CHAPTER 1

INTRODUCTION

Power Quality has been a problem bristling with snags ever since electrical power was invented. It has become a well projected area of interest in recent years because of the electrical appliances (load) it affects. The electric current that the customers appliances draws from the supply network flows through the impedances of the supply system and causes a voltage drop, which affects the voltage delivered to the customer. Hence both the voltage quality and the current quality are important. The power distribution supplier is responsible for the voltage quality and the customer is accountable for the quality of electric current that they draw from the utility. The categorization of power system electromagnetic phenomena that affects the power quality are transients, short duration variations, long duration variations and waveform distortions. The waveform distortion is defined as the steady state deviation from an ideal sine wave of power frequency principally characterised by the spectral content of the deviation given by Dugan et al (2004). One of the types in waveform distortion is harmonics. The increased awareness of harmonics in recent years is the result of concerns that harmonic distortion levels are increasing on many electrical power systems.

Power Quantity is another major global issue that resulted in increased demand for electrical power. This issue has stimulated the alternate energy sources drastically. It has been estimated by Cecati et al (2010) that the energy produced by renewable sources is expected to satisfy 50% of the total needs in 2050. Due to fossil fuel exhaustion and environmental problems
caused by conventional power generation, renewable energy sources, particularly solar and wind energy have become very popular and demanding. But the quality of power from these sources has to be improved to protect the loads connected in the system and also to enable the continuity of supply to the consumers without any disturbances. Hence the combination of power quality and power quantity will certainly result in providing clean power from green energy sources.

To meet this objective, a power electronic interface with harmonic reduction capability needs to be connected between the source and load. Unlike the conventional inverters, Multi Level Inverters (MLI) are recommended as the synthesized multilevel outputs are superior in quality which result in reduced filter requirements and overall system size stated by Rahim et al (2013). The switching sequence for the MLI is controlled by intelligent techniques which enables the power quality. The input source considered is solar Photo Voltaic (PV) which intends the power quantity. It is convenient to integrate both functionalities of power generation and power quality improvement using the same hardware structure presented in the distributed generation system has been studied by Cavalcanti et al (2012).

1.1 POWER QUALITY IN ELECTRICAL SYSTEMS

Any power problem manifested in voltage, current or frequency deviations that result in failure or misoperation of customer equipment is termed as Power Quality. The issue of electric power quality is gaining importance because of several reasons. Some of them are quoted by Khalid & Vyas (2009): 1) Modern society is becoming increasingly dependent on the electrical supply. A small power outage has a great economic impact on the industrial consumers, 2) Advent of new power electronic equipment, 3) The deregulated environment which reduces the maintenance and investments into the power system and hence reduce the margins in the system and
4) Emerging distributed power generation. The key problems associated with
the power quality are: damage to sensitive equipment, interference,
malfunction, extra losses, personnel safety issues, poor utilization and poor
power factor.

The quality of electrical power may be described as a set of values
of parameters such as: continuity of service, variation in voltage magnitude,
transient voltages and currents and harmonic content in the waveforms for AC
power. Among these, harmonics play a vital role in all the segments of
electrical system. Harmonics are sinusoidal voltages or currents having
frequencies that are integer multiples of the frequency at which the supply
system is designed to operate at the fundamental frequency. Harmonic
distortion originates in the nonlinear characteristics of devices and loads on
the power system. The problems caused by harmonics are: transformer feeder
overheating, circuit breaker inadvertent trips, fuse blowing especially on
distribution feeder laterals, equipment malfunction (sensitive equipment),
increased kVA demand and need to oversize, reduction in power factor, waste
of electric energy and light flickering.

Total Harmonic Distortion (THD) is a measure of the effective
value of the harmonic components of a distorted waveform as given in the
Equation (1.1). This index can be calculated for either voltage or current. It is
the measure that quantifies “how close the waveform is to pure sine”.

\[
\text{THD} = \sqrt{\frac{\sum_{h=1}^{h_{\text{max}}} X_h^2}{X_i}}
\]

(1.1)

where \(X_h\) is the Root Mean Square (RMS) value of harmonic component \(h\) of
the quantity \(X\) and \(X_i\) is the fundamental component. The THD is calculated
up to the harmonic \(h_{\text{max}}\), which is typically 20. The THD may be calculated
with either the RMS values or the peak values of the output waveform. There exists a relationship between the THD and true RMS value $X_{\text{RMS}}$ of the waveform as shown in the Equation (1.2).

$$X_{\text{RMS}} = X_1 + \sqrt{I^2 \cdot \text{THD}^2}$$

provided that if no harmonics exist above $h_{\text{max}}$ and the waveform is periodic with a fundamental wave period, then the THD can be represented as in the Equation (1.3).

$$\text{THD} = \sqrt{\left( \frac{X_{\text{RMS}}}{X_1} \right)^2 - 1}$$

1.2 SOLUTIONS FOR POWER QUALITY PROBLEMS

There are two approaches to the mitigation of power quality problems which can be done from customer side or from utility side. The first approach is load conditioning which ensures that the equipment is less sensitive to power disturbances, allowing the operation even under significant voltage distortion. The second solution is to install line conditioning systems that suppress or counteracts the power system disturbances.

