Chapter 1

Introduction to Power Quality Issues and Solutions with Emphasis on Shunt Active Power Filters

1.1 Introduction

In last few decades industrial growth throughout the globe has been tremendous. Automation at various levels is one of the prime factors for this growth. Advancement in power semiconductor device technology, availability of fast & efficient power electronic devices (static/semiconductor switches) at higher power rating, and advent of fast digital signal processors (DSPs) have made it possible to implement control and automation for sustained industrial growth. Power electronic devices based converters have found numerous applications like, induction furnace, arc furnace, welding, lighting (electronic ballasts for tubular fluorescent lamps, compact fluorescent lamps and light emitting diode lights), power supplies (uninterruptible power supplies [UPS], switched mode power supplies [SMPS]), hybrid electric vehicles (HEV), high voltage dc (HVDC) transmission systems, flexible ac transmission (FACT) devices, variable frequency drives (VFDs) for motor control, cycloconverters, uncontrolled (diode based) and controlled (thyristor based) rectifiers (front-end converters), pulse width modulation (PWM) inverters, choppers, etc., are a few to name. Most of these power electronic converters are considered as non-linear loads that inject current harmonics in the power system.

Widespread interaction of these non-linear loads with utility draws non-sinusoidal currents from ac mains producing a considerable amount of harmonic current. Following are the problems created by harmonics currents [1]:

- Excessive heating and failure of capacitors, capacitor fuses, transformers, mo-
tors, fluorescent lighting ballasts, etc.

- Nuisance tripping of circuit breaker or blown fuses
- Presence of the third-harmonic and multiples of it in neutral grounding systems may require the derating of neutral conductors
- Noise from harmonics that lead to erroneous operation of control system components
- Damage to sensitive electronic equipment
- Electronic communications interference
- More severely, line voltage distortion (depending on the short-circuit ratio of the system and the harmonic constant of the converter used).

1.2 Power quality

In recent years, the issue of power quality has gained increased interest of researchers because of more and more usage of power quality sensitive loads. At the same time, improvement in power quality has become more challenging task as the loads themselves (mostly non-linear loads) become important causes of the degradation of power quality. For utilities, providing adequate power quality has been a prime focus because of changes in consumer (mainly industrial) equipment and requirements. For the user, problems of new equipment sensitivity to service quality have come as unexpected surprises. Many electronic devices, such as computers, process controls, medical equipment, communication equipment and power supplies, are sensitive to power system disturbances. Several authors have attempted to define the term ‘power quality’ in literature [2]-[3], however there is a lack of universally accepted definition. For example, International Electrotechnical Commission (IEC) defines power quality as a set of parameters defining the properties of the power supply as delivered to the user in normal operating conditions in terms of continuity of supply and characteristics of voltage (symmetry, frequency, magnitude, and waveform) [2]. Further, Institute of Electrical and Electronics Engineers (IEEE) standard 1100-2005 [3] defines power quality as the concept of powering and grounding electronic equipment in a manner that is suitable to the operation of that equipment and compatible with the premise wiring system and other connected equipment. In a broader perspective, power quality includes considerations regarding different aspects of reliability of electrical power supply such as distortion, phase unbalance, line interruptions, amplitude variations, frequency changes, flicker, and transients, etc. But while narrowing down, the focus
of power quality revolves around distortion in waveforms of voltage (at system level) and current (at equipment level). Due to the extensive use of power converters and other non-linear loads in industry and by consumers in general, an increasing deterioration of the power systems voltage and current waveforms is observed. The causes of power quality problems can be categorized as:

- Disturbances arising in the power system (for instance disturbances involving power lines, and switching to clear faults, lightning strikes, vehicle hit the poles, etc.)

- Disturbances induced by the operation of customer equipment (for example, starting of heavy loads, switched mode power supplies, arc furnaces, etc.)

1.3 Mitigation of power quality problems

It is difficult for electric utilities to always ensure a perfect quality of power supply because some causes of power quality problems are beyond the control of utilities. For instance, the operation of customer equipment (e.g., power electronic converters) can cause power disturbances. Thus users of utility power should also play an active role in the mitigation of power quality problems, especially at equipment level. The same philosophy is also conveyed by IEEE in its standard 519-1992 [1] that the utility should be responsible for maintaining quality of voltage waveform, and side-by-side, consumer should be responsible for limiting harmonic currents injected onto the power system. Hence, it becomes very essential for the researchers to work for the improvement of power quality at system level as well as at equipment level. The quality of power can be improved in two basic ways: [4]

- Circuit arrangement.

