Chapter 1

1. Introduction

1.1 Motivation

Power electronics has become an inevitable part of most of the gadgets, systems, and equipment today and has become indispensable part of human life. The interdisciplinary nature of the subject and with more and more faster, efficient power semiconductors and a variety of digital signal controllers available at easily affordable price has fascinated researchers worldwide to contribute in power electronic applications for making human life better.

The proposed research work belongs to power electronic applications to power quality improvement devices. The research work was funded by Shreem Electric Ltd., a leading name in the field of manufacturing reactive power compensation equipment in India. With Indian Railways as the potential customer, SHREEM had planned an outlay on development of a single phase D-STATCOM. Indian railways have over 3000 Traction substations. Each substation is a 25kV single phase unit with a demand of about 1200 KVAR reactive power. Since 2007, Indian railways have started taking strict measures to improve power quality at the TSS (Traction Substations). It was decided to install STATCOM (STATic COMpenator), a step less dynamic reactive power compensator in place of the existing fixed capacitor compensation, at each traction substation, to maintain unity power factor, to reduce
KVA demand and to improve voltage profile. After the field visits to Lasalgaoon, Nashik TSS, (where ABB has installed 1200 KVAr STATCOM), TATA Motors, Pune (ABB’s STATCOM for dynamic voltage restoration at the welding shop) and Hindustan Latex, Trivendrum (200KVAr STATCOM developed by C-DAC, Trivendrum), it was decided to develop prototype of single phase D-STATCOM as first milestone.

The design issues of single phase D-STATCOM are rarely discussed in literature except for load balancing and in multilevel converters. Here, there was a coincidence of need and the opportunity and finally turned into my research problem to design and develop a prototype of 1 ph. D-STATCOM.

Before D-STATCOM, as it forms the part of power quality conditioning equipment, design of a single phase SAF (Shunt Active Filter) was carried out and validated through simulation study. \( I \cos(\theta) \) technique [G1] was used in the SAF to derive reference current and hysteresis current control for tracking SAF current. The work was presented in international conferences [L1] [L2]. Later on, it was modified by using a novel technique based on SSI (Sine-Signal-Integrator). Simulation results of the SSI based SAF are also presented later in this thesis which are very encouraging for practical implementation.

Let us begin with a recap of a few terms related to power quality.

### 1.2 Power Quality

The awareness about “power quality” has been growing since last two decades and is being dealt with in a systems approach rather than tackling individual problems. The quality of electric supply can be measured in terms of [J3]:

- Constant voltage magnitudes.
- Constant frequency.
- Constant power factor.
- Balanced phases.
- Purely sinusoidal waveforms.
- Free of interruptions.
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- Ability to withstand faults and recover quickly.

In addition to above, utilities have to supply increasing loads of consumers, preferably by maximizing the use of existing transmission network rather than building new interconnections. Widespread use of power electronic equipment has become detrimental to power quality. Interestingly though, the power electronics itself is both the cause and the solution of the problem. Developments in power semiconductors and fast, powerful digital signal controllers have made it possible for the researchers to realize novel ideas to develop “power line conditioning” devices. The term “power line conditioning” covers a wide spectrum of problems like harmonic filtering, reactive power control, power flow control, load balancing, voltage flicker reduction, and/or their combinations [J5]. A power line conditioner is a device intended to compensate for the degradation of power quality caused by non-linear loads in the network and hence it could be called a “power quality conditioner” as well. Essentially, they are based on PWM controlled power electronic inverters and operate in such a manner so as to maintain pure sinusoidal voltage and current conditions at the supply end. This prevents power line disturbances from disrupting operation of critical loads (medical, industrial processes …). In this dissertation, two devices namely, single phase D-STATCOM (Distribution STATic COMpensator) and single phase Shunt Active Filter (SAF) are considered. These devices belong to custom power devices family. The main reason behind selecting D-STATCOM is its multi-functional nature i.e. voltage regulation, load compensation, voltage profile improvement and capability of even compensating active power fluctuations in the feeder when operated with energy storage device, and above all its potential market.

The basic function of SAF is to compensate for load harmonic currents. So it is installed at load locations so as to prevent propagation of current harmonics in the system. In addition to that, it can also compensate for fundamental reactive power of the load. Taking into account, the multifunctional capabilities of the two devices and their growing need in the Indian
market at an affordable price, an attempt has been made here to address their
design and implementation aspects.

1.3 Background on Electric Power Definitions

The concept and definitions of electric power for sinusoidal AC sys
tems are well established and accepted worldwide. The conventional
concepts of reactive and apparent power lose their usefulness in the presence
of non-sinusoidal signals. However, under distorted conditions, there are
different approaches to define power [J5]. A review of various definitions
under sinusoidal and distorted conditions and review of some power quality
terms is presented in this topic.

1.3.1 Power definitions under sinusoidal conditions

A single phase electrical system depicted in Fig. 1.1 is considered. The
ideal ac source generates a sinusoidal voltage at an angular frequency $\omega$. The
frequency of oscillation in Hz is $f = \frac{2\pi}{\omega}$. The ac source is connected to the
linear load. The instantaneous voltage and current can be analytically
represented as,

$$v(t) = \sqrt{2} V \sin (\omega t + \phi^{'})$$  \hspace{1cm} (1.1)

where, $\phi'$ is phase angle of the voltage.

$$i(t) = \sqrt{2} I \sin (\omega t + \phi')$$  \hspace{1cm} (1.2)

where, $\phi'$ and $\phi'$ are respectively the phase angles of voltage and current with
respect to common reference.

The relative angle between $v(t)$ and $i(t)$, $\phi$, is given by,

$$\phi = \phi' - \phi'$$  \hspace{1cm} (1.3)

$\phi > 0$ (the current lags the voltage) for inductive loads.

$\phi < 0$ (the current leads the voltage) for capacitive loads.

The value of $\phi$ is limited in the range, $-90^0 \leq \phi \leq 90^0$. The instantaneous power
is given by the product of instantaneous voltage and current, i.e.,
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\[ p(t) = 2VI \sin(\omega t) \sin(\omega t - \phi) \]  
\[ p(t) = P[1 - \cos(2\omega t)] - Q \sin(2\omega t) \]  
\[ p(t) = VI \cos \phi [1 - \cos(2\omega t)] - VI \sin(\phi) \sin(2\omega t) \]

Where,

\[ P = VI \cos \phi \]  
\[ Q = VI \sin \phi \]

P is Active power and is measured in Watts [W].