A versatile and flexible solution to voltage quality problems is offered by active power filters. Shunt active power filters operate as a controllable current source and series active power filters operates as a controllable voltage source. Both schemes are implemented preferable with voltage source Pulse Width Modulation (PWM) inverters, with a Direct Current (DC) bus having a reactive element such as a capacitor. Active power filters can perform one or more of the functions required to compensate power systems and to improve power quality. Their performance also depends on the power rating and the speed of response. However, with the restructuring of
power sector and with shifting trend towards distributed and dispersed generation, the line conditioning systems or utility side solutions will play a major role in improving the inherent supply quality. From the utility perspective, power quality has been defined as the parameter of the voltage that affects the customer’s supersensitive equipment.

1.3 MULTILEVEL INVERTERS AND THEIR STRUCTURES

A multilevel power converter structure has been introduced as an alternative in high power medium voltage applications. Even though the conventional PWM inverters are widely used in industrial applications, they possess several drawbacks listed by Luo & Ye (2013) are as follows:

- The carrier frequency must be very high. If the output waveform has frequency of 50Hz, then the carrier frequency should be greater than 1kHz

- The pulse height is very high. In a normal PWM waveform (not multistage PWM), all the pulse height is equal to DC link voltage and its output voltage has a large jumping span. This results in large dv/dt and strong Electro Magnetic Interference (EMI)

- The pulse width would be very narrow when the output voltage has a low value

- PWM causes plenty of harmonics results in poor THD. In a very rigorous switching condition, the switching devices experience large switching power losses
• Control circuitry for the switching pulses generation and devices used are complex and costly

A multilevel power converter accumulates the output voltage in horizontal levels and overcomes the drawbacks of conventional inverters as given below:

• The switching frequencies of the switching devices are low, which are equal to or only a small multiple of the output signal frequency

• The pulse heights are quite low. For an ‘m’ level inverter with output amplitude $V_m$ the pulse heights are $V_m/m$ or only a small multiple of it. Usually, it causes low $dv/dt$ and ignorable EMI

• The pulse widths of all pulses have reasonable values that are comparable to the output signal

• Multilevel converters cannot cause plenty of harmonics and produces less THD

• Offers smooth switching condition and the switching devices have small switching power losses

• Control circuitry is simple and the devices are not costly

The term multilevel comes from the three level converters. The commutation of the power switches aggregates these multiple DC sources in order to achieve high voltage at the output. The advantages of this multilevel approach include good power quality, better electromagnetic compatibility, low switching losses and high voltage capability. The three structures of MLI are Neutral Point Clamped (NPC) or Diode Clamped Multi Level Inverter
(DCMLI), Flying Capacitor Multilevel Inverter (FCMLI) and Cascaded Multilevel Inverter (CMLI).

The first multilevel converter can be attributed to Baker and Bannister who patented Cascaded H Bridge (CHB) in 1975. This cascaded inverter was first defined with a format that connects separately DC sourced full bridge cells in series to synthesize a staircase AC output voltage. Nabae, Takahashi and Akagi presented a diode clamped topology in 1981 which utilizes a bank of series capacitors to split the DC bus voltage. The diode clamped inverter also called as the Neutral Point Clamped (NPC) inverter when it was first used in a three level inverter the mid voltage level is defined as the neutral point. The NPC inverter effectively doubles the device voltage level without requiring precise voltage matching. Meynard and Foch in 1992 patented the Flying Capacitor (FC) architecture which uses floating capacitors to clamp the voltage levels.

In 1992, Osagawara presented a standard Current Source Inverter (CSI), but increased the number of current levels instead of voltage levels (Babaei 2010). Vázquez et al (2010) pointed the drawback of the current source topologies which lies in the limited dynamic performance due to the use of large DC chokes as DC link whereas Voltage Source Inverter (VSI) has high dynamic performance. Although the cascade inverter was invented earlier, its applications did not prevail until the mid 1990s. Rodríguez et al (2002) have surveyed that due to the great demand for medium voltage high power inverters, the cascade inverter has drawn tremendous interest.

