CHAPTER-2

POWER QUALITY PROBLEMS & SOLUTIONS

There can be completely different definitions of power quality (PQ), depending on one's frame of reference. Power quality is ultimately a consumer-driven issue, and the user's point of reference takes precedence.

Institute of Electrical and Electronics Engineers (IEEE) standard IEEE 1100 defines power quality as "the concept of powering and grounding sensitive electronic equipment in a manner suitable for the equipment".

Power quality problem can be defined as:
Any power problem manifested in voltage, current, or frequency deviations that result in failure or misoperation of customer equipment.

2.1 Power Quality Problems

2.1.1 Transients

These are events which are undesirable and momentary in nature. Transients can be classified into two categories; impulsive and oscillatory. Impulsive transients can be characterized by peak magnitude, rise time and duration. While the oscillatory transients can be characterized by peak magnitude, rise time and duration. Oscillatory transients can be of high, medium or low frequency types.

Lightning strikes, Transformer energization, Capacitor switching, Line load switching and Load switching are the typical causes for occurrence of impulsive and oscillatory transients.

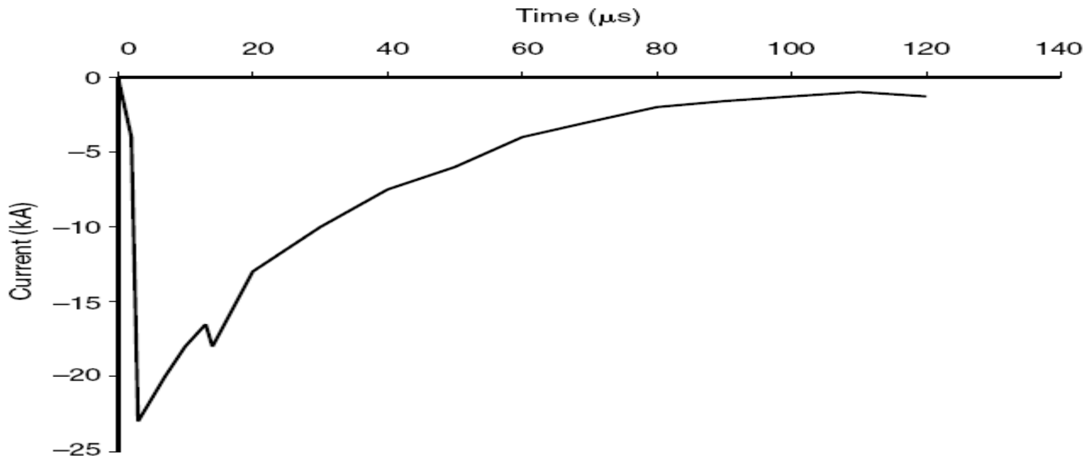

Fig 2.1 Current impulsive transient created by Lightning Stroke

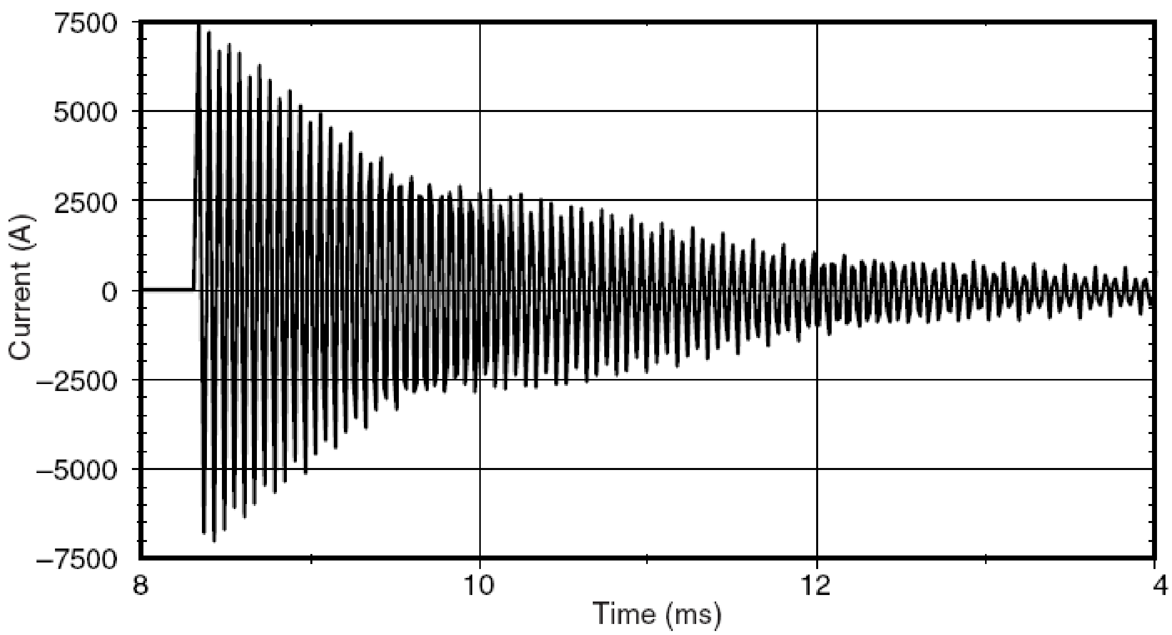

Fig 2.2 Oscillatory transient current caused by back-to-back capacitor switching

2.1.2 Short duration voltage variation

These are disturbances in the voltage levels [4, 5] which occur for time duration of 0.5 cycles to 1 min. The variations in voltage levels may cause problems such as loss of production in automated processes, crashing of data processing system or a computer system, loss of efficiency in electrical rotating machines. These voltage variations can be categorized on the basis of magnitude and duration for which they occur.

(a) Voltage Sag (dip): A decrease of the normal voltage level between 0.1-0.9 pu is known as voltage sag or dip. Duration of these variations remains between 0.5 cycles to 1 min. Fig 2.3 shows the waveform for voltage sag from t = 0.04 to t = 0.12 sec.