- Utilization of power quality improvement equipment.

1.3.1 Circuit arrangement

Quality of power can be improved by electric circuit configuration in following ways:

- Sensitive electronic equipments can be protected from distorted waveforms by supplying them from dedicated line through separate transformer from feeder that feeds other loads.

- Making provision of a separate regulating transformer for each sensitive load.
1.3.2 Utilization of power quality improvement equipment

Different types of equipment are available for improving the power quality varying from cheaper (providing less protection or compensation) to expensive devices (higher grade of protection or compensation) as per the requirement of power quality improvement. For example, transient voltage surge suppressors are used to detect surges and reduce them to a safe level while voltage regulators maintain voltage output within given limits, despite fluctuations in the input. An isolation transformer used for changing the voltage level can be helpful in compensating for required high or low voltage.

Devices like passive filters are used to remove harmonics. Active power filters are used to eliminate harmonics. In broader sense active power filters have wider scope and serve as active power line conditioners are used to compensate for reactive power, harmonics and flicker [5]-[16]. An uninterruptible power supply (UPS) along with ensuring continuity of power supply in case of outages also provides protection against disturbances like harmonics and electrical noise. Also, different types of flexible ac transmission devices (FACTS) are used to enhance power quality, mostly at system level.

Power quality improvement is responsibility not only of the utility supplying power, but is equal responsibility of the consumers as well. Utilities ensure appropriate quality of power by installing power quality improvement devices like FACTS at transmission and distribution level, while consumers enhance power quality by installing capacitor banks, passive filters or Active Power Filters (APFs) at load side. The research work documented in the thesis is focused on power quality improvement at load side by installing Shunt Active Power Filter (SAPF).

1.4 Power quality improvement devices - passive filters

Passive harmonic filters consisting of passive components capacitors, inductors, and/or resistors are connected in parallel with non-linear loads. Figure 1.1 shows different configurations of series and shunt type passive filters. Series passive harmonic filters block the flow of harmonic currents by providing a high harmonic series impedance. Shunt passive filters installed in the vicinity of a non-linear load provide low-impedance paths for specific harmonic frequencies. Hence they absorb the dominant harmonic currents injected by the load. Further passive harmonic filters help in power-factor...
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correction for inductive loads. Conventionally such passive filters have been broadly used to suppress harmonics because of low initial cost and high efficiency. However, passive filters have many disadvantages [17], such as:

- Fixed compensation
- Due to large passive components size is bulky
- Possibility for occurrence of parallel and series resonance with both load and supply impedances
- Coordination of passive filter ratings with reactive power requirements of the loads and quite often it is difficult to design the filters in order to avoid leading power factor operation for certain load conditions.

![Figure 1.1: Fundamental types of passive filters](image)

1.5 Need of active power filter

In order to overcome these drawbacks of passive filters, active power filters (APF) are developed [18]. Active power filters are power electronic converter based devices used for power quality improvement by mitigating harmonics. Unlike passive filters APF does not require passive components for harmonic elimination. Advantages of APF over passive filters are as follows [19]:

- Only one filter is required to eliminate all the unwanted harmonics
- Smaller in size
- Superior in filtering performance and more flexible in application compared to passive filters
- Fast dynamic response
• Active filters are being able to compensate for harmonics without reactive power concerns.

Thus active power filter is a better solution as compared to passive filters for elimination of harmonics and hence improving the power quality.

1.6 Different types of active power filter

Active power filters are power electronic converter based devices that are used for power quality improvement. Active power filters are basically of three types: - shunt, series and hybrid APF.

1.6.1 Shunt active power filter

When the active power filter is connected in parallel with the harmonic load, it is called shunt APF (SAPF). The SAPF injects a compensating current which in turn cancels the harmonic produced by non-linear loads. The shunt APF is thus suitable for non-linear loads which introduce current harmonics [19],[20]. Figure 1.2 demonstrates the basic operation of shunt active power filter (SAPF). SAPF works in following manner:-

• The shunt APF detects non-linear load current \( i_L \) which contains harmonics.

• It then extracts the harmonic current from non-linear load current with the help of mathematical computations implemented using digital signal processors (DSP).

• The SAPF supplies compensating current which is equal in magnitude of the extracted harmonic current but out of phase (opposite), to the supply mains at point of common coupling (PCC).

• Due to this, harmonics injected by the load in to the supply gets cancelled out and the supply current becomes sinusoidal.