The two terminologies which constitute the working of MLI’s are ‘stages’ and ‘levels’. The individual H bridge inverter is termed as a single ‘stage’. During its conduction it produces the output voltage with square shape in both positive and negative half cycles which is termed as two ‘level’. The common zero potential is also included as the additional level which
results in a ‘single stage three level’ inverter. Any number of inverter output voltage levels can be achieved by increasing the number of inverter stages. While increasing the levels, consideration should be focused on the number of switching devices used and their corresponding control circuits. Figure 1.1 (a) and (b) represents the power circuit of a fifteen level diode clamped and flying capacitor type MLI with solar PV array at its input. These two MLI configurations are well-suited for the applications with single input supply. The design of solar PV array in these cases requires a high power rating or a boost converter circuit to step up its voltage inorder to reach the higher levels.

Figure 1.1 (a) Power circuit of fifteen level DCMLI and (b) Power circuit of fifteen level FCMLI
1.3.1 Diode Clamped Multilevel Inverter (DCMLI)

Figure 1.1 (a) shows the power circuit of fifteen level DCMLI. It is also termed as Neutral Point Clamped Multilevel Inverter (NPCMLI) where the switching devices are connected in series to make up the desired voltage rating and output levels. The inner voltage points are clamped by either two extra diodes or one high frequency capacitor. The switching devices of an m level inverter are required to block a voltage level of \( V_{dc}/(m-1) \). The clamping diodes need different voltage ratings for different inner voltage levels.

In the power circuit, the DC bus voltage (PV array) is split into fifteen levels by seven series connected bulk capacitors. The middle point of the each two capacitors can be defined as the neutral point. The key components that distinguish this circuit from a conventional inverter are the diodes. These diodes clamp the switch voltage to half the level of the DC bus voltage.

The disadvantages of DCMLI are: a) Real power flow is difficult for a single inverter because the intermediate DC levels will tend to overcharge or discharge without precise monitoring and control and b) The number of clamping diodes required is quadratically related to the number of levels, which can be cumbersome for units with a high number of levels.

1.3.2 Flying Capacitor Multilevel Inverter (FCMLI)

The circuit has been called the capacitor clamped inverter with dependent capacitors clamping the device voltage to one capacitor voltage level. This topology has a ladder structure of DC side capacitors, where the voltage on each capacitor differs from that of the next capacitor. The voltage increment between two adjacent capacitor legs gives the size of the voltage
steps in the output waveform. The FCML inverter power circuit illustrated in Figure 1.1 (b) provides a fifteen level output.

The voltage synthesis in a fifteen level capacitor clamped inverter has more flexibility than a diode clamped converter. Unlike the diode clamped inverter, the flying capacitor inverter does not require all of the switches that are ON (conducting) in a consecutive series. Moreover, the flying capacitor inverter has phase redundancies, whereas the diode clamped inverter has only line-line redundancies. These redundancies allow a choice of charging/discharging specific capacitors and can be incorporated in the control system for balancing the voltages across the various levels.

The disadvantages of FCMLI are: a) Control is complicated to track the voltage levels of all the capacitors. Also, precharging all of the capacitors to the same voltage level and start up are complex, b) Switching utilization and efficiency are poor for real power transmission and c) The large numbers of capacitors are both more expensive and bulky than clamping diodes in multilevel diode clamped converters. Packaging is also more difficult in inverters with a high number of levels.

In order to overcome these drawbacks of both NPCMLI and FCMLI, the structure suitable for solar PV with the aid of power quality improvement is considered in the proposed system.

1.3.3 Cascade H Bridge Multi Level Inverter (CHBMLI)

A Cascaded Multi Level Inverter (CMLI) consists of series H bridge (single phase full bridge) inverter units. The general function of this MLI is to synthesize a desired voltage from separate DC sources (SDCs) which may be obtained from batteries, fuel cells or solar cells. The resulting phase voltage is synthesized by the addition of the voltages generated by
different H bridges. If the DC link voltages of the HBs are identical, then the CMLI is termed as symmetrical. However, it is possible to have different values among the DC link voltages of HBs, and the circuit can be called as asymmetrical. As solar PV voltages are variable with respect to environmental factors, asymmetrical inverters are highly recommended. Figure 1.2 shows the power circuit of a solar fed cascaded fifteen level inverter along with its output voltage waveform. The AC terminal voltages of different level inverters are connected in series. Unlike the NPCMILI or FCMLI, the CMLI does not require any voltage clamping diodes or voltage balancing capacitors as compared in the literature (Rashid 2004).

Figure 1.2 Solar fed cascaded fifteen level inverter and its output voltage waveform
Among the various MLI topologies, cascade configuration has been utilized for medium voltage and high voltage renewable energy systems such as solar photovoltaic due to its modular and simple structure. Application of the cascade inverter for renewable energy systems is reviewed by Kjaer et al (2005) and Carrasco et al (2006). Cascaded inverters are ideal for connecting renewable energy sources with an AC grid, because of the need for separate DC sources. This is the case in regard to applications such as photovoltaics or fuel cells. Liu et al (2014) found that the higher number of voltage levels can effectively decrease harmonics content of staircase output, thus significantly simplifying the output filter design.