Causes for voltage sags are:-

(a) Ferro resonant transformers

(b) Single line-to-ground (SLG) faults

(c) Starting of large motors

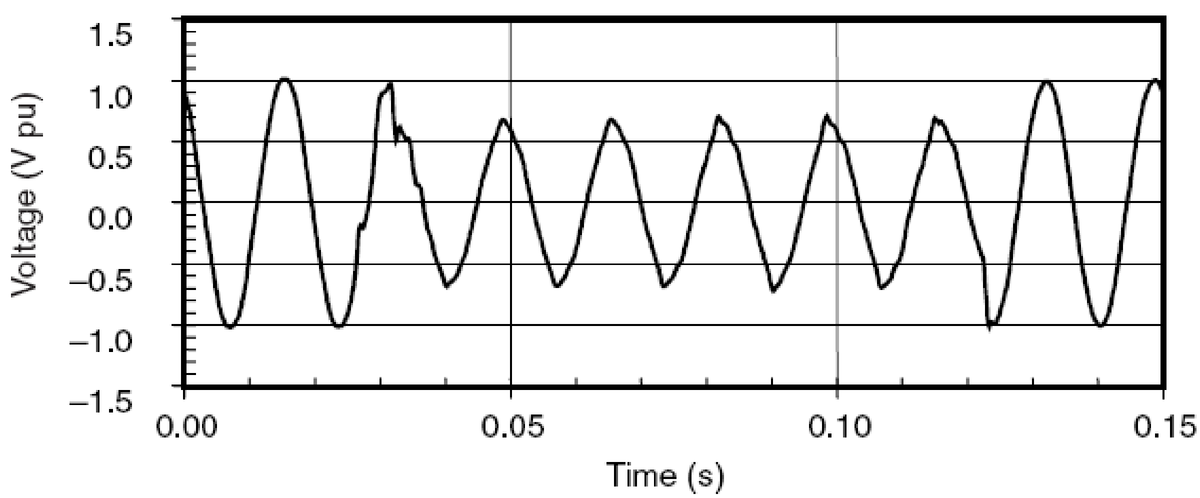

Fig 2.3 Voltage Sag waveform

(b) Voltage Swell: An increase of the normal voltage level between 1.1-1.8 pu [3, 4] is known as voltage swell. Duration of these variations remains between 0.5 cycles to 1 min. Causes of voltage swells are similar to that of voltage sags such as start /stop of heavy loads, SLG fault. Fig 2.4 shows voltage swell for the time duration from 0.03 sec to 0.15 sec.

(c) Voltage Interruption: An interruption occurs when the supply voltage or load current decreases to less than 0.1 pu for a period of time not exceeding 1 min. The interruptions are measured by their duration since the voltage magnitude is always less than 10 percent of nominal and are caused by temporary (self-clearing) faults. Fig 2.5 shows an interruption in voltage due to a fault.

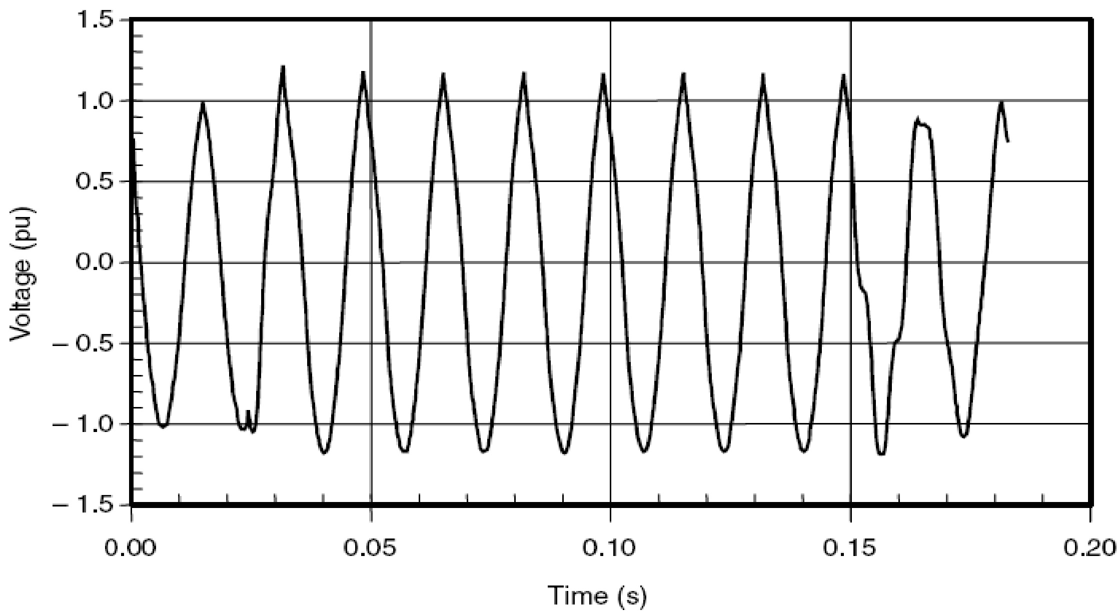

Fig 2.4 Voltage Swell Waveform

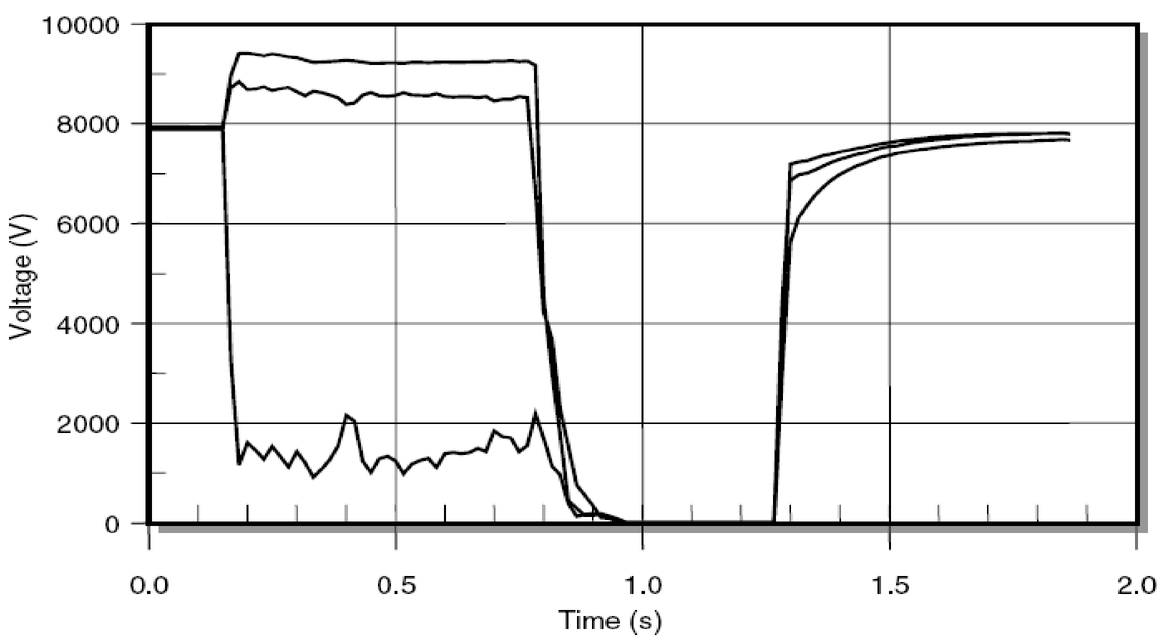

Fig 2.5 Three-phase rms voltages for a momentary interruption due to a fault and subsequent recloser operation

2.1.3 Long duration voltage variation

Long-duration variations encompass root-mean-square (rms) deviations at power frequencies for longer than 1 min [4, 5]. The impact of long duration variations is greater than those of short duration variations. A sustained overvoltage lasting for few hours can cause damage to household appliances without their owner knowing it, until it is too late. These variations can be categorized as Undervoltage, Overvoltage and Sustained Interruptions on the basis of magnitude and the duration for which they occur.

(a) Overvoltage: An overvoltage is an increase in the rms ac voltage greater than 1.1 pu at the power frequency for a duration longer than 1 min.

Overvoltages are usually the result of load switching (e.g., switching off a large load or energizing a capacitor bank). The over voltages result because either the system is too weak for the desired voltage regulation or voltage controls are inadequate. Incorrect tap settings on transformers can also result in system over voltages.

(b) Undervoltage: An undervoltage is a decrease in the rms ac voltage to less than 90 percent at the power frequency for duration longer than 1 min.