• So, as a whole (combination of non-linear load with SAPF) the arrangement will be seen as linear load by the supply.

1.6.2 Series active power filter

The series active filter is connected in series with the supply mains through a three-phase transformer or three single-phase transformers as shown in figure 1.3. Series APF is generally used to compensate for voltage harmonics present in the system [19], [21]. Series APF operates in following manner:
• The series APF detects the supply current.

• It then extracts the harmonic current from supply current with the help of mathematical calculations implemented using DSP.

• In accordance with the extracted harmonics, series APF supplies compensating voltage across the primary of the transformer, which in turn reduces supply voltage harmonics.

Hence, basically shunt active power filters are used for mitigation of current harmonics while series active power filters mitigate voltage harmonics. In other words, shunt
active power filter is employed for current stiff circuits whereas the series active power filter is employed for voltage stiff circuits.

1.6.3 Hybrid active power filter

Hybrid filter is a combination of series and shunt active power filter or active power filter and passive filter [22]-[27]. Combination of active power filter with the passive filter makes it possible to significantly reduce the rating (as well as burden of compensation) of the active power filter, and also improves the dynamic performance of APF. Figure 1.4 shows different configurations of hybrid active power filter like parallel active parallel passive (shunt active filter connected in parallel with passive filter), parallel active series passive (shunt active filter connected in parallel with passive filter), series active parallel passive (series active filter connected in series with passive filter), series active series passive (series active filter connected in series with passive filter). As current harmonic injection in supply mains due to non-linear load is a grave issue of power quality to be tackled with, the proposed research work documented in thesis is focused on operation and control of Shunt APF.

Figure 1.4: Different configurations of hybrid active power filter
1.7 Control of shunt active power filters

As explained above, shunt APF extracts harmonics injected due to non-linear loads by mathematical computations. These computations are reference compensating current generation methods. Reference compensating current generation schemes are used to generate reference compensating currents which will be used as reference to remove the harmonics from the distorted supply current. Following methods are conventionally used for reference current generation [28]-[39]:

- Instantaneous reactive power theory
- Synchronous reference frame
- Dc-link voltage control
- Notch filter
- Sliding mode control
- Predictive scheme
- State feedback scheme
- Fast fourier transform method

Detail description of the reference compensating current generation schemes is presented in Chapter - 3 of this thesis. These reference compensating currents generated are provided to current controller. Main function of the current controller is to ensure that compensating current supplied by APF at PCC remains in line with the reference compensating current generated by mathematical computations. Hence, current controller ensures that APF compensating current tracks the reference compensating current. Various types of current controllers are used in APFs, among which hysteresis controllers are extensively used due to their inherent simplicity in implementation and fast dynamic response. However, conventional hysteresis current controller scheme used in APFs suffer from draw backs like limit cycle oscillations, overshoot in current error, random selection of voltage vectors (not-adjacent) and generation of sub-harmonic components in current. This is because of no communication between hysteresis controllers of individual phases. Research work has been carried out and reported in literature to reduce these problems for their applications in induction motor drives. [40]-[45].

Current error (generated due to the difference between APF compensating current and reference compensating current) movement if restricted within a specified boundary will help in compensating for harmonics. Application of current error space vector
based hysteresis controller for control of induction motor drives is studied and doc-
umented in literature [40]-[55]. Researchers have worked upon application of space
vector modulation based hysteresis current controllers for control of SAPF [56]-[59].In
the proposed research work application of current error space phasor based hysteresis
controller to Shunt APF is investigated for power quality improvement.

1.8 Voltage space phasor structure for two-level
inverter

Consider a two-level inverter shown in figure 1.5. The point 'O' shown in figure 1.5
is a fictitious neutral-point (mid-point of the dc-link) considered for representation
of pole voltages $V_{ao}$, $V_{bo}$ and $V_{co}$. When a star connected three-phase balanced load
is connected at the output of the inverter, the relationship between inverter pole
evoltage with phase to load neutral-point voltage and load neutral to inverter dc-link
neutral-point voltage is given by (1.1).

\[
\begin{bmatrix}
V_{ao} \\
V_{bo} \\
V_{co}
\end{bmatrix}
= \begin{bmatrix}
V_{an} + V_{no} \\
V_{bn} + V_{no} \\
V_{cn} + V_{no}
\end{bmatrix}
\]  \hspace{1cm} (1.1)