Figure 1.2 also shows the phase voltage waveform of a fifteen level cascaded inverter with seven PV array inputs. The phase voltage is synthesized by the sum of seven inverter outputs given by the relation as
\[ v_{an} = v_{a1} + v_{a2} + v_{a3} + v_{a4} + v_{a5} + v_{a6} + v_{a7} \]. Each inverter level can generate three different voltage outputs, \( +V_{dc} \), 0 and \( -V_{dc} \) by connecting the PV array source to the AC output side by different combinations of the four switches in the individual inverter stage. As a case, in the first stage of the inverter, turning S1 and S4 ON yields the output \( +V_{dc} \) and turning S2 and S3 ON yields the output \( -V_{dc} \). Turning OFF all the switches yields the output 0. Similarly, the AC output at each level can be obtained in the same manner. If \( N_s \) is the number of input PV sources, the output phase voltage level is \( m = 2N_s + 1 \). Thus, a fifteen level cascaded inverter needs seven SDCs and seven full bridges. Controlling the switching angles at different inverter stages can minimize the harmonic distortion of the output voltage which in turn improves the power quality.

Compared with NPCMLI and FCMLI, CMLI requires the least number of components to achieve the same number of voltage levels. Optimized circuit layout and packaging are possible because each level
has the same structure. The only disadvantage of the CMLI is that it needs separate DC sources for real power conversions. However this disadvantage can be compensated by utilizing solar PV at its input in the proposed design.

1.3.4 Reduced Order Multilevel Inverter

Besides the three basic MLI structures, new topologies based on the existing multilevel concepts have been classified as hybrid MLI. The hybrid multilevel topologies are constituted by using the combination of two basic topologies such as NPCMLI or FCMLI to replace the H-bridge as the basic module of the CMLI, in order to reduce the number of the separated DC sources. The asymmetric hybrid MLIs synthesize the output voltage waveforms with reduced harmonic content. This advantage is achieved by using distinct voltage levels in different modules, which can generate more number of levels in output voltage waveform. It also reduces the THD value, while preventing the increase in number of switching devices and sources.

Each power module of a hybrid MLI can be operated at distinctive DC voltage and switching frequency, improving the efficiency and THD compensation characteristics of inverter. Nevertheless, conventional PWM strategies, which generate switching frequency at fundamental frequency (50Hz) are not appropriate for the hybrid inverters due to switching devices of the higher voltage modules. Besides, they would have to operate at high frequencies only during some inverting instants. To achieve this control strategy, hybrid modulation methods can be used in such a way that higher power cells are switched at low frequency and low power cells switched with high frequency.

Hybrid MLIs promise significant improvements for medium voltage and high power industrial drives. Farokhnia et al (2011) dealt with five level CMLI and found that asymmetrical multilevel inverters help in
minimizing the harmonic contents of output voltage without increasing the number of power devices. The use of various DC voltages in supply leads the hybrid MLI topologies in an effort to optimize the power processing of the entire system.

1.3.5 Comparison of Multilevel Inverters

NPCMLI offers the advantage of having common DC input capacitors for the three phases. Its main disadvantage is that too many diodes are used for clamping, which also make the implementation of the physical layout difficult. NPCMLI structure can be extended to a higher number of levels but these are less attractive because of additional losses and uneven distribution of these losses in the outer and inner devices. The clamping diodes, which have to be connected in series to block the higher voltages, introduce more conduction losses and produce reverse recovery currents during commutation that affects the switching losses of the other devices even more.

In a FCMLI, the clamping capacitor voltages can be balanced within a few cycles by using voltage synthesis redundancies. Its main disadvantage is that many capacitors are used for clamping, though these capacitors are cheaper compared to the clamping diodes of the DCMLI. Furthermore, for low switching frequency, the clamping capacitors become large in size thus decreasing the power density of the inverter.

In a CMLI, no clamping capacitors or diodes are required. Furthermore, a low switching frequency can be used. Modularized circuit layout and packaging is possible because each cell has the same structure and there are no extra flying capacitors or clamping diodes. Its main disadvantage is the use of an independent DC source for every cell. For this reason, the
CMLI can be used in the applications pertaining to solar PV and fuel cell based power generation systems.

Examining the power circuits of the three MLIs it is observed that they use the same number of semiconductor switches per phase. However, the NPCMLI uses \((m-1) (m-2)\) clamping diodes thus increasing the cost compared to the other two structures. The FCMLI and CMLI need \(2 (m-1)\) heat sinks whereas the NPCMLI needs \(2(m-1) + (m-1) (m-2)\). In order to generate an \(m\) level inverter output, the CMLI uses the least amount of semiconductor devices and consequently requires the lowest implementation cost.