Undervoltages are the result of switching events that are the opposite of the events that cause overvoltage. A load switching on or a capacitor bank switching off can cause an undervoltage until voltage regulation equipment on the system can bring the voltage back to within tolerances. Overloaded circuits can result in undervoltage also.

(c) Sustained Interruptions: When the supply voltage has been zero for a period of time in excess of 1 min, the long-duration voltage variation is considered a sustained interruption. Voltage interruptions longer than 1 min are often permanent and require human intervention to repair the system for restoration. Faults are the major cause of sustained interruptions. Fig 2.6 shows a sustained interruption.

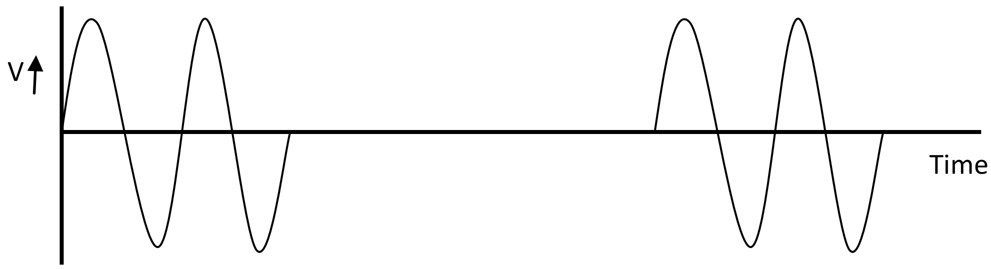

Fig 2.6 Sustained Interruptions

2.1.4 Voltage Imbalance

Voltage imbalance (also called voltage unbalance) is sometimes defined as the maximum deviation from the average of the three-phase voltages or currents, divided by the average of the three-phase voltages or currents expressed in percent [4, 5]. Imbalance is more rigorously defined using symmetrical components. Imbalance produces negative sequence currents and voltages that are harmful to all three phase loads. The most affected loads are three-phase induction machines.

The primary source of voltage unbalances of less than 2 percent is single-phase loads on a three-phase circuit. Voltage unbalance can also due to result of blown fuses in one phase of a three-phase capacitor bank. Severe voltage unbalance (greater than 5 percent) can result from single-phasing conditions. Fig 2.7 shows a voltage unbalance trend for a residential feeder.

2.1.5 Waveform Distortion

Waveform distortion [4, 5] is defined as a steady-state deviation from an ideal sine wave of power frequency principally characterized by the spectral content of the deviation.

There are five primary types of waveform distortion:

- DC offset
- Harmonics
- Interharmonics
- Notching
- Noise

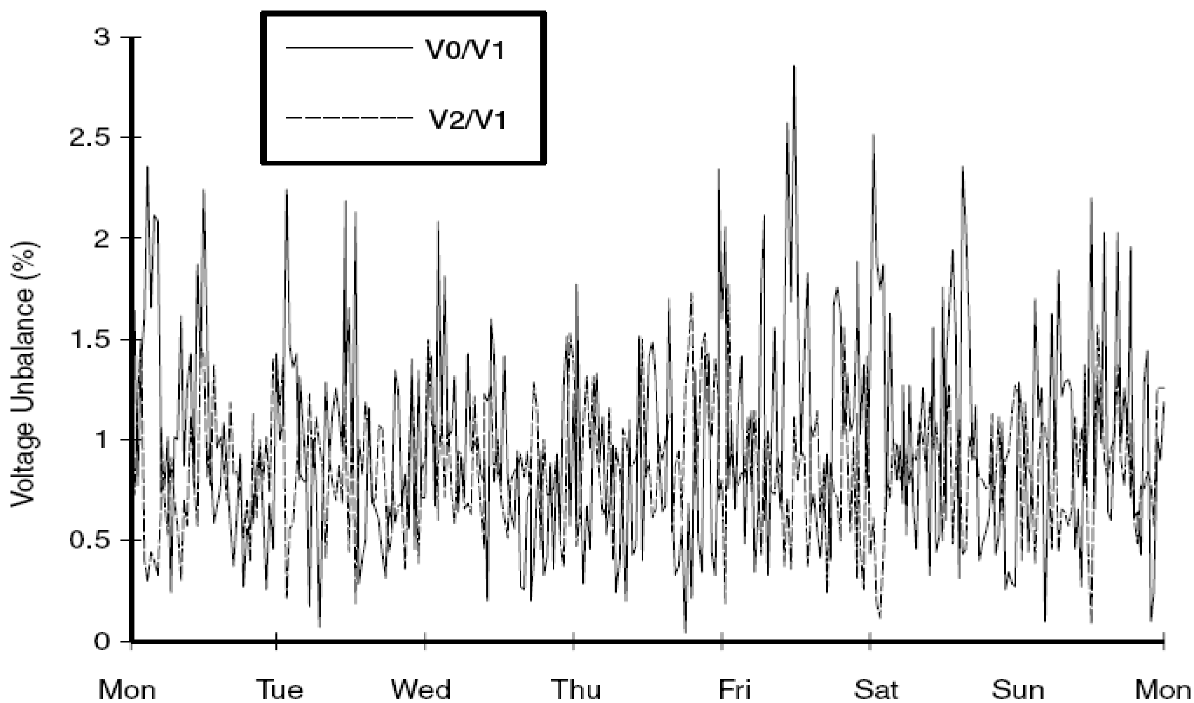

Fig 2.7 Voltage unbalance trend for a residential feeder

(a) DC offset: The presence of a dc voltage or current in an ac power system is termed dc offset. This can occur as the result of a geomagnetic disturbance or asymmetry of electronic power converters. Incandescent light bulb life extenders, for example, may consist of diodes that reduce the rms voltage supplied to the light bulb by half-wave rectification. Direct current in ac networks can have a detrimental effect by biasing transformer cores so they saturate in normal operation. This causes additional heating and loss of transformer life. Direct current may also cause the electrolytic erosion of grounding electrodes and other connectors.

(b) 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 (termed the fundamental frequency; usually 50 or 60 Hz). Periodically distorted waveforms can be decomposed into a sum of the fundamental frequency and the harmonics. Harmonic distortion originates in the nonlinear characteristics of devices and loads on the power system.

Harmonic distortion levels are described by the complete harmonic spectrum with magnitudes and phase angles of each individual harmonic component. It is also common to use a single quantity, the total harmonic distortion (THD), as a measure of the effective value of harmonic distortion.

(c) Interharmonics: Voltages or currents having frequency components that are not integer multiples of the frequency at which the supply system is designed to operate (e.g., 50 or 60 Hz) are called interharmonics. They can appear as discrete frequencies or as a wideband spectrum. Interharmonics can be found in networks of all voltage classes. The main sources of interharmonic waveform distortion are static frequency converters, cycloconverters, induction furnaces, and arcing devices. Power line carrier signals can also be considered as interharmonics.

(d) Notching: Notching is a periodic voltage disturbance caused by the normal operation of power electronic devices when current is commutated from one phase to another.

Since notching occurs continuously, it can be characterized through the harmonic spectrum of the affected voltage. However, it is generally treated as a special case. The frequency components associated with notching can be quite high and may not be readily characterized with measurement equipment normally used for harmonic analysis. Fig 2.8 shows the voltage waveform with notching.