Considering three-phase balanced load system (i.e. $V_{an}+V_{bn}+V_{cn}=0$), (1.1) can be
written as (1.2). The voltage $V_{no}$ is known as common-mode voltage. Using (1.1)
and (1.2), phase to load neutral-point voltages is expressed in terms of inverter pole
voltages by (1.3). Also, the load line-to-line voltages are given by (1.4).

\[
V_{no} = \frac{1}{3}(V_{ao} + V_{bo} + V_{co})
\]  \hspace{1cm} (1.2)
\[
\begin{bmatrix}
V_{an} \\
V_{bn} \\
V_{cn}
\end{bmatrix} = \frac{1}{3} \begin{bmatrix}
2 & -1 & -1 \\
-1 & 2 & -1 \\
-1 & -1 & 2
\end{bmatrix}
\begin{bmatrix}
V_{ao} \\
V_{bo} \\
V_{co}
\end{bmatrix}
\]  
(1.3)

\[
\begin{bmatrix}
V_{ab} \\
V_{bc} \\
V_{ca}
\end{bmatrix} = \begin{bmatrix}
1 & -1 & 0 \\
0 & 1 & -1 \\
-1 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
V_{ao} \\
V_{bo} \\
V_{co}
\end{bmatrix}
\]  
(1.4)

The inverter voltage space phasor \(V_s\) is represented in terms of three pole voltages as given by (1.5). It is known from (1.1) and (1.2) that the phase voltages \(V_{an}, V_{bn}, V_{cn}\) also result in the same voltage space phasor. Thus, the inverter voltage space phasor is a combination of all the three phase voltages. The space phasor voltage is resolved into rectangular components along \(\alpha\) and \(\beta\) as shown in (1.6). The relationship between the components of \(V_s\) and instantaneous phase voltages of inverter output (derived by conventional abc-\(\alpha\beta\) transformation) is shown in (1.7).

\[
V_s = V_{ao} + aV_{bo} + a^2V_{co}
\]  
(1.5)

Where, \(a=e^{j\frac{2\pi}{3}}\)

\[
V_s = V_{s(\alpha)} + jV_{s(\beta)}
\]  
(1.6)

\[
\begin{bmatrix}
V_{s(\alpha)} \\
V_{s(\beta)}
\end{bmatrix} = \begin{bmatrix}
1 & -1/2 & -1/2 \\
0 & \sqrt{3}/2 & -\sqrt{3}/2
\end{bmatrix}
\begin{bmatrix}
V_{an} \\
V_{bn} \\
V_{cn}
\end{bmatrix}
\]  
(1.7)

\[
\begin{bmatrix}
V_{an} \\
V_{bn} \\
V_{cn}
\end{bmatrix} = \begin{bmatrix}
2/3 & 0 \\
-1/3 & 1/\sqrt{3} \\
-1/3 & -1/\sqrt{3}
\end{bmatrix}
\begin{bmatrix}
V_{s(\alpha)} \\
V_{s(\beta)}
\end{bmatrix}
\]  
(1.8)

As shown in figure 1.5, each pole of two-level inverter can attain two voltage levels \(V_{dc}/2\) and \(-V_{dc}/2\). Thus total number of switching states a two-level inverter can generate is \(2^3=8\). For each pole of the two-level inverter, the voltage level \(V_{dc}/2\) (top device of the pole is ON) is indicated as '+', while voltage level \(-V_{dc}/2\) (lower device of the pole is ON) is indicated as `-'. Thus switching states of the inverter are represented as (+ - -), (+ + -), (- + -), (- + +), (- - +), (+ - +), (- - -) and (+ + +) as shown in figure 1.6 and 1.7. For each switching states signs within the bracket indicate state of the switches (voltage level), of inverter pole a, b and c respectively. The two-level inverter voltage space vectors corresponding to these eight switching states are defined as \(V_1, V_2, V_3, V_4, V_5, V_6, V_7\) and \(V_8\) respectively, as shown in voltage space phasor structure of two-level inverter in figure 1.8. Voltage space vectors and corresponding switching states are mentioned in table 1.1. It is necessary to place \(\alpha-\)
axis along the A-phase axis of the inverter. Six triangular sectors of the voltage space phasor structure are indicated by encircled numbers 1 to 6. There is power transfer between dc-link and load during switching of voltage vectors $V_1$-$V_6$, and hence are known as active voltage vectors. While during switching of voltage vectors $V_7$ and $V_8$ there is no power transfer between dc-link and load, hence these vectors are known as zero voltage vectors ($V_Z$).

