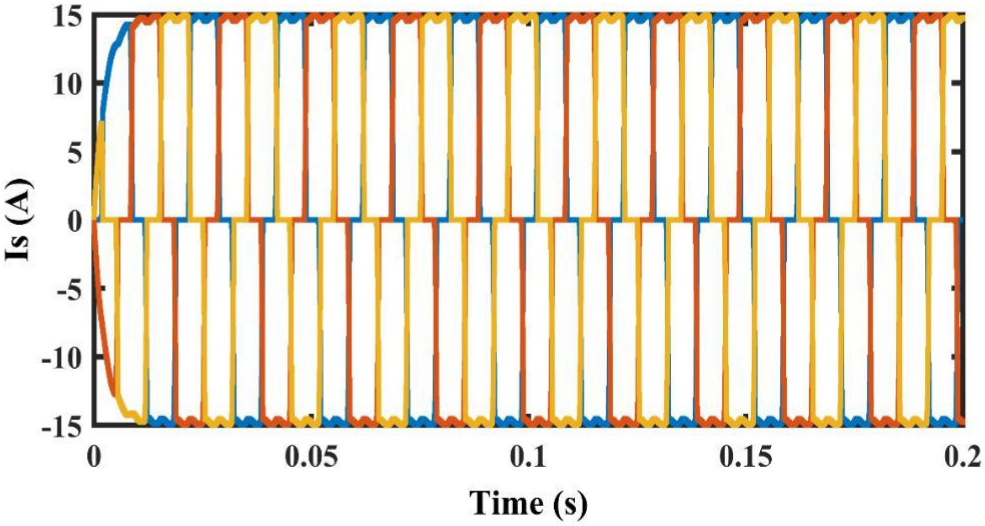


Figure 5.4:*after SAPF connection*

Fig. 5.4 depicts the after correction, indicating that the is sinusoidal. SAPF compensation implies that the sinusoidal and in phase with the after compensation