One additional advantage of the CHB converter is that if any device fails in the H-bridges, the inverter can still be operated at reduced power level. This fault tolerant configuration of CHB was revealed by Song & Huang (2010) and Lezana et al (2010).

### 1.3.6 Applications of Multilevel Inverters

Multilevel converters are finding increased attention in industry and commercial sectors as the preferred choices of electrical power conversion for medium and high power applications. There are many applications for MLIs, such as Flexible AC Transmission System (FACTS) equipment dealt by Song & Liu (2009), High Voltage Direct Current (HVDC) lines exhibited by Flourentzou et al (2009) and electrical drives manifested by Hagiwara et al (2010). Kouro et al (2010) conveyed that MLIs are currently commercialized in standard and customized products that power a wide range of applications, such as compressors, extruders, pumps, fans, grinding mills, rolling mills, conveyors, crushers, blast furnace blowers, gas turbine starters, mixers, mine hoists, reactive power compensation, marine propulsion, hydro pumped storage, wind energy conversion and railway traction.
1.4 INTEGRATION OF MLI WITH SOLAR PV SYSTEMS

The ever rising demand for electrical energy and depleting fossil fuel reserves are compelling reasons to use existing resources more efficiently. Abu-Rub et al (2010) projected that new highly efficient power electronic technologies and proper control strategies are therefore needed to reduce energy waste and to improve power quality. The increasing demand for energy has stimulated the development of alternative power sources such as PV modules, fuel cells and wind turbines. The PV modules are particularly attractive as renewable sources due to their relative small size, noiseless operation, simple installation and the possibility of installing them closer to the user. PV power generators convert the energy of solar radiation directly to electrical energy without any moving parts. PV power generators can be classified into stand alone and grid connected systems. In standalone system, the energy storage has a big influence on the design of the systems. In grid connected system, the grid acts as an energy storage into which the PV power generator can inject power whenever power is available which has been elucidated by M’aki & Valkealahti (2012).

In PV modules, the output voltage has low DC amplitude. In order to be connected to the grid, the PV modules output voltage should be boosted and converted into an AC voltage. This task can be performed using one or more conversion stages (multi-stage). Blaabjerg (2006) found that many topologies for PV systems are multi stage, having a DC to DC converter with a high frequency transformer that adjusts the inverter DC voltage and isolates the PV modules from the grid. However, the conversion stages decrease the efficiency and make the system more complex.

In PV systems where series modules are connected to a conventional two level inverter, the occurrence of partial shades and the mismatching of the modules lead to a reduction of the generated power.
In addition, the conventional two level voltage source converters will not be able to deliver the performance parameters such as improved power quality, maximum allowed switching frequency, higher voltage operation and reduction in filter size. To overcome these problems, the connection of the modules can be made using a multilevel converter. Monge et al (2008) have claimed that multilevel converter maximizes the power obtained from the arrays, reduces the device voltage stress, and generates output voltages with lower THD.

Grid connection of PV systems has been traditionally performed by three different types of configurations: centralized conversion topology (large three phase system), string topology (medium single phase system) and the AC module topology (small single phase system). More recently a hybrid between the centralized and the string configuration, called multi-string topology (for medium to large, single or three phase system) has gained more attention. The centralized topology uses a single three phase inverter to connect to the grid. The advantages are its simple structure and control which come at the expense of reduced power generation due to module mismatch and partial shading. This topology is considered nowadays obsolete.

The string topology uses one inverter per string, improving the total generated power. It also increases modularity, since additional strings can be added to the system without the need of changing the inverter dimensions. Depending on the size of the string, a boost DC to DC converter or a step up transformer is necessary to reach the grid voltage. The string topology is the most widely installed solution for PV grid connected systems today.

The AC module topology or converter integrated module, is the most modular and has the best maximum power tracking capability, since one converter is dedicated per module. This is intended for smaller systems and more domestic use. The main disadvantage is that a DC-DC boost stage or
step up transformer is a must, which increases the cost if an AC module system of the same power of a string system is compared.

The CMLI has attracted attention for the PV integration as each H Bridge (or power cell) needs isolated DC sources, which can be easily given by PV modules or strings. Furthermore, it adds interesting benefits such as higher voltage operation by interconnecting enough modules or strings in series to reach grid voltage, eliminating the need of step up transformer or boost DC-DC converters. In addition the inherent improved power quality of multilevel converters reduces filter size and switching frequency, improving the system efficiency.