Figure 1.6: Two-level inverter switching states

Figure 1.7: Two-level inverter switching states
Figure 1.8: Voltage space phasor structure of two-level inverter

Table 1.1: Two-level inverter voltage vectors and corresponding switching states

<table>
<thead>
<tr>
<th>Voltage vectors</th>
<th>Switching states</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_1$</td>
<td>(+ - -)</td>
</tr>
<tr>
<td>$V_2$</td>
<td>(+ + -)</td>
</tr>
<tr>
<td>$V_3$</td>
<td>(- + -)</td>
</tr>
<tr>
<td>$V_4$</td>
<td>(- + +)</td>
</tr>
<tr>
<td>$V_5$</td>
<td>(- - +)</td>
</tr>
<tr>
<td>$V_6$</td>
<td>(+ - +)</td>
</tr>
<tr>
<td>$V_7$</td>
<td>(- - -)</td>
</tr>
<tr>
<td>$V_8$</td>
<td>(+ + +)</td>
</tr>
</tbody>
</table>
1.9 Current error space phasor based hysteresis controller for two-level shunt active power filter

A current error space phasor based hysteresis controller for two-level SAPF is developed which allows precise compensation of harmonic currents produced by non-linear loads. The proposed controller is self-adaptive in nature and does not require any particular calculation of point of common coupling (PCC) voltage vector for deciding the position and amplitude of reference voltage vector of SAPF because of proper sector change detection logic used. The controller keeps the current error space phasor within the hexagonal boundary (fixed band) by always applying SAPF voltage vectors which are adjacent to the reference voltage vector of SAPF. This leads to the switching of optimal (adjacent) voltage vectors unlike the random selection of the voltage vectors in conventional hysteresis controller based schemes. Figure 1.9 shows the APF voltage vectors and direction of current error space phasor movement for positions of reference voltage vector $V_o^*$ in two different sectors (i.e., Sector-1 and Sector-2). When $V_o^*$ is in Sector-1 (OP), PA, PB and OP’ are the directions along which minimum deviation of current error takes place when $V_1$, $V_2$ and $V_0$ are switched, respectively. Similar is the case for other sectors. These sets of directions of current error movement form triangular boundaries for all the sectors. Triangular boundaries are again divided into regions and appropriate APF vector is identified for each region which will bring the current error within desired boundary when particular region is hit.

Proposed controller uses two hysteresis bands. Inner hysteresis band is used for region detection. As explained above region detection logic enables switching of SAPF voltage vector which keeps the current error well within the prescribed hexagonal boundary while outer hysteresis band is used for appropriate sector change detection. Detailed behavior of the proposed controller based SAPF is explained in Chapter 4 of the thesis. The proposed current controller based SAPF utilizing outer hysteresis band, compensates the load harmonics effectively. For this SAPF uses outer hysteresis band for detecting necessary sector changes (keeping track of movement of reference voltage vector of SAPF). Hence during each sector change, the current error space phasor moves out of the hexagonal boundary to hit the outer hysteresis band. Because of a total of six sectors in voltage space phasor structure, it happens six times in one fundamental cycle of supply for two-level converter based SAPF. This puts slight limitation on the harmonic elimination in the supply current. Here in order to further improve the distortion in supply current, current error is restricted within hexagonal boundary even during appropriate sector changes by avoiding outer
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Figure 1.9: Voltage space phasor structure and direction of current error space phasor for two-level APF

hysteresis band. The outer hysteresis band is eliminated and SAPF compensating currents are generated with the help of two different logics for sector change:

- Sector change detection by zero crossing detection of voltage at the point of common coupling
- Sector change detection by instantaneous values of voltages at the point of common coupling

With advancement in power electronic device technology, use of multi-level converters has gained popularity. As multi-level converters have inherent characteristics of staircase type output, their use in SAPF helps in further reducing the harmonic distortion as compared to a conventional two-level SAPF. This helps in providing better compensation of current with low dv/dt at the converter output for the same dc-link voltage. It also demands the less voltage blocking ratings of the devices (IGBTs - Insulated Gate Bipolar Transistors) used in converter. With this aim and focus current error space phasor based hysteresis controller developed for two-level SAPF is extended for three-level operation of SAPF.