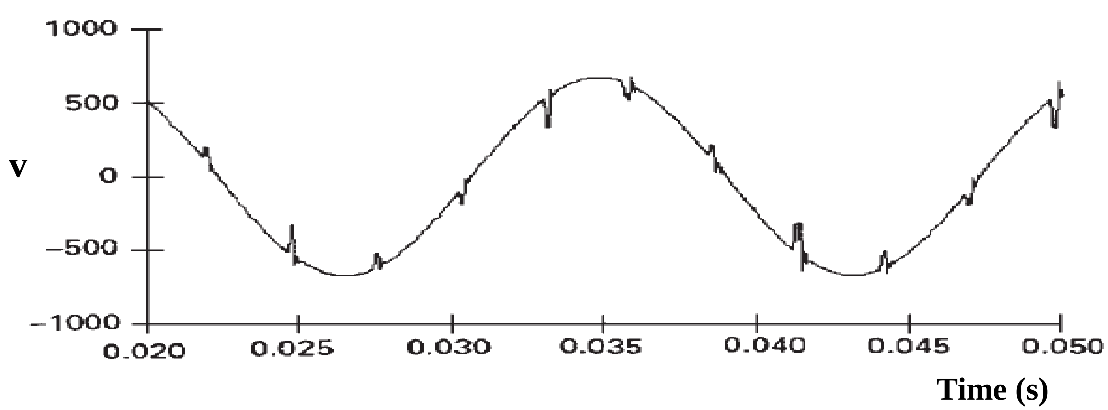

Fig 2.8 Example of Notching

(e) Noise: Noise is defined as unwanted electrical signals with broadband spectral content lower than 200 kHz superimposed upon the power system voltage or current in phase conductors, or found on neutral conductors or signal lines.

Noise in power systems can be caused by power electronic devices, control circuits, arcing equipment, loads with solid-state rectifiers, and switching power supplies. Basically, noise consists of any unwanted distortion of the power signal that cannot be classified as harmonic distortion or transients. Noise disturbs electronic devices such as microcomputer and programmable controllers. The problem can be mitigated by using filters, isolation transformers, and line conditioners.

Fig 2.9 Noise

2.1.6 Voltage Flicker

Voltage flicker refers to systematic variations of the voltage envelope or a series of random voltage changes, the magnitude of which does not normally exceed the voltage ranges of 0.9 to1.1 pu. The term flicker is derived from the impact of the voltage fluctuation on lamps such that they are perceived by the human eye to flicker. Arc furnace and arc lamps are the major causes of voltage flicker.

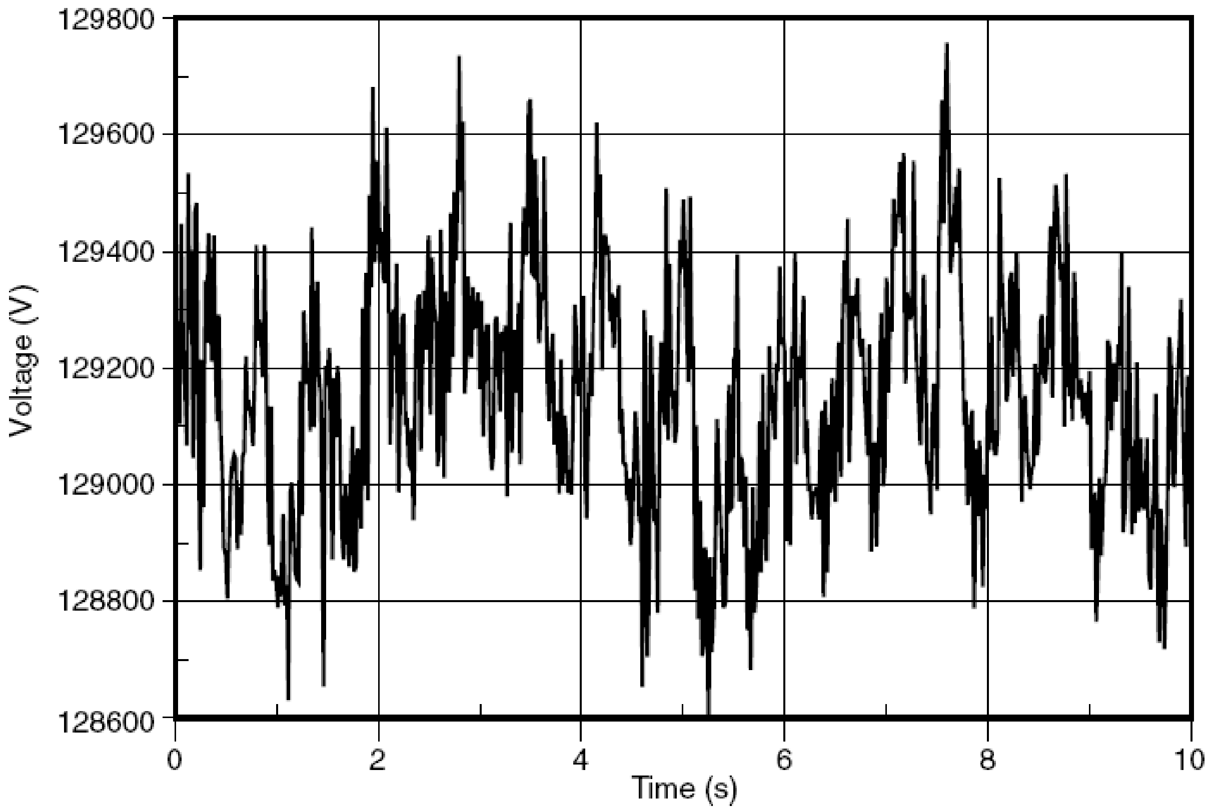

Fig 2.10 Voltage flicker caused by arc furnace

2.2 Distribution Static Compensator (DSTATCOM)

Voltage sags is the most common power quality problem faced by many industries and utilities, it contributes to more than 80% of power quality problems that exist in power system. Various methods have been applied to mitigate or reduce voltage sags. The conventional methods are by using capacitor banks, introduction of new parallel feeders and by installing uninterruptible power supplies (UPS). However, the PQ problems are not solved completely due to uncontrollable reactive power compensation and high cost of new feeders and UPS. DSTATCOM has emerged as a promising device for voltage sag mitigation as well as a host of other power quality problems such as voltage stabilization, flicker suppression, power factor correction and harmonic control. DSATCOM has additional capability to provide reactive power at low voltage, reduce land use and can be developed as a voltage and frequency support by replacing capacitors with batteries as energy storage.

According to definition of IEEE PES Task Force of FACTS Working Group:

Static Synchronous Compensator (STATCOM): A Static synchronous generator operates as a shunt-connected static var compensator whose capacitive or inductive output current can be controlled independent of the ac system voltage.

The DSTATCOM configuration consists of a two-level VSC, a dc energy storage device, a coupling transformer connected in shunt with the ac system. Fig 2.11 shows the schematic representation of the DSTATCOM. The VSC converts the dc voltage across the storage device into a set of three-phase ac output voltages. These voltages are in phase and coupled with the ac system through the reactance of the coupling transformer. Suitable adjustment of the phase and magnitude of the DSTATCOM output voltages allows effective control of active and reactive power exchanges between the DSTATCOM and the ac system.