CMLI can be used as a series connection of string inverters or as a series connection of AC module inverters. In the first case, less PV modules are necessary per string, as voltage will be elevated by series connection. This improves Maximum Power Point Tracking (MPPT), since lesser modules are concentrated to a single converter. The second case, i.e., if used as the series connection of several AC modules, the internal DC-DC boost stage is not longer necessary, simplifying each converter (less semiconductors, no boost inductor, lower switching frequency, improved efficiency etc.). In addition, since they are connected in series at the AC side, DC cables are no longer necessary as with the multi string topology. Finally, compared to any of the traditional topologies, the CHB multilevel approach has by far the best power quality, reducing filter needs while improving efficiency and overall performance as listed by Chavarría at al (2013).

The same configurations can also be extended to the stand alone PV systems. The major advantage of this system is its potential to supply abundant electricity in areas not provided by the general power grid. In many stand alone photovoltaic inverters, alternating current is required to operate at 230 V, 50 Hz for home or office appliances. Generally, stand alone inverters
operate at voltages of 12, 24, 48, 96, 120 or 230 relying on the power level. Possibility of MLI for the standalone systems is presented by Daher et al (2008).

In the case where the amplitude of voltage produced by solar array is low, there is the need for an additional boost converter or a step up transformer to obtain high output voltage. It converts power from DC to AC and is commonly connected in series with a PWM inverter. However, a somewhat high switching frequency of PWM inverter and its stress result in low efficiency and occasionally EMI problems. In addition, an output filter is required to reduce high switch frequency components and to produce sinusoidal output from the inverter. For alleviating these problems, Kang et al, (2005) have claimed MLIs can substitute the conventional PWM inverter. Gu et al (2013) have pointed the advantages of transformerless PV inverters such as higher efficiency, lower cost, less complexity and smaller volume compared to their counterparts with transformer galvanic isolation. Hence the CMLI is well-suited for both standalone and grid connected systems with respect to output voltage regulation and harmonic reduction.

1.5 POWER QUALITY IMPROVEMENT TECHNIQUES FOR A SOLAR FED CMLI

In the recent years the demand for solar electric energy has grown consistently, which is mainly due to the decreasing costs and prices. Selvaraj & Rahim (2009) have advocated that this decline has been driven by the following factors: 1) an increasing efficiency of solar cells, 2) improvements in manufacturing technology and 3) economies of scale. The economies of scale are referred as the marginal cost arising from an increase of an operating unit. PV inverter, which is the heart of a PV system, is used to convert DC power obtained from PV modules into AC power to be before it fed into the grid. Improving the output waveform of the inverter reduces its respective
harmonic content and, hence, the size of the filter used. It also reduces the level of Electro Magnetic Interference (EMI) generated by switching operation of the inverter. Govindaraju & Baskaran (2011) have found that one area where multilevel converters are particularly suitable for renewable photovoltaic energy which is of great concern is efficiency and power quality. The performance of the MLI can be improved by: a) Harmonic elimination, b) control strategies and c) new MLC topologies. These three extremes of performance improvement measures are enlisted into modulation strategies, intelligent techniques and Voltage Regulation (VR) methodologies in order to meet the objective of improving the power quality. Kulkarni & John (2013) have noted that attenuating the lower order harmonics using a larger output filter inductance is not a good option as it increases losses in the system along with a larger fundamental voltage drop and with a higher cost.

1.5.1 Modulation Strategies

Modulation is the process of providing appropriate switching signals to the inverter switches. Modulation strategies are aimed at generating a stepped switched waveform that best approximates an arbitrary reference signal with adjustable amplitude, frequency and phase fundamental component that is usually sinusoid in steady state. Since the modulation scheme is intended to be used in high power converters, the main figures of merit pursued are high power quality and minimum switching frequency. These two requirements compete with each other, and therefore, it is considered one of the major challenges in multilevel converter technology. Figure 1.3 depicts the classification of various modulation control strategies. Methods that work with high switching frequencies have many commutations for the power semiconductors in one period of the fundamental output voltage.
Figure 1.3 Classification of MLI modulation strategies

A very popular method in industrial applications is the classic carrier based Sinusoidal PWM (SPWM) that uses the phase shifting technique to reduce the harmonics in the load voltage. Several multicarrier techniques can be used to reduce the distortion in MLIs, based on the classical SPWM with triangular carriers. Some methods use carrier disposition and others use phase shifting of multiple carrier signals.

An advantageous feature of multilevel SPWM is that the effective switching frequency of the load voltage is $N_s$ (where $N_s$ is the number of inverter stages) times the switching frequency of each cell, as determined by its carrier signal. This property allows a reduction in the switching frequency of each cell, thus reducing the switching losses. Space Vector Modulation (SVM) generally has the following features: good utilization of DC link voltage, low current ripple and relatively easy hardware implementation by a Digital Signal Processor (DSP). These features make it suitable for high voltage high power applications. As the number of levels increases, redundant
switching states and the complexity of selecting switching states increase dramatically.