1.10 Multi-level inverters

As the power level is increasing demand of power converters which can work at such high power level is also increasing. It is difficult to use conventional two-level converter
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at high power levels. In order to overcome this problem multi-level inverters are used at high power levels. Due to this application of multi-level inverter has recently increased in diversified fields like industries, power system, hybrid vehicles and many more. Multi-level inverters generate output voltage with stepped waveform with the help of a number of power semiconductor devices and capacitor voltage sources [60]-[61]. Multi-level inverters start with three level inverter topology [62]. As the output of such inverters is a staircase type waveform, initially the aim was to reduce the harmonic content of generated current or voltage waveforms. Then the multi-level inverters application was extended to motor drive applications and now they are extensively used in high power applications [60]. Advantages of multi-level inverters over conventional two-level inverters are:

- As the output voltage is staircase type waveform total harmonic distortion (THD) reduces as the number of voltage levels increases.

- Lower voltage rating power semiconductor devices can be used to achieve high voltage levels at inverter output.

- As the output voltage is stepped waveform dv/dt stress and EMI problems are reduced.

- Multilevel inverter draw input current with less distortion.

- Multilevel inverters generate less common mode voltage as a result of which bearing current and hence stress on bearing is less.

- Lower switching frequency operation of multilevel inverter is possible, due to which switching losses are reduced.

At the same time as the level increases number of power semiconductor devices and hence complexity of their control increases which is a drawback of multi-level inverters. Voltage unbalance of dc-link capacitors is also one of the disadvantages of multi-level inverter structure.

Multi-level inverters are basically of three types:

- Cascaded H-bridge type.

- Neutral-point clamped (NPC) or Diode-clamped.

- Flying capacitor type
1.10.1 Cascaded H-bridge type inverter

Figure 1.10 shows three-level cascaded H-bridge inverter. Operation of A-phase of the three-level inverter is explained here. The output voltage $V_{an}$ has three states: $V_{dc}$, 0 and $-V_{dc}$. For output voltage level $V_{dc}$, switches $S_{a1}$ and $S_{a4}$ need to be turned on while for $-V_{dc}$, switches $S_{a3}$ and $S_{a2}$ need to be turned on. For 0 voltage level there is redundancy in switching states, either switches $S_{a1}$ and $S_{a2}$ or $S_{a3}$ and $S_{a4}$ need to be turned on in pairs respectively.

![Three-level cascaded H-bridge inverter](image)

Figure 1.10: Three-level cascaded H-bridge inverter

1.10.2 Neutral point clamped (NPC) or Diode-clamped inverter

Figure 1.11 shows three-level neutral point clamped inverter. In this circuit, the dc-bus voltage is split into three levels by two series-connected capacitors $C_1$ and $C_2$. The middle point of the two capacitors N can be defined as the neutral point. Operation of A-phase of the three-level inverter is explained here. The output voltage $V_{an}$ has three states: $V_{dc}/2$, 0, and $-V_{dc}/2$. For voltage level $V_{dc}/2$, switches $S_{11}$ and $S_{12}$ need to be turned on while for $-V_{dc}/2$ switches $S_{13}$ and $S_{14}$ need to be turned on. For the 0 voltage level $S_{12}$ and $S_{13}$ need to be turned on. $D_{11}$ and $D_{12}$ are clamping diodes.

1.10.3 Flying capacitor type inverter

Figure 1.12 shows three-level flying capacitor inverter. It has independent capacitors clamping the device voltage to one capacitor voltage level. Operation of A-phase of the three-level inverter is explained here. The converter in figure 1.12 provides a three-level output across A and n, i.e. $V_{an}=V_{dc}/2$, 0, or $-V_{dc}/2$. For voltage level $V_{dc}/2$, switches $S_{11}$ and $S_{12}$ need to be turned on while for $-V_{dc}/2$ switches $S_{13}$ and $S_{14}$ need to be turned on. For the 0 voltage level, either pair $(S_{11}, S_{13})$ or $(S_{12}, S_{14})$ needs
to be turned on. Clamping capacitor $C_3$ is charged when $S_{11}$ and $S_{13}$ are turned on, and is discharged when $S_{12}$ and $S_{14}$ are turned on. The charge of $C_3$ can be balanced by proper selection of the 0-level switch combination.

As it is difficult to connect conventional two-level converter to medium or high voltage grid, multilevel inverters are founding popularity in application grid connected systems like flexible ac transmission system (FACTS) controllers, power quality improvement devices like active power filters and renewable energy systems. Thus, the application of current error space phasor based hysteresis controller is extended to three-level operation of SAPF.