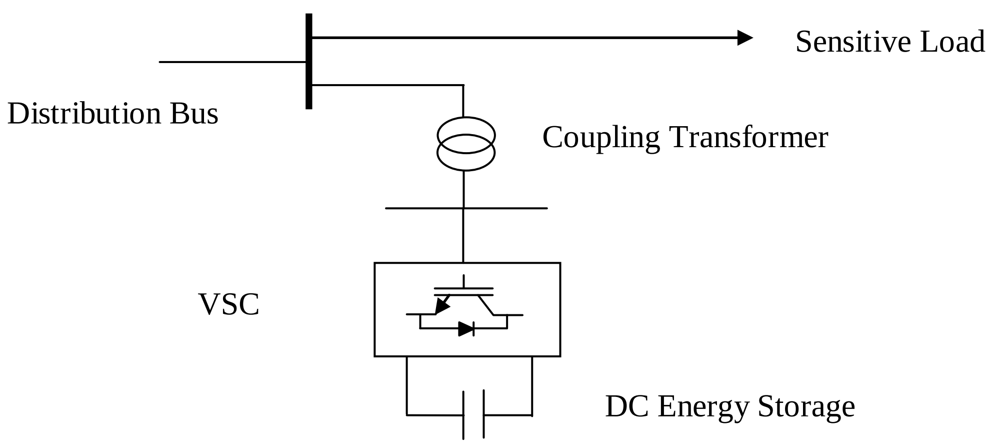

Fig 2.11 DSTATCOM

2.3 Principle and Working of DSTATCOM

The basic principle of reactive power generation by a voltage source converter (VSC) is similar to that of conventional rotating synchronous machine [1]. The basic voltage source converter scheme for reactive power generation is shown in Fig. 2.12, in the form of a single line diagram. From a dc input voltage source, provided by the charged capacitor C_s, the converter produces a set of controllable three phase output voltages with the frequency of the ac power system. Each output voltage is in phase with, and coupled to the corresponding ac system voltage via a relatively small (0.1-0.15 pu) tie reactance.

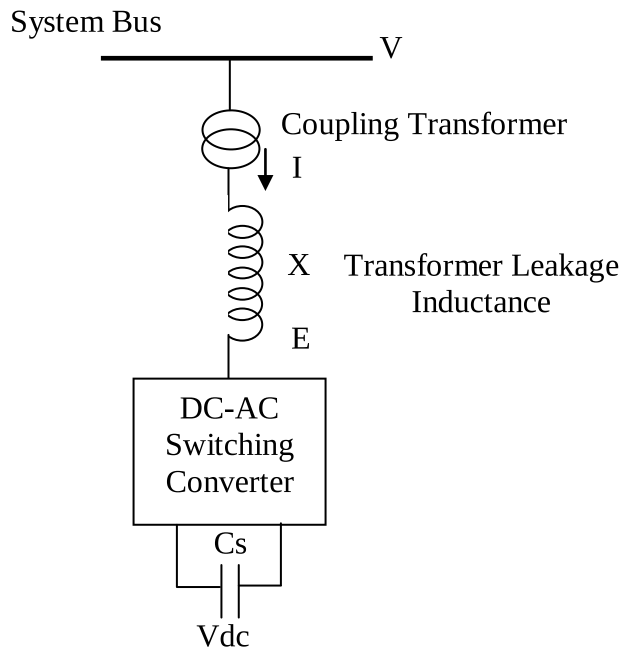

Fig. 2.12 Basic Voltage Source Converter Scheme for Reactive Power Generation

By varying the amplitude of the output voltage produced, the reactive power exchanged between the converter and the ac system can be controlled in a manner similar to that of the rotating synchronous machine. When the amplitude of the output voltage (E) is increased above that of ac system voltage (V), then the current flows through the tie reactance from the converter to the ac system and the converter generates reactive (capacitive) power for the ac system. If the amplitude of the output voltage (E) is decreased below that of the ac system (V), then the reactive current flows from the ac system to the converter, and the converter absorbs reactive (inductive) power.

$$I = \frac{V-E}{X} \quad 2.1$$

$$Q = \frac{1-{E}/{V}}{X} * V^2 \quad 2.2$$

where, I is the current drawn by converter .

V is the magnitude of system voltage.

E is the output voltage of converter.

X is the total circuit reactance**.**

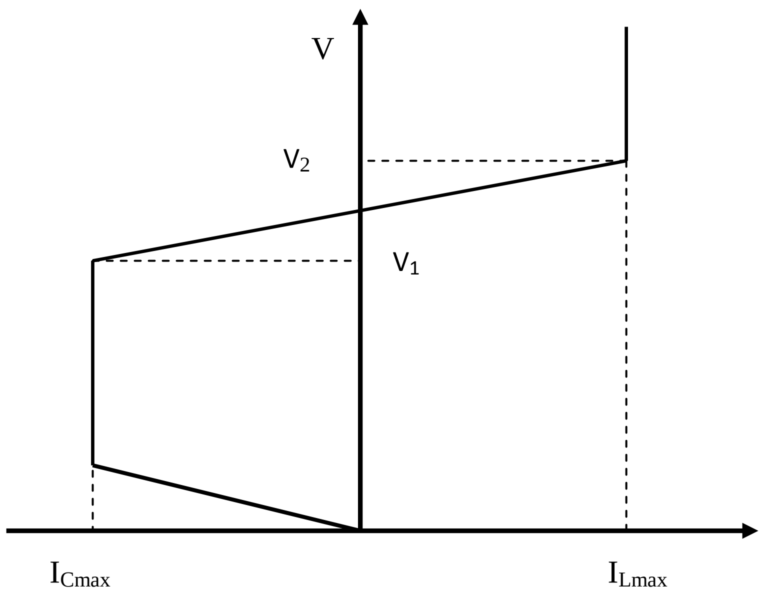

Fig 2.13 V-I Characteristics of DSTATCOM

2.4 Configuration of DSTATCOM in 1-phase and 3-phase systems

There are various configurations of converters which are used in DSTATCOM. One of the configurations consists of three separate H-bridge inverters. This configuration has an advantage that three independent currents are injected by the three separate H-bridge inverters which helps in compensating zero sequence current that might be flowing in the load. The valves used in the elementary converters usually comprise a number (3 to 10) of series connected power semiconductors such as GTO thyristors with reverse-parallel diodes. Each elementary converter produces a quasi-square or a pulse-width modulated output voltage waveform. These component voltage waveforms are phase-shifted from each other and then combined with the use of appropriate magnetic components to produce the final output voltage of the total converter. Some of the configurations of DSTATCOM inverters are shown below in Fig. 2.14 & 2.15.