Methods that work with low switching frequencies generally perform one or two commutations of the power semiconductors during one cycle of the output voltages, generating a staircase waveform. Representatives of this family are the multilevel Selective Harmonic Elimination (SHE) and the Space Vector Control (SVC). In SHE, the most significant low frequency harmonics are chosen for elimination by properly selecting switching instances among different level inverters, and high frequency harmonic components can be readily removed by using additional filter circuits. This modulation strategy basically provides a narrow range of modulation index, which is its main disadvantage.

Space Vector Control (SVC) works with low switching frequencies and does not generate the mean value of the desired load voltage in every switching interval, as is the principle of SVM. Predominantly, space vector schemes are highly applicable to three phase systems. Zambra et al (2010) found that the application of SVM in cascaded topologies is usually limited to a small number of levels, due to the large number of switching vectors

1.5.2 Intelligent Techniques

Inspite of the fact that SHE was introduced in 1973 as quoted by Li et al (2000), considerable amount of works needs to be addressed with aid of intelligent techniques. In recent years, the control techniques are modified into intelligent based in order to achieve high precision output inspite of the situations of imprecision, uncertainty and partial truth. In order to improve the performance parameters of solar fed CMLI, the intelligent techniques such as Artificial Neural Networks (ANN), Fuzzy Logic Controllers (FLC) and Optimization Techniques such as Genetic Algorithm (GA), Particle Swarm
Optimization (PSO) and Bees Optimization (BO) were developed. In fact each and every technique has its own control algorithm based on the natural phenomenon. Neural Networks are simplified models of the biological nervous system and therefore have drawn their motivation from the kind of computing performed by a human brain. In general, it is a highly interconnected network of a large number of processing elements called neurons in an architecture inspired by the brain. It can massively parallel and intend to exhibit parallel distributed processing. Neural Networks learn from examples. They can be trained with known examples of problem to acquire knowledge about it. Once approximately trained, the network can be put to effective use in solving unknown or untrained instances of the problem.

Fuzzy Logic is a generalization of classical set theory. Fuzzy logic representations founded on Fuzzy set theory try to capture the way humans represent and reason with real world knowledge in the face of uncertainty. A fuzzy set can be defined mathematically by assigning to each possible individual in the universe of discourse, a value representing its grade of membership in the fuzzy set. This grade corresponds to the degree to which the individual is similar or compactable with the concept represented by the fuzzy set.

Optimization techniques provides the best solution in the given search space based on the condition that the solution satisfies the constraints. This can be classified as derivative free and derivative based methods. GA, PSO and BO fall under the category of derivative free optimization methods. The GA repeatedly modifies a population of individual solutions. At each step, the genetic algorithm selects individuals at random from the current population to be parents and uses them in generating the offspring’s for the next generation. Over successive generations, the population “evolves” toward an optimal solution.
PSO was inspired by the sociological behavior associated with swarms such as flocks of birds and schools of fish. The individuals in the population are called particles. Each particle is a potential solution for the optimization problem and tries to search the best position through flying in a multidimensional space. BO is an optimization algorithm based on the natural foraging behavior of honeybees to find the optimal solution. This algorithm proceeds with the three phases representing the three types of bees available in the colony.

1.5.3 Voltage Regulation (VR) Methods

It is the process of maintaining a constant output voltage before it delivered to the consumers. Two basic categories of voltage regulation are: line regulation and load regulation. In line regulation, the purpose of voltage regulation is to maintain a nearly constant output voltage when the input voltage varies whereas in load regulation, the purpose of regulation is to maintain a nearly constant output voltage when the load varies. The important parameter of the inverter which it has to satisfy is to deliver fixed voltage and frequency.

As the input of the inverter is fed with solar PV system, it brings variation of the voltage due to changes in irradiance and temperature. To achieve the desired output voltage and frequency, the number of input blocks from solar PV to the inverter needs to be increased. These blocks include DC-DC converters, front end rectifiers and output transformers which increases the complexity of the entire conversion process. Eliminating the transformer will reduce cost, space, weight, and associated losses. Hence a line regulation
is required to maintain a constant output voltage inspite of variations at the input PV array.

1.6 PROBLEM STATEMENT

In solar PV systems enhancing the power quality is one of the challenging problems. The major problem in the solar PV conversion system lies in providing a pure form of power to the consumers. In addition to the power quality, availability and reliability of the power also need to be accounted. On considering these problems, the power quality improvement techniques are proposed for a solar fed fifteen level inverter to enhance both power quality and power quantity in the system.