### 1.11 Voltage space phasor structure for three-level inverter

For a n-level inverter the number of switching states ‘t’ generated by the inverter is given by (1.9), while the number of voltage vectors ‘k’ generated by the inverter is given by (1.10). Hence, for three-level inverter number of switching states are 27, the inverter voltage vectors are 19 and triangular sectors are 24 as shown in figure 1.13. For a three-level inverter (figure 1.10, 1.11 and 1.12) each pole can attain three voltage levels $V_{dc}/2$, 0 and $-V_{dc}/2$. For each pole the three-level inverter the voltage
level $V_{dc}/2$ is indicated as ‘+’, voltage level $-V_{dc}/2$ is indicated as ‘-’ and voltage level 0 is indicated as ‘0’. Switching states for three-level inverter voltage vectors $V_1$-$V_{19}$ are given in table 1.2. $V_{19}$ is zero voltage vector and is termed as $V_0$. When more than one switching state of inverter generates a particular inverter voltage vector, such switching states are known as redundant switching states. It is evident from table 1.2 that three-level inverter voltage vectors have redundancy as compared to two-level inverter. This redundant switching states are helpful in eliminating dc-link capacitor voltage imbalance and common-mode voltage [53]. It seen from figure 1.13 and table 1.2, that the redundancy increases for voltage vectors near to the center of the voltage space phasor structure.

\begin{align*}
t &= n^3 \\
k &= 3(n)(n - 1) + 1
\end{align*}
Table 1.2: Three-level inverter voltage vectors and corresponding switching states

<table>
<thead>
<tr>
<th>Voltage vectors</th>
<th>Switching states</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_1$</td>
<td>(+ 0 0) ; (0 - -)</td>
</tr>
<tr>
<td>$V_2$</td>
<td>(+ + 0) ; (0 0 -)</td>
</tr>
<tr>
<td>$V_3$</td>
<td>(0 + 0) ; (- 0 -)</td>
</tr>
<tr>
<td>$V_4$</td>
<td>(- 0 0) ; (0 + +)</td>
</tr>
<tr>
<td>$V_5$</td>
<td>(0 0 +) ; (- - 0)</td>
</tr>
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<td>$V_6$</td>
<td>(+ 0 +) ; (0 - 0)</td>
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<tr>
<td>$V_7$</td>
<td>(+ - 0)</td>
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<td>$V_8$</td>
<td>(+ - -)</td>
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<td>$V_9$</td>
<td>(+ 0 -)</td>
</tr>
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</tr>
<tr>
<td>$V_{12}$</td>
<td>(- + -)</td>
</tr>
<tr>
<td>$V_{13}$</td>
<td>(- + 0)</td>
</tr>
<tr>
<td>$V_{14}$</td>
<td>(- + +)</td>
</tr>
<tr>
<td>$V_{15}$</td>
<td>(- 0 +)</td>
</tr>
<tr>
<td>$V_{16}$</td>
<td>(- - +)</td>
</tr>
<tr>
<td>$V_{17}$</td>
<td>(0 - +)</td>
</tr>
<tr>
<td>$V_{18}$</td>
<td>(+ - +)</td>
</tr>
<tr>
<td>$V_0$</td>
<td>(+ + +) ; (0 0 0) ; (- - -)</td>
</tr>
</tbody>
</table>
1.12 **Current error space phasor based hysteresis controller for three-level shunt active power filter**

Current error space phasor based hysteresis controller is applied to three-level SAPF. Proposed controller has been implemented for three-level neutral point clamped (NPC) SAPF and flying capacitor (FC) SAPF. The proposed controller is versatile and can be used for any SAPF whose converter generates three-level voltage phasor structure shown in figure 1.14. Figure 1.14 shows the movement of current error for position of reference voltage phasor in sector-7 and sector-8. The current error space phasor based hysteresis controller controlled three-level SAPF uses two hysteresis band, inner hysteresis band is used to restrict the current error within desired hexagonal boundary and outer hysteresis band for necessary sector change detection.

![Figure 1.14: Voltage space phasor structure and direction of current error space phasor for three-level APF](image)

Proposed three-level NPC based SAPF operation is studied for reference compensating current generation schemes like instantaneous reactive power theory (IRP) and
Chapter 1 Introduction to Power Quality Issues and Solutions with Emphasis on SAPF

dc-link voltage regulation scheme. The SAPF compensates the current harmonics efficiently. In application of IRP theory, issue of dc-link voltage imbalance is reported. Hence to overcome this issue dc-link voltage regulation scheme is used for proposed three-level SAPF. This helps in regulating the dc-link of SAPF, but as dc-link is split with the help of two capacitors, problem of individual dc-link capacitor voltage imbalance still persist causing imbalance in SAPF output voltage. Separate voltage balancing circuitry and control algorithm would be required to eliminate this problem. In order to overcome this issue, the proposed controller is applied to three-level flying capacitor SAPF as its dc-link is not split in to two capacitors. A problem of clamping capacitor voltage imbalance is encountered. The same is solved using appropriate logic for switching of SAPF by effectively utilizing the redundancy of switching states. Proposed flying capacitor SAPF operates effectively keeping the current error within the desired hexagonal boundary.