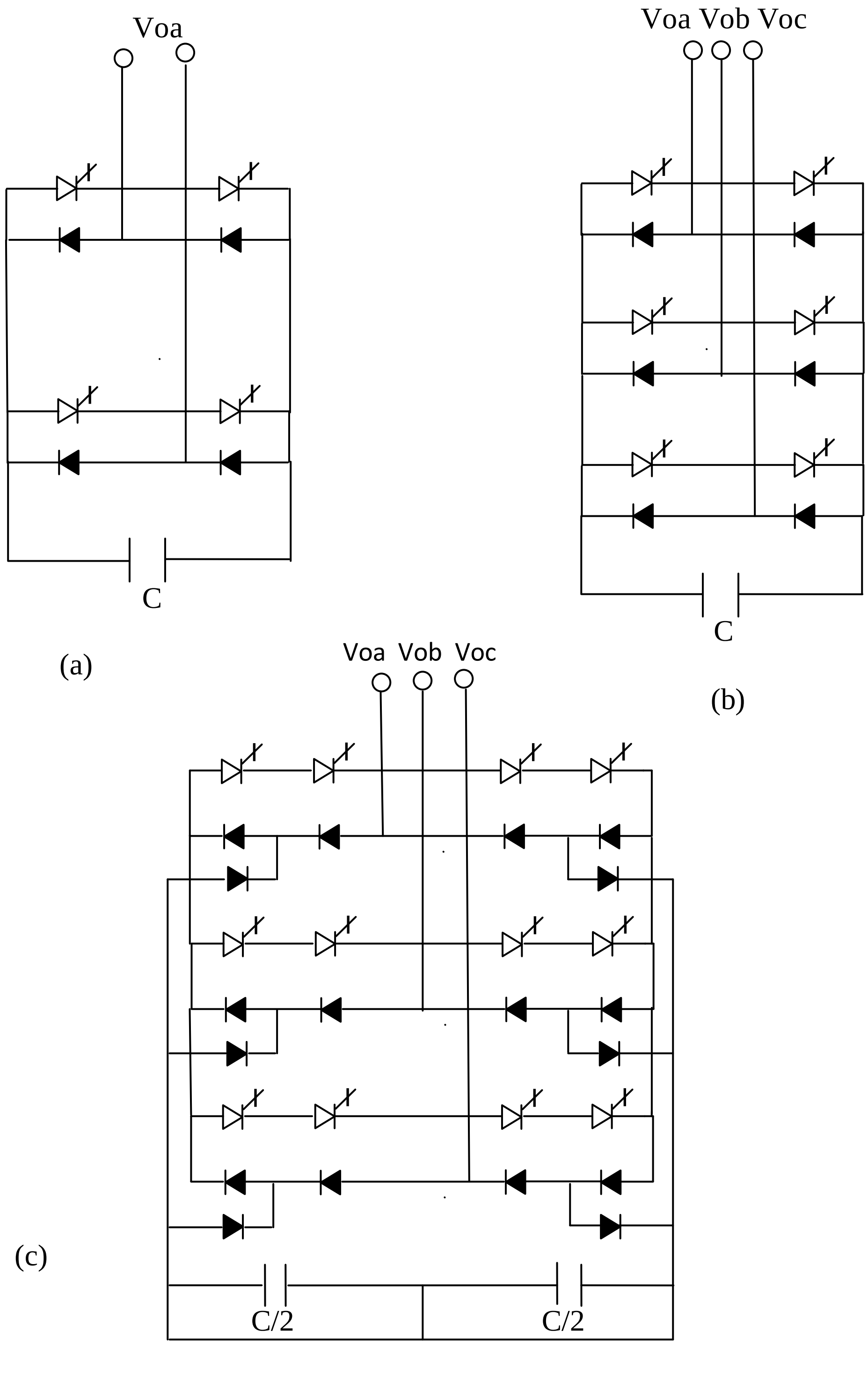

Fig 2.14 (a) Single-phase two level H-bridge, (b) Three phase, two-level six-pulse bridge
(c) Three phase three-level 12-pulse bridge.

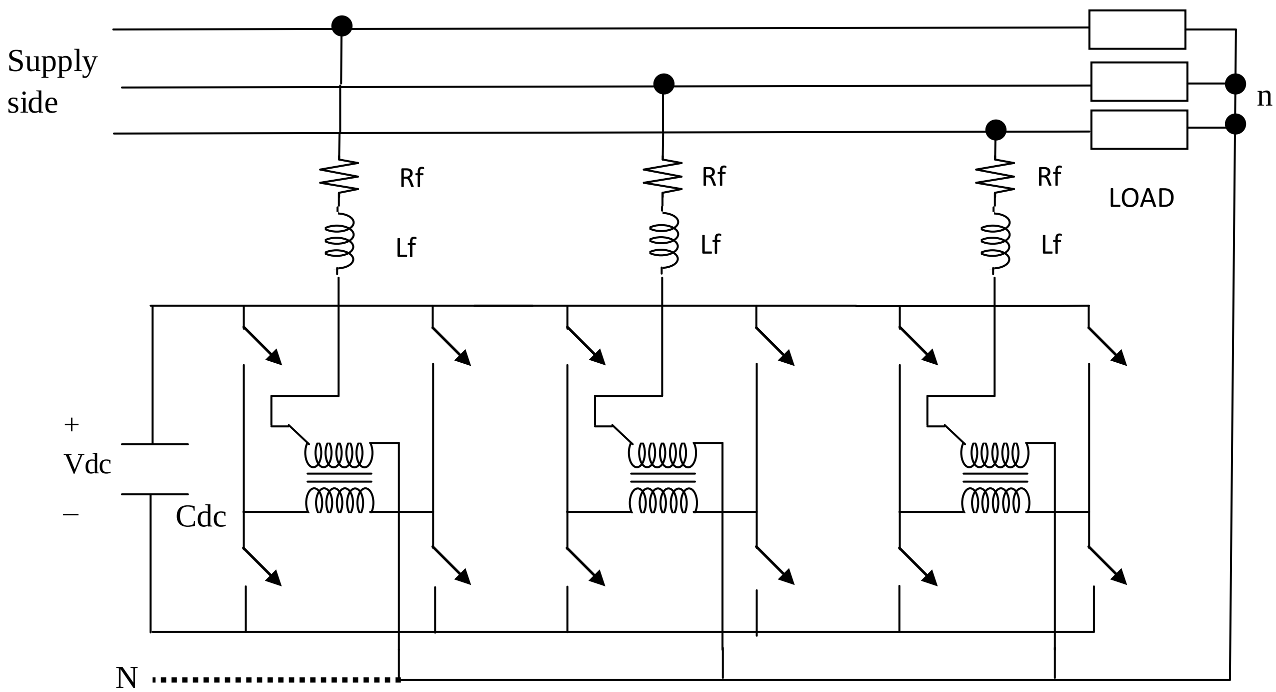

Fig 2.15 A typical configuration of DSTATCOM using H-bridge inverters

2.5 Control Algorithms for DSTATCOM

DSTATCOM is used for compensation of reactive power and unbalance caused by various loads in distribution systems. The performance of DSTATCOM depends on the control algorithms i.e. extraction of compensating currents. Various control algorithms [21-23] have been proposed for determining the compensating currents for a DSTATCOM, some of these are instantaneous reactive power (IRP) theory, instantaneous compensation, instantaneous symmetrical components, synchronous reference frame (SRF) theory, computation based on per phase basis, scheme based on neural network & fuzzy logic, fast adaptive linear element (Adaline) based theory. Among these control schemes instantaneous reactive power (IRP) theory and synchronous rotating reference frame (SRF) are the most widely used.