Q is Reactive power and is measured in volt-ampere reactive [VAR].

From above equations, it is clear that part I indicated in (1.6) is associated with oscillating active power with an average value \( P \) which represents unidirectional power flow from ac source to load provided \(-90 \leq \phi \leq 90\). Part II is associated with reactive power \( Q \) which has an oscillating component at \( 2\omega \) with zero average value. The net power transferred to load over entire cycle of part II is zero. This is the reason for attributing \( Q \) to undesired effect. It indicates portion of the power that does not realize work but keep on tossing between supply and load every half cycle.

The Apparent power, \( S \) is defined as product of RMS value of voltage and current.

\[ S = VI \]

The unit of \( S \) is volt-ampere [VA].
$S = VI$ \hspace{1cm} (1.9)

The unit of $S$ is volt-ampere [VA].

The power factor (PF) is defined as

$$cos \phi = \frac{P}{S} \hspace{1cm} (1.10)$$

From (1.9) and (1.10) it is clear that $S$ represents maximum reachable active power at unity power factor. Unity PF is the goal of electric utility companies, since, PF less than one means they have to supply more current to the

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Figure 1-2: Power waveforms associated with single phase circuit
customer for the required power consumption. The more the current higher are the line losses and equipment size and so on. The above considered single phase ac circuit is simulated with SIMULINK and the associated waveforms are given in Fig. 1.2. The waveforms of instantaneous voltage and current are for an inductive load. The instantaneous power \( p(t) \) and its positive average value \( P \) is indicated. The \( p(t) \) has larger positive part and less negative part. The negative part indicates energy being fed back to the source. Part I and II of (1.6) are separately shown. When the load is purely reactive, \( p(t) \) has equal negative and positive halves.

### 1.3.2 Electrical variables in phasor notation

Any sinusoidal time function \( x(t) \) alternating at \( \omega \) rad/sec can be represented as real part of a complex number

\[
x(t) = A \cos(\omega t + \phi)
\]

(1.11)

\[
x(t) = \Re \{ A e^{j(\omega t + \phi)} \}
\]

\[
x(t) = \Re \{ A e^{j\phi} \}
\]

(1.12)

The voltage and current can be represented as,

\[
\vec{V} = V_{rms} e^{j\phi}
\]

(1.13)

\[
\vec{I} = I_{rms} e^{j\phi}
\]

(1.14)

Assuming the phase angle of one variable (e.g. voltage) as reference it is set to zero, so that the phasor diagram could be represented as represented in Fig. 1.3. Extending phasors to power definition, complex power or apparent power, \( S \), can be defined as,

\[
\vec{S} = \vec{V} \cdot \vec{I}^*
\]

(1.15)

\[
\vec{S} = VI \cos \phi + jVI \sin \phi
\]

(1.16)

\( S \) can be represented in complex plane as a function of \( P,Q \) as shown in Fig. 1.4. Sign of \( Q \) is plus for inductive load and minus for capacitive load.
Power definitions under non-sinusoidal conditions

When the system voltages and currents contain non fundamental frequencies, it is said to be distorted. The origin of distortion is mostly from the non-linear consumer load. Power definitions under non-sinusoidal conditions are not uniquely defined. There are two sets of power definitions: the power definitions based on frequency domain by Budeanu (1927)[K1], and the power definitions based on time domain by Fryze (1932)[K2]. According to Budeanu, electric circuit under non-sinusoidal conditions can be treated as several independent circuits operating at each frequency component. Since the power definitions are defined in frequency domain, they are for steady state analysis and thus inadequate for instantaneous control of power line conditioners [J5]. Both of the approaches are described in subsequent sections.

1.3.3.1 Power definitions by Budeanu

Power definitions by Budeanu are still very useful for analysis of power systems in frequency domain. However, as they are defined in frequency domain, they can be applied to only in steady state analysis. These definitions are valid for generic currents and voltages in steady state. A periodic ac signal, can be decomposed in Fourier series and the corresponding phasor for each harmonic order can be calculated.
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The Budeanu definitions are:

**1.3.3.1.1 Apparent power $S$:**

\[ S = VI \]

where $V$ and $I$ are voltage and current rms values. The rms values can be calculated as,

\[ V = \sqrt{\frac{1}{T} \int_0^T \left( \frac{v(t)}{T} \right)^2 dt} = \sqrt{\sum_{n=1}^{\infty} V_{rms,n}^2} \quad (1.17) \]

And

\[ I = \sqrt{\frac{1}{T} \int_0^T \left( \frac{i(t)}{T} \right)^2 dt} = \sqrt{\sum_{n=1}^{\infty} I_{rms,n}^2} \quad (1.18) \]

Here $V_{rms,n}$ and $I_{rms,n}$ correspond to rms value of the $n^{th}$ harmonic of the Fourier series without considering direct component and $T$ is the fundamental period. Considering displacement angle $\phi_n$ of each pair of $n^{th}$ order harmonic voltage and current,

**1.3.3.1.2 Active Power $P$:**

\[ P = \sum_{n=1}^{\infty} V_n I_n \cos \phi_n \quad (1.19) \]

**1.3.3.1.3 Reactive Power $Q$:**

\[ Q = \sum_{n=1}^{\infty} V_n I_n \sin \phi_n \quad (1.20) \]

Under non-sinusoidal conditions, a new complex power, $S_{PQ}$ can be defined that corresponds to new active and reactive powers defined in (1.19) and (1.20) above.

**1.3.3.1.4 Complex power $S_{PQ}$:**

\[ S_{PQ} = P + jQ = \sum_{n=1}^{\infty} P_n + j \sum_{n=1}^{\infty} Q_n \quad (1.21) \]
Budeanu also defined the distortion power $D$ to quantify loss of power quality due to harmonic distortion. Considering $D$ as distortion power present under non-sinusoidal conditions, the relationship between apparent power $S$ and complex power $S_{PQ}$ is given by,

$$S = VI = \sqrt{\left|S_{PQ}\right|^2 + D^2} \quad (1.22)$$

The different powers defined by Budeanu can be represented in the power tetrahedron as shown in Fig. 1.5.