1.13 Motivation of the work

Power demand of the world is ever increasing and with this increased demand comes increased problem of current harmonics. Thus harmonic elimination is a serious issue which cannot be neglected and hence becomes an area of research that should be dealt with utmost priority which in turn would help in solving the power quality problems of power system. Hence it is evident that APF, especially shunt APF have a very crucial role to play in today’s and future’s power system as it mitigates current harmonics. Thus continuous research work should be done for improving performance of Shunt APF.

1.14 Scope of the work

Many researchers have been working actively to contribute in the field of active power filters. Researchers have put their keen efforts to extend the application of APF from harmonic compensation to harmonic damping, harmonic isolation, harmonic termination, reactive-power control for power factor correction and voltage regulation, load balancing, voltage-flicker reduction, and/or their combinations. Work is also reported on development of novel and efficient techniques for generating reference compensation current like; instantaneous reactive power theory, synchronous reference frame method, Fryze current computation, dc-link voltage control method, notch filter technique, sliding mode control, predictive scheme, state feedback scheme, fast Fourier transform method, etc.

Selection of current controller (current control strategy) affects the performance of
SAPF. In order to achieve effective compensation of current harmonics, the SAPF current should track the reference compensating current. The job of current controller is to force the SAPF current (actual compensating current) to follow the reference compensating current. Amongst different types of current controllers, hysteresis current controllers are widely used in SAPFs, due to their inherent implementation simplicity and fast dynamic response. Conventional hysteresis current controller (HCC) scheme used in APFs uses three independent hysteresis controllers one for each phase and hence suffers from lack of coordination between the three individual HCCs. This results in the basic drawbacks of conventional HCCs, such as higher number of switching and selection of non adjacent (random) voltage vectors. They also suffer from drawbacks like limit cycle oscillations, overshoot in current error and generation of sub-harmonic components in current.

In order to get rid of limit cycle oscillations, space vector modulation technique is applied to current hysteresis controller which enables the use of zero switching vector along with nonzero vectors. Researchers have worked upon application of space vector modulation based hysteresis current controllers for control of SAPF [56]-[59]. Current error space phasor based hysteresis controller is more popularly used in variable frequency drive application of induction motors [40]-[55]. This is basically to control the voltage source inverter (VSI) with current controlled pulse width modulation (CC-PWM) for high performance drives (HPDs) employing induction motors. This controller allows the current error space phasor to move within a specified fixed boundary.

In the field of active power filters main focus till now has been on development of novel techniques for reference compensating current generation in order to improve the compensation characteristic. The proposed research work is focused on development of self-adaptive current controller which overcomes the drawbacks of random voltage vector selection, and limit cycle oscillations encountered in conventional hysteresis controllers used for SAPF. The research also focuses on the extension of the same current controller for high power applications of SAPF by using multi-level converter topologies for SAPF.

1.15 Outline of the thesis

The thesis is structured in a total of eight chapters preceded by list of symbols, list of abbreviations, list of figures and list of tables. Chapter - 1 gives introduction and background of the research work. This chapter addresses motivation and scope of the work done. Chapter - 2 provides in depth literature survey for the research work carried out. Chapter - 3 discusses about the shunt active power filter and
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the reference compensating current generation methods used. It also presents the design considerations for the converter of proposed SAPF. Chapter - 4 explains the working of proposed current error space phasor based hysteresis controller for two-level SAPF. Chapter - 5 presents the simulation results and analysis of current error space phasor based hysteresis controller for two-level shunt SAPF. Chapter - 6 explains the working of current error space phasor based hysteresis controller for three-level SAPF. Hardware implementation considerations and experimental results of current error space phasor based hysteresis controller for two-level shunt APF are presented and discussed in Chapter - 7. Chapter - 8 presents the summary of the results achieved and conclusion of the research work. It also includes scope for future work. These chapters are followed by references and list of publications from proposed research work.

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