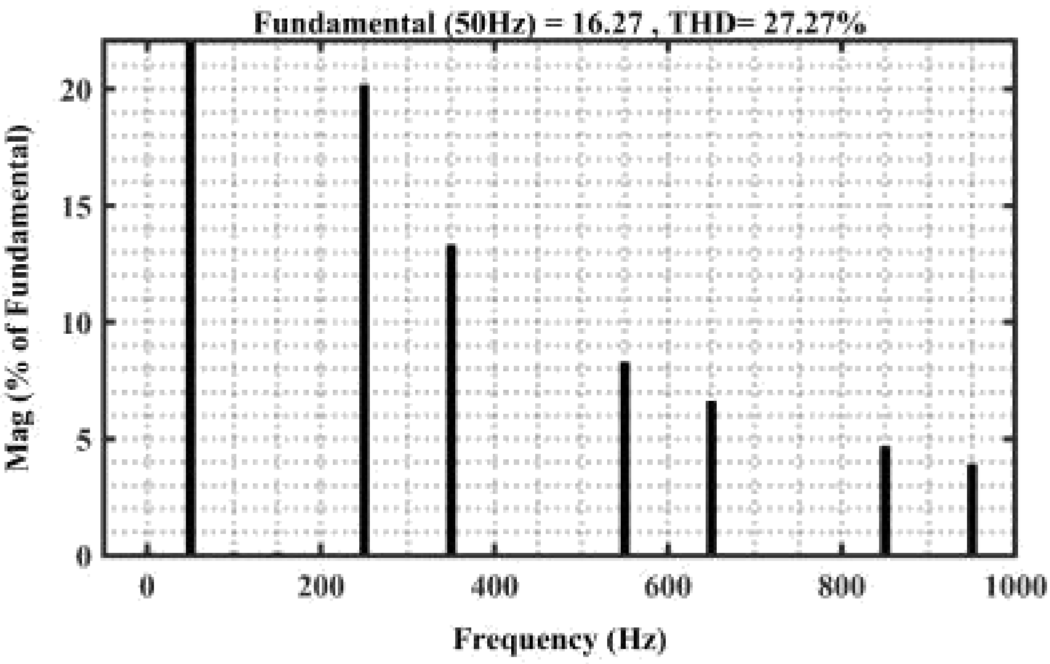


Figure 5.5: ***THD ofbefore SAPF connection***

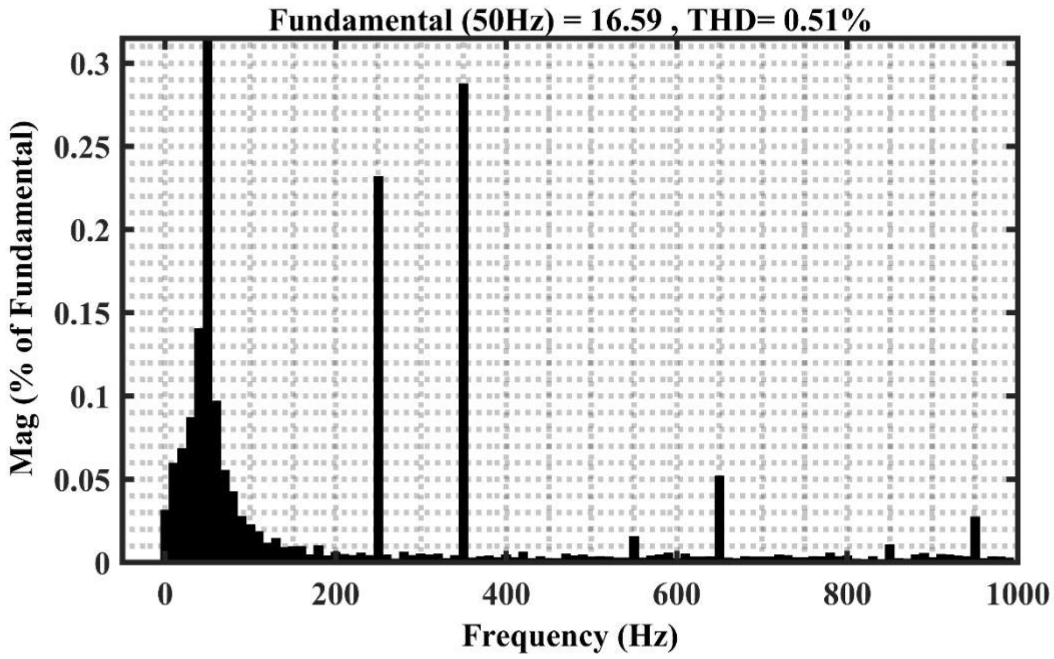


Figure 5.6: ***THD ofafter SAPF connection***

Plot of the magnitude in source current vs frequency, without and with SAPF are shown in Fig. 5.5 and 5.6. Under the non-linear load, the THD without SAPF is 27.27%. Harmonic order is decreased to 0.51%, which is less than 5% with SAPF. Source current has its THD value of less than 5% (IEEE 519 harmonic standard).

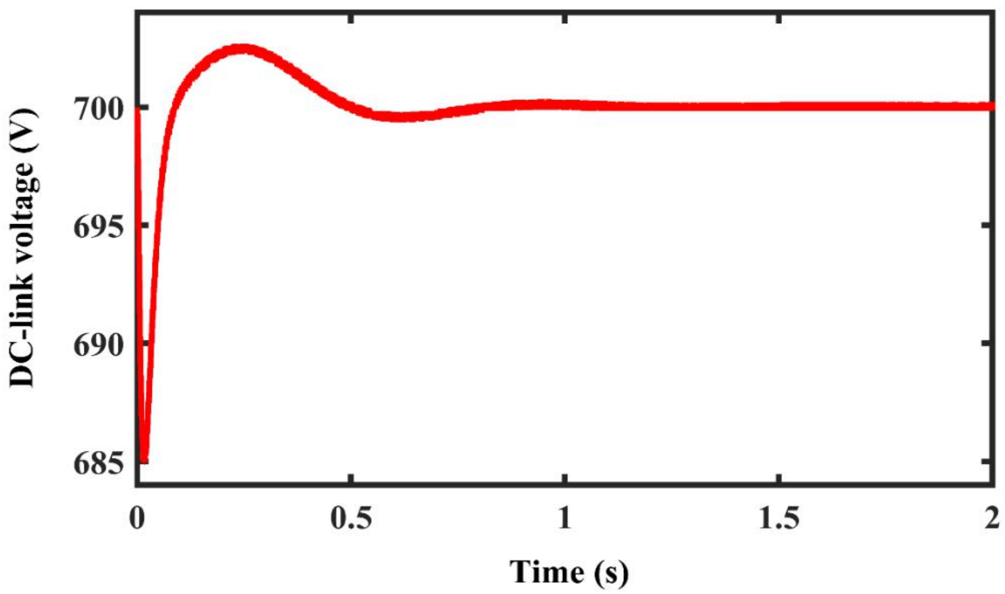


Figure 5.7: ***DC-link voltage***

SAPF draws very less amount of active power from the main grid to regulate the DC-link voltage throughout the normal operation and it compensate switching and conduction losses. Proportional and integral gain are used to adjust and maintain the inverter's dc voltage. Fig. 5.7 depicts the waveform of constant dc-bus voltage, and this is required to generate the switching pulses for VSI.

CONCLUSION AND SCOPE FOR FUTURE WORK
6.1 CONCLUSION
Power quality goal is the Current and voltage waveform must be sinusoidal with a magnitude of 1 p.u. and 120 degrees phase difference between adjacent phases. Harmonics have become a serious concern with power quality issues as a result of the introduction of non-linear power electronics devices that draw non-sinusoidal current from the source. In this article, the Simulink platform was used to simulate the design of a SAPF based on the SRF approach and a PI-controller. SAPF

reduces current harmonics under balanced non-linear load conditions. The filter was able to keep the harmonic current in a balanced non-linear load below the range adopted by IEEE standards. THD was reduced from 27.27% to 0.51% for balanced non-linear load using SRF-based SAPF, according to FFT spectrum analysis.

6.2 FUTURE SCOPE

The following can be used for future projects.

Harmonic compensation requires a high frequency low power inverter, whereas reactive power compensation requires a low frequency high power operation. As a result, developing a system that allows these functions to be decoupled and compensated by two independent inverter is crucial.

The different soft computing technique can be used for tuning the PI-controller. Hardware implementation of the setup.

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