1.3.3.1.5 Power factor $\lambda$:

$$\lambda = \cos \theta = \frac{P}{S} \quad (1.23)$$

1.3.3.1.6 Displacement factor $\cos \phi$:

$$\cos \phi = \frac{P}{\left|S_{PQ}\right|} \quad (1.24)$$

1.3.3.1.7 Distortion factor $\cos \gamma$:

$$\cos \gamma = \frac{\left|S_{PQ}\right|}{S} \quad (1.25)$$

![Figure 1-5: Power tetrahedron](image)
1.3.3.2 Power Definitions by Fryze:

Fryze proposed a set of power definitions based on rms values of voltage and current. According to Fryze [K2],

1.3.3.2.1 Active power $P_w$:

$$P_w = \frac{1}{T} \int_0^T p(t)dt = \frac{1}{T} \int_0^T v(t)i(t)dt = V_wI = VI_w$$  \hspace{1cm} (1.26)

where $V$ and $I$ are the voltage current rms values and $V_w$ and $I_w$ are the active voltage and active current defined below. The rms values of voltage and current are calculated as given in (1.17) and (1.18). To gather with the active power $P_w$, these rms values form the basis for Fryze’s approach. From them, all other parameters can be defined and calculated as follows,

1.3.3.2.2 Apparent power $P_s$:

$$P_s = VI$$  \hspace{1cm} (1.27)

1.3.3.2.3 Active power factor $\lambda$:

$$\lambda = \frac{P_w}{P_s} = \frac{P_w}{VI}$$  \hspace{1cm} (1.28)

1.3.3.2.4 Reactive power $P_q$:

$$P_q = \sqrt{P_s^2 - P_w^2} = VI_q = V_qI$$  \hspace{1cm} (1.29)

Where $V_q$ and $I_q$ are the reactive voltage and current as defined ahead,

1.3.3.2.5 Reactive power factor $\lambda_q$:

$$\lambda_q = \sqrt{1 - \lambda^2}$$  \hspace{1cm} (1.30)
1.3.3.2.6 Active voltage $V_w$ and Active current $I_w$:

$$V_w = \lambda V$$  \hspace{1cm} (1.31)

$$I_w = \lambda I$$  \hspace{1cm} (1.32)

1.3.3.2.7 Reactive Voltage $V_q$ and Reactive Current $I_q$:

$$V_q = \lambda_q V$$  \hspace{1cm} (1.33)

$$I_q = \lambda_q I$$  \hspace{1cm} (1.34)

Fryze defined reactive power as comprising of all components of voltage and current which does not contribute to active power, $P_w$ which is the average of instantaneous power. This concept of active power is well accepted nowadays. There is no difference in the active power defined in (1.19) by Budeanu in frequency domain and in (1.26) by Fryze in time domain. Both apparent powers are also same. However, reactive power given in (1.20) is different from that in (1.29) by Fryze. According to Fryze’s definitions, it is not necessary to decompose generic voltages and currents in Fourier series, although it requires the calculation of rms values of voltage and current which makes it unsuitable under transient phenomena and instantaneous compensation as required in active filters[J5].

1.3.4 Power definitions for power electronic converter control

Considering the speed of response today’s non-linear power electronic loads and the way reactive power and harmonics are generated, the traditional approach of taking rms and average values is not certainly sufficient. In 1982, Akagi [H1] proposed Instantaneous Reactive Power (IRP) theory (also known as p-q theory, explained in next chapter), a concept based on instantaneous power defined in time domain, especially for controlling power electronic based converters. While applying IRP theory, there are no restrictions on the voltage and current waveforms and hence it can be applied to steady state as well as transient conditions. The theory considers the system as unit and not the traditional approach of superposition.
An alternative to IRP theory, Bhattacharya et. al. [H2] proposed Synchronous Reference Frame theory (SRF). The SRF theory is based upon transforming three phase variables \((a,b,c)\) into synchronous variables \((d,q,0)\). The direct \((d)\) and quadrature \((q)\) axis rotate in space at a synchronous speed which corresponds to fundamental frequency of the supply.

### 1.4 Background on Power quality

The term power quality is an umbrella concept associated with variety of individual power system disturbances. Ironically, these disturbances or problems have already existed for decades but they had a little effect on most of the loads connected to the power system. In the present time, with the increasing customer awareness and proliferating use of non-linear loads, power quality problems are addressed in a systems approach rather than tackling individual ones. The specific object of power quality is the “purity” of the supply including voltage variations and waveform distortion. A power quality problem is any occurrence manifested in voltage, current, or frequency deviation that results in failure or misoperation of customer equipment [J1]. Although people talk of “power quality” quite often, they are actually referring to “voltage quality” because most of the time the controlled quantity is voltage [J4]. Power system disturbances and continually changing demand of consumers give rise to voltage variations. Deviation from the sinusoidal voltage supply can be due to transient phenomena or to the presence of nonlinear components. This section summarizes most common disturbances which deteriorate power quality.

#### 1.4.1 Transients

It refers to a very short duration undesirable events in voltage, current or power in an electric circuit. As shown in Fig. 1.6 and 1.7, they can be impulsive, generally caused by lightning and load switching, and oscillatory, usually due to capacitor-bank switching. Surges are high-energy pulses
arising from power system switching disturbances, either directly or as a result of resonating circuits associated with switching devices.

According to their duration, transient over voltages can be divided into:

1) **Switching surge** (duration in the range of ms)

2) **Impulse, spike** (duration in the range of μs)

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**1.4.2 Voltage Fluctuations and flicker**

This group includes two broad categories[6]: 1) Step changes, regular or irregular in time such as those produced by welding machines, rolling mills, mine winders, etc. 2) Cyclic or random voltage changes produced by corresponding variations in the load impedance most common being arc furnace load as shown in Fig. 1.8.

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![Figure 1-6: Impulsive transient](image1)

![Figure 1-7: Capacitor bank switching surge](image2)

![Figure 1-8: Fluctuations and Flicker](image3)

![Figure 1-9: Sag, Interruption and Swell](image4)
1.4.3 Brief Interruptions, Sags, and Swells

1.4.3.1 Voltage Dips (SAGS)

A voltage dip is a sudden reduction (between 10 and 90%) of the voltage, at a point in the electrical system, such as that shown in Fig. 1.9, and lasting for 0.5 cycles to several seconds. Dips with durations of less than half a cycle are regarded as transients. A voltage dip may be caused by switching operations associated with temporary disconnection of supply, the flow of heavy current associated with the start of large motor loads or the flow of fault currents.