2.5.1 Instantaneous Reactive Power (IRP) Theory

Instantaneous reactive power theory has been initially proposed by Akagi in 1983[15]. The theory is based on the transformation of three phase quantities to two phase quantities in α-β frame and calculation of instantaneous active and reactive power in this frame. The basic block diagram of the theory is shown in Fig. 2.16 and the mathematical derivation is explained as follows.

If the system voltages are given as

$v_a = V_m \sin(\omega t)$;
$v_b = V_m \sin(\omega t-120)$; 2.3
$v_c = V_m \sin(\omega t-240)$;

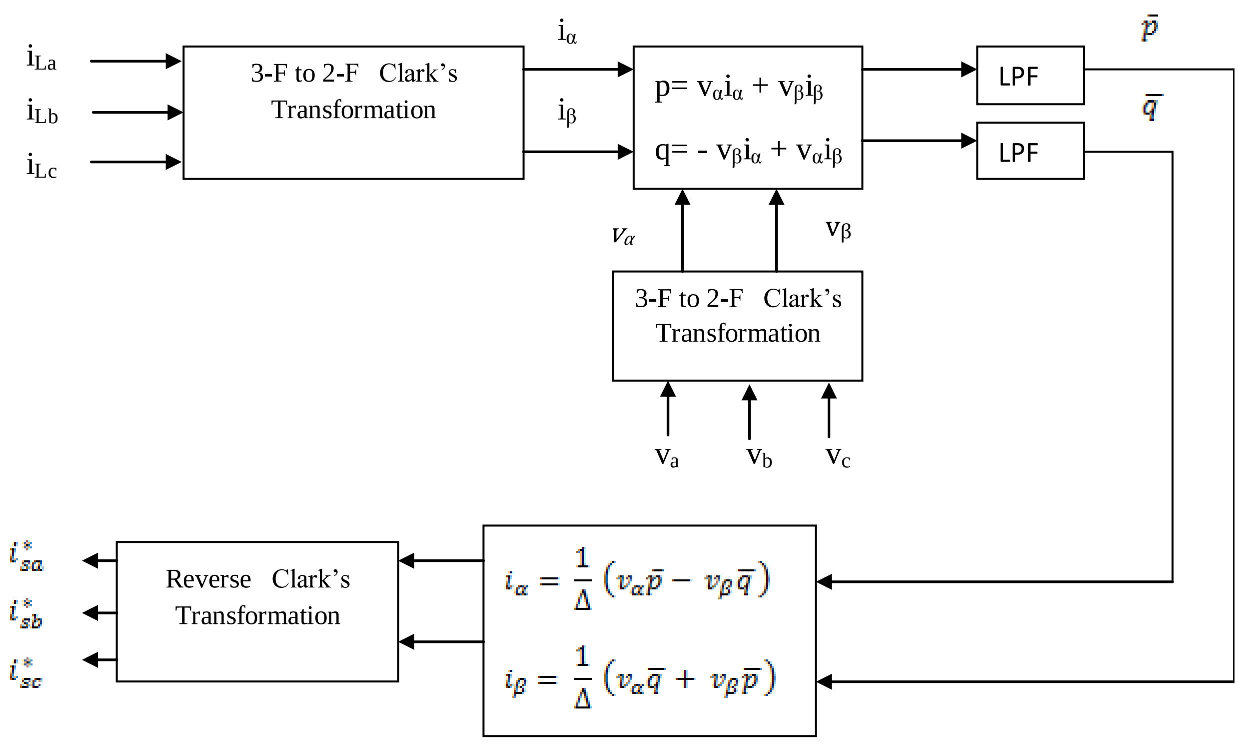

Fig 2.16 Basic block diagram of the reference current extraction through p-q theory

and respective load currents are given as

$i_{La} = \sum I_{Lan} \sin\{n(\omega t) - \theta_{an}\}$
$i_{Lb} = \sum I_{Lbn} \sin\{n(\omega t - 120) - \theta_{bn}\}$ 2.4
$i_{Lc} = \sum I_{Lcn} \sin\{n(\omega t - 240) - \theta_{cn}\}$

In a-b-c coordinates the a,b,c axes are fixed on the same plane, and are phase apart each other by 120^0. The instantaneous space vectors, v_a and i_{La} are set on the a axis and their amplitude varies in positive and negative direction with the time. This is true for other phases also. These phases can be transformed into α-β coordinates using the Clarke's transformation as in eq^n 2.5.

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \qquad 2.5$$

The currents in abc frame can be converted to α-β coordinates using eq^n 2.6.

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \qquad 2.6$$

where the α and β axes are the orthogonal coordinates. The conventional instantaneous power in the three phase circuit can be defined using eq^n 2.7 as:

$$p = v_\alpha i_\alpha + v_\beta i_\beta \qquad 2.7$$

which is same as the instantaneous real power, p is calculated using three phase voltages (v_a, v_b,v_c) and three phase currents (i_a, i_b, i_c) in eq^n 2.8 as:

$$p = v_a i_a + v_b i_b + v_c i_c \qquad 2.8$$

Similarly the instantaneous reactive power q is defined in eq^n 2.9 as:

$$q = -v_\beta i_\alpha + v_\alpha i_\beta \qquad 2.9$$

These equations can be written in matrix form as:

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\alpha & v_\beta \\ -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \qquad 2.10$$

The α-β currents can be obtained as:

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \frac{1}{\Delta} \begin{bmatrix} v_\alpha & -v_\beta \\ v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} p \\ q \end{bmatrix} \qquad 2.11$$

where $\Delta = v_\alpha^2 + v_\beta^2$ 2.12

The instantaneous active and reactive powers can be decomposed into the average $(\bar{p}, \bar{q})$ and an oscillatory component $(\tilde{p}, \tilde{q})$.

$$p = \bar{p} + \tilde{p} \qquad 2.13$$

$$q = \bar{q} + \tilde{q} \qquad 2.14$$

where $\bar{p}$ and $\bar{q}$ are the average part and $\tilde{p}$ and $\tilde{q}$ are the oscillatory parts of real and reactive instantaneous powers. The compensating currents are calculated to compensate the instantaneous reactive power and the oscillatory component of the instantaneous active power. The LPF (Low Pass Filter) showed in Fig 2.16 extracts the average and the oscillatory parts of real and reactive power. The α-β components of current can be transformed in a-b-c quantities to find the reference currents in a-b-c coordinate using inverse Clarke's transformation given in eq^n 2.15:

$$\begin{bmatrix} i_{sa}^* \\ i_{sb}^* \\ i_{sc}^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1/\sqrt{2} & 1 & 0 \\ 1/\sqrt{2} & -1/2 & \sqrt{3}/2 \\ 1/\sqrt{2} & -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} \qquad 2.15$$

where i_0 is the zero sequence component which is zero in 3-phase 3-wire system.

2.5.2 Synchronous Reference Frame (SRF) Theory

The synchronous reference frame theory is based on the transformation of currents in synchronously rotating d-q frame. Basic building blocks of this theory are shown in Fig 2.17. The load currents which are in a-b-c frame are first transformed into α-β frame using Clark's transformation, and then these currents in α-β frame are transformed in d-q frame. If θ is the transformation angle, then the currents transformation from α-β to d-q is defined as:

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} \qquad 2.16$$

This is also called as Park's transformation.