Abu-Rub et al (2010) revealed that the output voltage waveform of the MLIs is affected by the following factors: 1) the topology used, 2) application, 3) control algorithm, 4) size of the filter and 5) choice of switching frequency. The proposed work provides the solutions for each factor such that 1) CMLI topology and Modified Multilevel Converter (MMC) are used, 2) in order to meet the application specific, voltage regulation techniques are used to provide constant output voltage and frequency, 3) the control algorithm involves intelligent techniques such as ANN, FLC and optimization techniques to reduce the harmonic distortions, 4) the usage of filter is completely eliminated in the system in meeting the objective of improving power quality without using the output filter circuits and 5) a minimum switching frequency (1000Hz) is used for the modulation techniques and fundamental switching frequency (50Hz) for SHE techniques. In this connection low switching frequency methods are preferred as they reduce the switching losses.
The power quality improvement techniques include:

- Modulation Techniques
- Selective Harmonic Elimination
- Digital Control Strategy
- Output Voltage Regulation

The method of enhancing power quality in a solar fed cascaded fifteen level inverter is proposed. The simulation studies are carried out with MATLAB (R2010b and R2013a) software package in which the simulations are extensively made from three level to maximum of levels greater than 1000. The solar PV which serves as the input source for the MLI is modelled which also shows the variations with respect to irradiance and temperature. Experimental set up is implemented for a 3kWp solar PV plant system and the power quality analysis has been carried out to show the effectiveness of the proposed system.

1.7 OBJECTIVES OF THE THESIS

The thesis deals with four improved schemes proposed for power quality improvement with respect to minimization of the harmonic distortion in a solar PV system. The proposed techniques are simulated in MATLAB (R2010b and R2013a) and experimentally analysed in a 3kWp system. The objectives are:

1. To model the solar PV panel in both fixed and variable irradiance levels whose parameters adhere to the hardware specifications
2. To design the various modulation strategies for solar fed CMLIs to analyse the variation of THD experienced at various levels. To implement a single chip topology using Digital Signal Processor (TMS 320F2812) to generate the multiple carrier PWM signals above and below the zero reference.

3. To design SHE techniques for a solar fed CMLIs using Optimal Harmonic Stepped Waveform (OHSW), ANN and optimization techniques such as GA, PSO and BO. To implement a Field Programmable Gate Array (FPGA) SPARTAN 3E based controller for a 3kWp solar PV fed CMLI to reduce the harmonic distortions.

4. To design and develop a solar fed CMLI with reduced number of semiconductor switches. To consider the fact that increasing the number of switching devices tends to reduce the overall reliability and efficiency of the power converter.

5. To design an output voltage regulation techniques for a solar fed cascaded fifteen level inverter using ANN, FLC and Proportional Integral (PI) based controllers. To implement a Microcontroller (ATMEGA 16AVR) based closed loop topology for a 3kWp solar PV fed CMLI to achieve the desired voltage output.

1.8 ORGANIZATION OF THE THESIS

This thesis is organized into seven chapters reporting on the complete research work. Then it discusses and analyzes the results. Chapter 1 consists of a brief introduction describing the statement of the problem to be handled and the objectives of the thesis. The organization of the thesis is also given in this chapter.
Chapter 2 provides a literature survey on current topics of research in the field. It starts with a general overview of power quality, MLIs, applications and intelligent techniques.

Chapter 3 explains the modulation techniques for a CMLI using multiple carrier PWM techniques with modification made in both carrier and reference signals. A comparison of THD with respect to various levels of inverter from three to fifteen is carried out. An experimental investigation on a 3kWp system with DSP based controller for multiple carrier signals generation is highlighted and the comparison between simulation and hardware results is pointed out.

Chapter 4 delineates the implementation of ANN, OHSW, GA, PSO and BO based algorithms to enhance the power quality of the system with reduced magnitude of selected harmonic orders. The proposed approach is tested in a 3kWp solar PV inverter with FPGA based processor.

Chapter 5 discusses the implementation of Digital Control Strategy (DCS) for a solar fed fifteen level inverter to reduce the number of semiconductor devices. This method involves the three schemes such as ‘binary’, ‘trinary’ and ‘Modified Multilevel Connection (MMC)’ which are implemented using digital logic functions and embedded controller. For the purpose of comparison the switches reduction topology is also carried out for a seven level inverter. The proposed approach is tested experimentally in a 3kWp solar PV plant with 12 switches for fifteen level and again 7 switches for fifteen level inverters.

Chapter 6 investigates the voltage regulation topology with PI, FLC and ANN based controllers. The proposed approach is tested in a 3kWp solar PV inverter with microcontroller. Chapter 7 summarizes the concluding remarks of the research with suggestions to carry out future work.