1.4.3.2 Brief Interruptions

Brief interruptions can be considered as voltage sags with 100% amplitude (see Fig. 1.9). The cause may be a blown fuse or breaker opening and the effect an expensive shutdown.

1.4.3.3 Brief Voltage Increases (SWELLS)

Voltage swells, shown in Fig. 1.9, are brief increases in rms voltage that sometimes accompany voltage sags. They appear on the unfaulted phases of a three-phase circuit that has developed a single-phase short circuit. They also occur following a load rejection.

1.4.4 Unbalances

Unbalance describes a situation in which the voltages of a three-phase voltage source are not identical in magnitude, or the phase differences between them are not 120 electrical degrees, or both.

1.4.5 Waveform distortion

Waveform distortion is a steady state deviation from ideal sinusoidal waveform of fundamental frequency. There are five primary types of waveform distortion.
1.4.5.1 DC offset

It is the presence of dc voltage or current in an ac system. Geomagnetic disturbances and half wave rectification may lead to dc offset. Direct current in an ac system may lead to some damaging effects such as an increase in transformer saturation, additional stressing of insulation.

1.4.5.2 Harmonics

Harmonics are sinusoidal voltages or currents having frequencies that are integer multiples of the frequency at which the supply system is designed to operate (e.g., 50 Hz or 60 Hz). An illustration of fifth harmonic distortion is shown in Fig. 1.10.

![Figure 1-10: 5th Harmonic distortion in ac signal](image)

The non-linear loads draw non-sinusoidal current and their connection to the electrical grid produces introduction of reactive power component and distortion. Common examples of non-linear loads are the energy conservation equipment such as uncontrolled bridge rectifiers, switched mode power supplies, fluorescent lamp ballasts, dc arc furnaces, flexible ac transmission components, adjustable speed drives etc. The typical voltage, current waveforms and harmonic spectrum pertaining to single phase and three phase uncontrolled rectifiers are given in Fig. 1.11 and Fig. 1.12. In general, distorting equipment produces harmonic currents that, in turn, cause harmonic voltage drops across the impedances of the network. Harmonic distortion levels can be characterized by the complete harmonic spectrum (magnitude and phase) of the waveform. It is also common to use the term Total Harmonic Distortion (THD) which is defined as,
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\[ THD = \sqrt{\frac{\text{sum of all squares of amplitudes of harmonics}}{\text{amplitude of the fundamental component}}} \times 100\% \] (1.35)

\[ THD_v = \sqrt{\frac{\sum_{h=2}^{\infty} V_h^2}{V_1}} \times 100\% \] (1.36)

\[ THD_i = \sqrt{\frac{\sum_{h=2}^{\infty} I_h^2}{I_1}} \times 100\% \] (1.37)

1.4.5.3 Notching

It is a periodic voltage disturbance caused by normal operation of power electronic devices when there is commutation, notching occurs continuously so it can be characterized by frequency spectrum. But notching frequencies being high it is difficult to measure accurately by normal equipment. If not taken care of, it severely affects the performance of power converters employing zero cross detection technique.

1.4.5.4 Noise

Noise is unwanted electrical signal with broad band spectral content below 200kHz superimposed over the voltage and current in power system.
Harmonic standards

Harmonic distortion has become a major power quality problem in recent years. This is mainly attributed to increasing usage of non-linear power electronic based loads. Some of these are rectifier fed variable speed drives, light dimmers, temperature controllers, AC voltage regulators, SMPS and UPS. The users try to achieve highest efficiency at the expense of causing harmonic pollution. The presence of harmonics increases losses in the lines, overheating of machines, poor power factor, malfunctioning of protective devices, and resonance with parallel connected capacitors. Also, precision instruments, communication and control equipment are affected by EMI associated with high frequency current harmonics. Various adverse effects of harmonics and power quality issues are thoroughly discussed by Dugan [J1].

In view of the proliferation of power electronic equipment connected to utility distribution systems, various international agencies have proposed limits on the magnitude of harmonic current injected into the supply to maintain acceptable power quality. The most widely known is the IEEE519-1992 [F6] which proposes limits on the harmonic distortion at PCC. The $THD_i$ defining the current distortion level can exhibit quite high (misleading) values for nonlinear loads operating at light load conditions. However, since this magnitude of harmonic components is low, this $THD_i$ value is not critical and the influence of harmonic current on PCC voltage distortion is insignificant. In order to avoid such misinterpretation, IEEE-519 defines the term called Total Demand Distortion (TDD) which is given as,

$$TDD_i = \frac{\sqrt{\sum_{n=2}^{\infty} I_n^2}}{I_L} \times 100\%$$

(1.38)

Where $I_n$ is the rms value of the $n^{th}$ current harmonic and $I_L$ is the rated rms value of load current at fundamental frequency. Therefore, the harmonic
current limits proposed by IEEE-519 are expressed in terms of TDD rather than THD and are given in Table 1.1. To define the TDD limits as well as individual harmonic current limits for customers having various utilization capacities, IEEE-519 uses the short circuit ratio \( I_{SC}/I_L \), which is the ratio of the short circuit current \( I_{SC} \) at the PCC (point of common coupling) to the rated current (demand current, \( I_L \)) of the customer. As seen in Table 1.1, systems with low \( I_{SC}/I_L \) ratio (high impedance or weak distribution systems) are bounded by lower distortion limits in order to keep voltage distortion at the PCC at reasonably low levels.

IEEE-519 proposes voltage THD limits as well as individual harmonic voltage limits shown in Table 1.2. The limits for voltage THD should be lower than 5%. The main reason for voltage distortion is the load current harmonic content passing through the impedance of power system. Therefore, customers injecting harmonic currents to the line should mitigate their own harmonics maintain IEEE-519 limits. Therefore, harmonic compensation for individual customers becomes essential and will become mandatory in near future.

1.6 Harmonic mitigation techniques

Harmonic mitigation techniques are generally utilized to reduce the current THD and filters based on these techniques are classified in three main categories:

1) Passive filters
2) Active filters
3) Hybrid filters

Traditionally, passive filters (LC combination) have been used to absorb current harmonics. They possess the merits viz. simple structure, low cost, ability to compensate reactive power. As the passive filters are based on the resonant principle, they possess the drawbacks such as large size, fixed compensation, tuning problems. The supply impedance affects the compen-
sation characteristics of the filter and it is susceptible to series and/or parallel resonance with utility and/or load.