The DC components are extracted from these currents by passing them through a low pass filter (LPF). The extracted DC components i_{ddc} and i_{qdc} are transformed back into α-β frame as shown in eq^{n} 2.17 using inverse Park's transformation.

$$\begin{bmatrix} i_{\alpha dc} \\ i_{\beta dc} \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} i_{ddc} \\ i_{qdc} \end{bmatrix} \qquad 2.17$$

Inverse Clark's transformation can now be made to obtain three phase reference currents in a-b-c coordinates from the i_α, i_β dc components.

The PCC voltages are passed through a PLL for finding out the values of cosθ and sinθ. These values of cosθ and sinθ are used in Park's and Inverse Park's transformation for calculating the required currents.

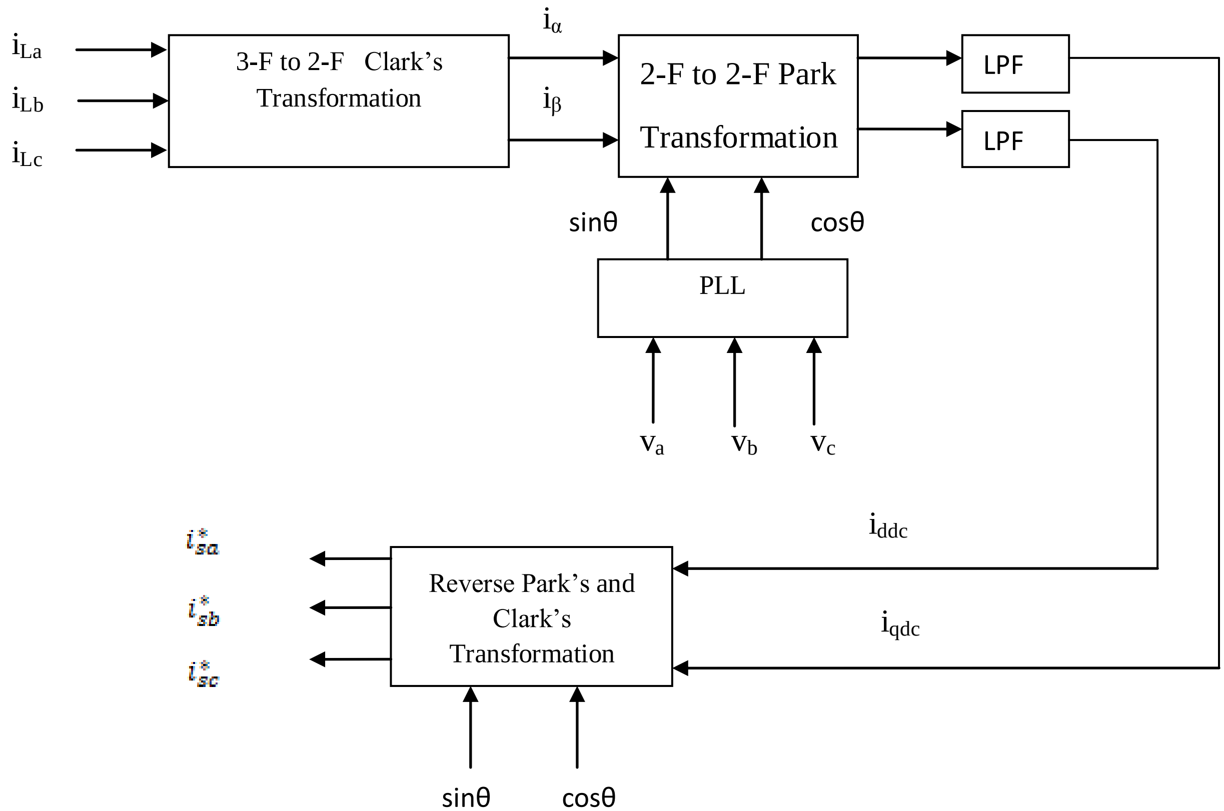

Fig 2.17 Block diagram of the reference current extraction through SRF theory

2.6 Applications of DSTATCOM

Literature Survey [27-34] presents numerous applications of DSTATCOM as a shunt compensator. Some of the applications for mitigation of PQ problems are listed as:

- Harmonic Filtering
- Power Factor Improvement
- Short Interruption Compensations
- High Speed Control of Reactive Power to Provide Voltage Stabilization
- Protects Distribution Systems from Voltage Sags caused by Non-Linear Dynamic Loads
- Arc Furnace Flicker Suppression
- Short-term Transient Overload Capability to Reduce the Size of the Compensation System to Handle Transients Events

Since 1991 till date a number of practical installations of STATCOM/DSTATCOM

Table 2.1: Practical Installations of STATCOM and DSTATCOM [36]

S.No.	Year Installed	Country	Capacity MVAR	Voltage Level (kv)	Purpose	Place
1.	1991	Japan	± 80 MVA	154	Power system and voltage stabilization	Inumaya substation
2.	1992	Japan	50 MVA	500	Reactive compensation	Shin Shinano Substation Nagona
3.	1995	U.S.A	±100 MVA	161	To regulate bus voltage	Sullivan substation in TVA power system
4.	2001	U.K	0 to +225	400	Dynamic reactive compensation	East Claydon 400 kV Substation
5.	2001	U.S.A	-41 to +133	115	Dynamic reactive compensation during critical contingencies	VELCO Essex substation
6.	2003	U.S.A	±100	138	Dynamic var control during peak load Conditions	SDG&E Talega substation
7.	1995	Canada	±2	4.16	Reactive power compensation to prevent flicker	Timber Mill in British Columbia
8.	1999	U.S.A	5 MVA	4.16	Voltage flicker compensation	Seattle Iron & Metals Corp. Seattle
9.	2001	India	15 MVA	33	To keep power factor to Unity	Titanium shop, MIDHANI, Hyderabad
10.	2003	Iran	±250 kvar	400 volts	Reactive power control for voltage regulation	Khoshnoodi substation, Tehran

2.7 Battery Energy Storage System (BESS)

Load fluctuation is one of the major problems in the distribution system. BESS acts as an alternating power source to take care of the uncertainty in power supply. It could operate in all four quadrants. The structural difference between DSTATCOM and BESS occurs across the DC link side. An additional battery is connected across the Dc link capacitor. BESS can also simultaneously absorb or deliver reactive power within the converter's MVA capacity. When not supplying active power to the system, the converter is used to charge the battery at an acceptable rate. Fig 2.18 shows a simple one-line diagram in which storage means is connected to a DSTATCOM.

BESS defined by IEEE as:

Battery Energy Storage System (BESS): A chemical-based energy storage system using shunt connected voltage-source converters capable of rapidly adjusting the amount of energy which is supplied to or absorbed from an ac system.

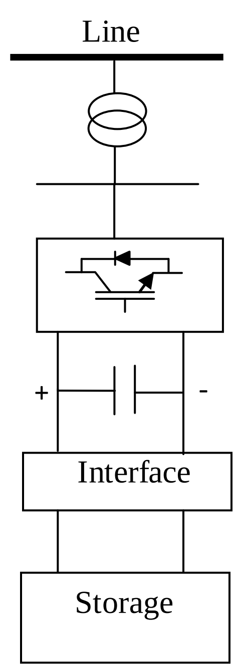

Fig. 2.18 Battery Energy Storage System (BESS)