Active filters are controlled current sources realized by using a VSI (Voltage Source Inverter). The VSI is controlled such that it supplies a current equal and opposite to harmonic and/or reactive current required by the load, therefore eliminating these components from source current.

Table 1-1: IEEE Standard 519 Harmonic Current Distortion Limits at a PCC

<table>
<thead>
<tr>
<th>Harmonic current distortion in % (120v TO 69kV)</th>
<th>Harmonic order</th>
<th>TDD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isc/I1</td>
<td>&lt;11</td>
<td>11 - 22</td>
</tr>
<tr>
<td>&lt;20</td>
<td>4</td>
<td>1.5</td>
</tr>
<tr>
<td>20 - 49.9</td>
<td>7.0</td>
<td>2.5</td>
</tr>
<tr>
<td>50 - 99.9</td>
<td>10.0</td>
<td>4.0</td>
</tr>
<tr>
<td>100 - 999</td>
<td>12.0</td>
<td>5.0</td>
</tr>
<tr>
<td>&gt;1000</td>
<td>15.0</td>
<td>8.0</td>
</tr>
</tbody>
</table>

Table 1-2: Recommended Harmonic Voltage Limits for power Producers.

<table>
<thead>
<tr>
<th>PCC Voltage</th>
<th>Individual Harmonic Magnitude</th>
<th>THD %</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;=69kV</td>
<td>3.0</td>
<td>5.0</td>
</tr>
<tr>
<td>69-161kV</td>
<td>1.5</td>
<td>2.5</td>
</tr>
<tr>
<td>&gt; 161kV</td>
<td>1.0</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Hybrid filters combine passive and active filters in various configurations in order to reduce initial cost and increase the efficiency of the filter structure. The basic principle of hybrid filtering is to improve the filtering capacity of a passive filter and to damp series and parallel resonances with a small rated active filter. However, they involve higher engineering effort than passive filter design.
1.6.1 Active filters

Compared to passive filters, active filters provide an excellent solution for dynamic reactive power compensation and harmonic current compensation in power distribution systems. Active filters are superior in filtering performance, smaller in size, and more flexible in application compared to traditional passive filters. With various successful circuit topologies and control strategies, active filters are capable of not only harmonic current compensation, but also reactive power, negative sequence current and neutral wire current (zero sequence current) compensation. Active filters are also utilized to suppress voltage harmonics and voltage flickering, regulate load terminal voltages, balance voltages in a power system, and damp resonances. Active filters can be parallel (shunt) type, series type, and combination of both depending on the type of nonlinear loads and the required functionalities. Nevertheless, active filters are slightly inferior in cost and operating loss, even at present [F5]. Various active filters configurations and state-of-the-art is discussed in [F1-F4].

1.6.1.1 Basic working principle of Shunt Active Filter (SAF)

Shunt active filters (SAF) basically works by detecting harmonic and reactive components from the distorted current signals obtained from load feedback and injecting these harmonic and reactive current components with same magnitude but opposite phase into the power system so that the source current is sinusoidal and in phase with the supply voltage.

Fig. 1.13 shows basic schematic for single phase SAF. The power circuit consists of a current controlled full bridge VSI, a coupling inductor, \( L_f \), and a self supported DC capacitor, \( C_{dc} \). VSI Bridge is formed by four switch cells \( S_1, S_2, S_3, S_4 \). Each switch cell is a unidirectional controlled switch, such as IGBT (Insulated Gate Bipolar Transistor) and an anti-parallel diode. The VSI operates at a switching frequency well above the frequency of the highest harmonic to be compensated. The capacitor is charged to a DC voltage, \( V_{dc} \).
which is greater than the peak value of the addition of mains voltage and drop across the coupling inductor. The VSI injects a current at PCC which contains those load current components that are supposed to be compensated. It has to absorb active power by drawing a fundamental frequency current in phase with the PCC voltage such that the capacitor voltage remains constant, despite of SAF losses. Controller is the heart of the SAF and is implemented in three sections. In first section, PCC voltage, load current, DC side voltage are sensed using potential transformer (PT), Hall sensors and isolation amplifier respectively. In the second stage, the necessary compensation current to be injected and the active current to be absorbed by SAF to maintain the DC bus voltage are derived. Calculation of compensation current can be performed time domain or frequency domain. First approach, addressed in this dissertation, is based upon on-line computation of an instantaneous evaluation of harmonic components of load current and the second uses principle of Fourier analysis and periodicity of distorted waveform to be corrected.

![Basic Schematic block diagram of single phase SAF](image)

**Figure 1-13 Basic Schematic block diagram of single phase SAF**
Phase locking mechanism is an essential component of the SAF controller that generates unit vector signal in synchronism with the fundamental component of the PCC voltage. The third section is the current controller. Using appropriate current control technique, gating signals are generated to control the switches of VSI, to track the compensation current.

### 1.6.1.2 SAF phasor diagram

The phasor diagram of SAF is shown in Fig. 1.14 as seen from the supply end. As indicated in Fig.1.2a, the fundamental VSI current $\bar{I}_{c,1}$ is generated by difference between the fundamental source voltage $\bar{V}_{s,1}$ and the fundamental VSI output voltage $\bar{V}_{c,1}$. It contains two components: the current for the load reactive power compensation, $\bar{I}_{c,q}$ and the current for the SAF loss compensation, $\bar{I}_{c,\text{loss}}$. As shown in the diagram, $\bar{I}_{c,q} = \bar{I}_{c,1}$. The component $\bar{I}_{c,\text{loss}}$ compensates for the losses on the SAF power circuit by drawing active power from the supply and current required to charge dc capacitor. The source current, $\bar{I}_{s,1}$ is equal to the resultant of the fundamental load current $\bar{I}_{l,1}$ and fundamental VSI current $\bar{I}_{c,1}$ and is in phase with $\bar{V}_{s,1}$. As shown in Fig. 1.14b, each harmonic component of the VSI current, $\bar{I}_{c,h}$, is produced by corresponding harmonic component in the VSI output voltage, $\bar{V}_{c,h}$.

### 1.6.1.3 SAF Control system

Using current and voltage sensors, four variables are measured and fed to the SAF control system: the load current $i_{L}$, the source voltage $v_{s}$, the converter output current $i_{c}$, and the DC side voltage $V_{dc}$. The SAF reference current generation system provides the current $i_{c}^{*}$ which compensates for the load harmonic and reactive current. The task of the current control system is to provide proper PWM switching pattern for the VSI switches, so that the VSI output voltage can inject such current at PCC.
Various control functions of the SAF control system are,

1) Instantaneous phase angle detection
2) Compensation current reference generation.
3) DC bus voltage control.
4) Current tracking.

The frequency and phase angle information of the utility voltage represent basic information for the grid connected power conditioning equipment. Accurate and fast detection of phase angle of fundamental utility voltage is necessary for generation of current reference signals. Generally, line frequency varies within limited range. In the event of grid fault, equipment becomes exposed to phase angle jumps and voltage sags. Furthermore, harmonics, notches, spikes and other kinds of undesirable perturbations are common in today’s industrial environment. This has necessitated developing a rigid phase synchronizing techniques.
The compensation current reference is an addition of three signals,

- Sum of harmonic components of load current. The sum includes all odd harmonics from 3rd to the highest harmonic level to be compensated.
- Reactive component of the load current
- Determination of fundamental frequency in phase current to drawn for VSI loss compensation and to maintain DC voltage.

Several intelligent techniques have been proposed for generation of SAF current reference. The pioneering work contributed by Akagi [H1] who proposed IRP (Instantaneous Reactive Power) theory and by Bhattacharya [H2] who proposed SRF (Synchronous Reference Frame) theory. Both approaches are discussed later.

1.6.1.4 SAF Inverter Control techniques

SAF reference current is far from sinusoidal signal as it has to compensate for harmonics. The current controller has to deal with high slope variations of the reference current corresponding to higher order harmonics in the load current. The current controller must ensure zero steady state error in the injected current. The performance of the current controller is evaluated in terms of Total Harmonic Distortion ($THD$) of the mains current and ripple generated by PWM output of SAF. [I1][I5] has given comparison of different current control techniques.

Use of non-linear regulators such as hysteresis current control gives simple and rigid solution for current control but suffers from serious drawback of variable switching frequency. Different techniques to maintain constant device frequency for hysteresis current control have been proposed by [I2] [I3] [I6][I7].

Constant switching frequency can also be achieved by using deadbeat control which exploits the advantages of digital control. The technique has been practically implemented. The main drawback of these methods is related to accuracy of system parameters [I4].
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Linear current control called as ramp comparison current control uses PI controller to produce voltage reference to triangular PWM modulator. The controller performance is satisfactory when significant harmonics present in the load are limited to frequency well below that of triangular carrier (less than $1/9$th)[I1].

1.7 Reactive power compensation and STATCOM

Besides, the power quality problem caused by harmonics, reactive power flow is another power quality problem. Reactive current drawn by linear/nonlinear loads connected to the PCC results in reactive power, which is a type of power that does no real work. The voltage plays important role in stable operation of power system. Presence of reactive current component gives rise to poor voltage regulation and voltage profile. Voltage levels are sensitive to the flow of reactive power and hence control of reactive power is important. Although there are no international standards for reactive current unlike the harmonics drawn by the loads, many countries post limitations and monetary punishments to the end-users for the reactive power they draw and thus use of power factor correction equipment is encouraged.

Reactive power compensation when seen from load end may be called as load compensation. When it is for the long distance high voltage transmission line, it may be called as transmission system compensation [J2]. Load compensation is the management of reactive power of a particular load to improve quality of supply at that particular load or group of loads. Load compensation has three main goals [J7],

1) Power factor correction.
2) Improvement of voltage regulation.
3) Load balancing.

Conventional methods of reactive power compensation relies on passive elements (L&C) having energy storage capability. Dynamic compensation is achieved by either connecting these elements if steps as in switched capacitor VAr compensators or applying variable voltage to these elements by using
anti-parallel thyristors as in the case of Thyristor Switched Capacitor (TSC) & Thyristor Controlled Reactor (TCR). Despite of the merits such as low cost, easy control, these techniques suffer from drawbacks such as increase in the size of passive elements with increasing demand, dependence of VAr generation on voltage existing at the point of compensation and slow response to transient conditions.

The STATCOM (STATic COMpensator) is the first VSI based reactive power compensator. STATCOM is a power electronic equivalent of synchronous condenser. Instead of directly deriving reactive power from energy storage components, STATCOM basically circulates reactive power with the network. The reactive components, therefore, are much smaller than those in conventional techniques[J2].

STATCOMs are often used in transmission systems for voltage regulation. When used is distribution systems, it is called as D-STATCOM and used for reactive power compensation for rapidly changing industrial load and stability improvement such as wind turbine systems. STATCOM has a potential to be exceptionally reliable with added capabilities that helps improving quality of supply such as,

1) Faster response and ability to inject lagging/leading reactive power.
2) Sustain reactive currents at low voltages.
3) Reduce land use as it occupies smaller footprint.
4) Be developed as voltage support.

1.7.1 Basic STATCOM topology

The basic schematic block diagram of 1ph. STATCOM is as shown in Fig. 1.15. It has the same power circuit as discussed as that of SAF as discussed previously. The VSI is connected to the ac supply via a small coupling inductor; $L_{ac}$ (coupling inductor). The VSI converts the DC voltage across DC capacitor into PWM output. The VSI switches are operated in such a manner as to generate a fundamental ac output voltage waveform with demanded magnitude and phase angle in synchronism with the ac supply. The sample
waveforms are as shown in Fig. 1.16. The VSI can be viewed as a synchronous sinusoidal voltage source behind coupling inductor. The difference between the inverter output and the AC supply voltage determines the direction of reactive power flow. If the magnitude of the VSI output fundamental voltage is increased above supply voltage, then the VSI generates capacitive reactive power and if the magnitude of VSI output voltage is decreased below the supply voltage, the VSI absorbs inductive reactive power.

Figure 1-15: Schematic block diagram of voltage controlled STATCOM

Figure 1-16: Output voltage waveform of VSI of STATCOM

The DC capacitor provides a circulating current path and acts as a DC voltage source for VSI. The VSI can also exchange real power with the supply system. This can be done by adjusting the phase angle between the supply
voltage and the VSI output fundamental voltage. If VSI output leads the supply voltage, VSI supplies real power and if it lags behind the supply voltage, it absorbs real power. The four quadrants of STATCOM operation are shown in Fig. 1.1. If VSI output is made equal to supply voltage, there is no reactive power exchange and the STATCOM is said to be in floating state. In practical STATCOM, a small lagging phase shift between supply voltage and VSI output fundamental voltage has to be maintained for the VSI to absorb active power for its losses and to maintain the DC voltage.

1.7.2 Reactive power control

The active power $P$ and reactive power $Q$ of the STATCOM can be expressed in terms of $V_s, V_o$ and the angle $\delta$ as,

\[ P = \frac{V_s V_o \sin \delta}{X_{ac}} \]  \hspace{1cm} (1.39)

\[ Q = V_s \frac{V_s - V_o \cos \delta}{X_{ac}} \]  \hspace{1cm} (1.40)

The detailed derivations of the above equations are given in Chapter 2.

Defining modulation index, $m$,

\[ m = \frac{\hat{V}_o}{V_{dc}} \]  \hspace{1cm} (1.41)

$\hat{V}_o$ is the peak value of the VSI output fundamental voltage.

Substituting,

\[ P = \frac{\sqrt{2} V_s m V_{dc} \sin \delta}{X_{ac}} \]  \hspace{1cm} (1.42)

\[ Q = V_s^2 - \sqrt{2} V_s m V_{dc} \cos \delta \] \hspace{1cm} (1.43)

In view of (1.43), reactive power can be controlled by one of the following,

1) Varying modulation index $m$ while keeping $V_{dc}$ constant

2) Varying $V_{dc}$ while keeping $m$ constant

3) By varying both $m$ and $V_{dc}$
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The VI characteristics are shown Fig. 1.18. Its inductive and capacitive output currents can be controlled independently from its connected AC bus voltage. STATCOM has increased transient ratings both in inductive as well as capacitive regions. The overload capacity is about 20% for several cycles in both regions. Thus, the STATCOM is more effective than the conventional SVCs (Static VAr Compensators) in providing voltage support under large system disturbances. The ability of the STATCOM to maintain full capacitive output current at low system voltage also makes it more effective than the SVC in improving the transient stability. The only drawbacks of STATCOM are higher cost/kVAr and higher operating loss compared to conventional SVCs.

Figure 1-17: STATCOM Phasor diagrams
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Most of the industrial loads are inductive and reactive power generation capability of D-STATCOM can be made purely capacitive by connecting a capacitor as shown in Fig. 1.19. The capacitor bank serves both as a low pass filter and also fundamental capacitive VAr generator. As shown in Fig. 1.19, power semiconductors operate at low voltages as the VSI is connected to the grid through a step down transformer. In such cases, the leakage reactance of the step down transformer serves as harmonic filter. The resulting reactive power compensation characteristic is as shown in Fig. 1.20.

Figure 1-19: D-STATCOM configurations
1.8 Literature Review:

1.8.1 Single Phase STATCOM

In past two decades, numerous research papers have discussed various control and design aspects of 3ph. STATCOM and led the technology to a quite mature level. On the other hand, 1ph. STATCOM design issues and applications are rarely reported except for load balancing, 3phase 4 Wire applications, multilevel converters [C2][A1][A2]. In the proposed work, which aims at single phase D-STATCOM, following design issues are addressed: 1) Control strategy 2) VSI switching logic with low switching frequency 3) Optimum selection of passive parameters.

The available PWM techniques for STATCOM applications are of two types viz. carrier modulated sine-PWM and SHE PWM (Selective Harmonic Elimination). Keeping in mind the proposed application of the STATCOM at TSS (high current rating), it is required that the VSI should operated at low switching frequency to limit the switching losses. Taking into account the merits of the SHE PWM techniques in [B3], SHE PWM methods are the best choice. The SHE technique was originally proposed by Patel and Hoft [B1][B2]. A critical evaluation of the different SHE PWM techniques is found in [B3]. Basically, a square wave can be chopped a number of times in a relationship that eliminates a number of harmonics as well as giving flexibility to control fundamental voltage. With \( N \) chops, there are \( N \) degrees of
freedom. One of them can be used to control the fundamental and the remaining $N-1$ degrees of freedom can be used to eliminate $N-1$ harmonics. The $N-1$ switching instants can be determined by solving a set of non-linear transcendental equations with coefficients obtained from Fourier series of the VSI output waveform. The traditional method of solving SHE problem is Newton-Raphson method which is an off-line method and the convergence largely depends upon choice of initial values.

More recent research focused on both the solution of the transcendental harmonic elimination equations and efficient implementation using microprocessor systems. Different techniques for online solution of SHE PWM problem [B4] [B5] [B6] [B8] [B9] [B10] [B11] [B12] [B13][B15] are reported in the literature. Apart from the available techniques which involve complex mathematics, a simple method based on curve fitting approach has been proposed for online calculation of SHE switching instants. The method reported in [B7] but without practical implementation and application to D-STATCOM. The solution trajectory for each switching instant is approximately represented by an $n^{th}$ order polynomial. A polynomial is used for online computation of SHE switching instants. With easy availability of digital signal processors with faster processing speed, the one line computation of switching angles based on polynomial approach can be easily implemented in real time.

1.8.2 Selection of passive components

Apart from the power electronic control and design aspects of the STATCOM, optimum selection of passive components viz. coupling inductor and DC capacitor are of subtle importance as it controls the performance, cost, size of STATCOM. The selection of the two passive elements, $L_{ac}$ $C_{dc}$ is mainly constrained by harmonic distortion of the STATCOM injected current at PCC at rated conditions and DC bus voltage ripple respectively. Selection methodology of passive elements of 3ph. STATCOM is discussed in [C1][C2][C3][C4] but that for single phase STATCOM is not reported in
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literature. In this work, a formula for selecting optimum value of coupling inductor has been derived for SHE PWM controlled 1 ph. D-STATCOM. Selection of coupling inductor is constrained by allowable TDD of the current injected by STATCOM. For single phase STATCOMs, there is second harmonic ripple component in dc bus voltage. Selection of optimum value of dc capacitor is based on minimization of ripple in the dc bus voltage.

1.8.3 Phase Synchronization

A rigid phase angle detection mechanism is an integral part of grid tied VSIs. Conventionally, Phase locked loops (PLL) have been used for the same. The PLL structure is a feedback control system that automatically adjusts the phase of a locally generated signal to match the phase of an input signal. The figures of merit of a PLL are [D5]:

1) Steady state behaviour and phase error.
2) Response to frequency variation and phase jumps.
3) Response to voltage sag/swell.
4) Response to harmonics present in utility voltage.
5) Simplicity in structure.

Conventionally, the frequency and phase angle of a single phase voltage are obtained by detecting the zero-cross point. Yet this method is unable to detect the utility-voltage information instantaneously and is very sensitive to noise. Among the various solutions to compute instantaneous phase angle SRF method is more preferred for single phase and three phase systems. In three phase systems, two phase conversion can be readily performed by using Clarke transformation to generate two orthogonal signals $V_a$ and $V_\beta$. However, for a single-phase system, the instantaneous phase angle information is much harder to obtain. SRF based single phase PLLs are presented in [D1-D4]. In general, these improved versions use specific "filtering" techniques in order to deliver a non distorted signal to the SRF-PLL. In the present work, a single phase PLL based on Sine Signal Integrator (SSI) has been proposed. Use of supply frequency tuned SSI eliminates the need of
additional filters to generate orthogonal component. The proposed PLL is simple in structure with better performance in case of distorted supply and frequency variations.

### 1.8.4 Single phase SAFs

Current harmonics and reactive power can be controlled by installing a three phase SAF at PCC as shown in Fig. 1.21. But this will not compensate for the circulating reactive power and harmonic current propagation among the individual loads. In spite of a large rated three phase SAF at PCC, this may cause power quality problems in the plant because of interference between individual loads. A better approach could be to install a small rated single phase SAF at each load. This will prevent flow of harmonic current, the possible interference and subsequent voltage distortion. Comparing to the three-phase SAF, the single phase one is rated to a lower power, so it is possible to operate with higher switching frequency leading to a better performance. However, a single phase SAF at individual load involves higher cost. Various single phase SAFs and their specific applications are discussed in [G1-G6].

### 1.8.5 Reference Current Generation techniques

Performance of SAF is strongly influenced by how rapidly and accurately it detects harmonic and reactive current of the load. The SAF control system consists of two control loops. The outer voltage loop is for regulating the dc capacitor voltage. The inner current loop performs the reference current tracking.

![Figure 1-21: A three phase SAF installed at plant point of common coupling.](image)

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For reference signal generation, in direct method, fundamental component of the load current is calculated and subtracted from the load current to derive the harmonic component of load current. Akagi et al. proposed $p$-$q$ theory [H1], also called as instantaneous reactive power theory (IRP) and Bhattacharya [H2] $d$-$q$ theory (Synchronous Reference Frame theory (SRF) for 3phase systems to generate instantaneous current reference for SAF. Literature presents different solutions to compute harmonic and reactive currents [H3-H18]. A generalized $p$-$q$ theory for single phase active filtering has been proposed by Singh et al. [H15]. In three phase system, both IRP and SRF techniques operate in reference with two orthogonal axes ($\alpha\beta$ alpha-beta in IRP and $dq$ in SRF). In single phase systems, since only one variable exists, it is necessary to create one fictitious or imaginary variable which is in quadrature with the original variable at all frequencies. Imaginary variable can be computed using Hilbert Transform as explained in [H7]. It is possible to approximate the transformation through a Finite Impulse Response (FIR) filter and in this case some phase delays are introduced in the fictitious variable and implicitly in the inverter current reference [H11].

Alternatively, computation of the reference current can be performed using a Sine Signal Integrator (SSI) along with IRP theory. This approach, proposed by Bojoi [H16], enables generation of orthogonal component needed for IRP theory without any delay elements and less computational burden. The method offers correct determination of reference current in presence grid voltage distortions. The selectivity of SSI filter can be adjusted by proper adjustment of the filter gain. In the present work, grid frequency tuned SSI filter has been proposed to extract compensation reference current for the SAF. The technique assures fast and correct detection of harmonic detection even in presence of grid voltage distortions and frequency variation.
1.9 Objectives of the research work

The research work is divided in two parts. The first part deals with the design, simulation and implementation of SHE PWM controlled single phase D-STATCOM and the second part is for design and simulation of single phase SAF. The research objectives are summarized as under,

PART A
1) A technique for control of 1ph. D-STATCOM using constant dc bus voltage and SHE PWM controlled VSI with low switching frequency.
2) An easy-to-implement technique for on-line solution of SHE PWM equations.
3) To propose a simplified method for passive parameter selection of single phase D-STATCOM.
4) To develop a simulation model of 0-100KVAr SHE PWM controlled STATCOM.
5) Development of single phase 230V, 20kVAR STATCOM prototype unit.
6) Performance appraisal by comparing test results of simulated model and prototype.

PART B
1) To develop a fast and accurate reference current generation technique for direct and indirect control of single phase non-linear loads based on SSI.
2) To develop rigid phase synchronization technique based on SSI and testing of its performance under distorted supply conditions and frequency variations.
3) To develop simulation model of direct and indirect current controlled single phase SAF and test its performance under normal conditions and distorted supply conditions.
1.10 Outline of the thesis

Chapter 2 begins with the explanation on basic D-STATCOM operation with the help of mathematical equations and phasor diagrams. Various methods of controlling reactive power and PWM techniques are also discussed. A detailed analysis of SHE PWM technique is given later in the chapter. The curve fitting technique for on-line solution of SHE-PWM equation is discussed in detail along with the method of least squares to evaluate polynomial constants used for curve fitting.

Chapter 3 deals with the selection of passive elements of a SHE PWM controlled single phase D-STATCOM. A detailed procedure is given to select passive parameters i.e. $L_{ac}$ (coupling inductor) and $C_{dc}$ (dc capacitor).

In Chapter 4, simulation model and its responses of 100 KVAR STATCOM are presented. Design of ripple filter to reduce the distortion in the STATCOM current is also exhibited in this chapter.

In chapter 5, a detailed description about the digital electronic hardware of 230V, 20KVAR D-STATCOM prototype is given. The performance of the prototype is demonstrated with the help of test results obtained at different operating conditions.

Chapter 6 begins with a review of reference current generation techniques, i.e. Instantaneous Reactive Power (IRP) theory and Synchronous Rotating Frame theory (SRF). Single phase implementation of both IRP and SRF theories is discussed along with its mathematical analysis and case studies. A novel SAF reference current generation technique based on SSI is proposed for indirect control of SAF. A single phase PLL based on SSI is also presented in the same chapter.
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In Chapter 7, a detailed design procedure of single phase SAF is presented. The results of computer simulation for direct and indirect controlled single phase SAF are presented at the end.

Chapter 8 gives summarizes the outcome of the research work and highlights future scope of work.