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PV to Grid Connected Cascaded T-type Multilevel Inverter with Improved Harmonic Performance

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ABSTRACT

Multilevel inverters act as a promising solution for medium voltage, high power applications due to their modularity and reduced voltage stress across the switches. Cascaded T Bridge Multilevel Inverters (CTB-MLI) are being considered as the best choice for grid connected Photovoltaic (PV) systems since they require several sources on the DC side. By means of MLI's, high quality output with less harmonic distortion is obtained compared to a two-level inverter. In this work, a comparative analysis of three levels of MLI's is presented. Control scheme based on Sinusoidal Pulse Width Modulation (SPWM) is adopted due to its ease of implementation. More number of levels results in reduced THD and nearly sinusoidal output. Simulation is performed using MATLAB/Simulink.

KEYWORDS: *Cascaded T Bridge Multilevel Inverter (CHB- MLI), Photovoltaic (PV), THD, SPWM*

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1. INTRODUCTION

1.1. Background:

Presently energy consumption is continuously increasing and it had increased the environmental pollution due to increased usage of fossil fuels. Solar, wind, small hydro etc. are alternative sources of energy which are being used so as to mitigate the environmental pollution. However, there are several drawbacks of renewable energy-based systems such as non-reliability, intermittency, power quality and security. To overcoming these problems one of the solution is use of distributed or dispersed generation system. The advantage of distributed generation system using renewable energy sources such as solar, wind or small hydro is production of power near the load centres, thereby eliminating the losses during transmission. To increase reliability the renewable based system are connected to grid. The Kyoto agreement on global reduction of greenhouse gas emissions has prompted renewed interest in renewable energy system worldwide. Today many renewable energy technologies are well matured, reliable, and cost effective. The demand and production of renewable energy based system are increasing and hence the cost of it is continuously decreasing. There are two types of the renewable energy system namely, stand-alone system and grid-connected system [6]. Both systems have a number of similarities, but are dissimilar in terms of control functions. The stand-alone system are used as off-grid system with battery storage. Its control algorithm must have an ability of bidirectional operation, which is battery charging and inverting [8]. The grid-connected system, on the other hand, converts dc into ac and supplies electrical energy directly to power grid [6] [9]. The Government of India and State Governments had taken a major initiative of the National Solar Mission for promoting ecologically sustainable growth while addressing India's energy security challenge. This initiative made a major contribution by India to the global effort to meet the challenges of climate change. As a result of the National Solar Mission and the successful completion of the first stage by end of 2011, it was expected that solar PV based power plants will become an exciting business opportunity. Power production through solar energy is possible using both solar thermal and solar photovoltaic, but worldwide electricity generation is more prominent through solar PV than through solar thermal. The solar energy has many advantages for instance clean, unlimited energy and it has potential to provide sustainable electricity in those areas which are not served by the conventional power grid(Monica and Pop). Nevertheless, a photovoltaic (PV) system is still much more costly than traditional energy sources, due to the high manufacturing costs of PV panels, but the energy that drives them, the light from the sun, is freely available almost everywhere [9] [8] [5]. Additional advantage of PV technology is that it has no moving parts. Therefore, the hardware is very robust. It has a long lifetime and low maintenance requirements. Finally it offers environmentally friendly power generation. The solar energy produces dc power, and hence power electronics and control equipment's are needed to convert dc power into ac [12].

1.2. Components of Solar PV Grid Connected Inverter System: Main components of a solar PV based grid interactive inverter system are shown in figure 1.1

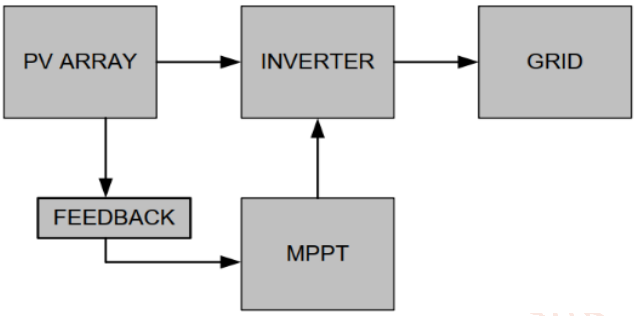

Figure 1.1 Components of a grid interactive inverter system

1.2.1. Solar PV array

A photovoltaic (PV) array is a device by which an electrical energy is generated as a result of the photovoltaic effect. The photovoltaic effect is a phenomenon by which an electrical potential is developed between two semiconductor materials when their common junction is illuminated with radiation of photons [9]. The basic building element of a PV array is the PV cell, which is referred as a solar cell. A typical solar cell generates less than 2 W at approximately 0.5 V. Therefore, in order to obtain sufficient voltage for practical applications several cells are connected in series to form a PV panel. Commercially available PV panels may have peak output power ranging from a few watts to more than 300 W at voltages ranging from 12 V to 48 V. Grid-connected PV applications often require higher voltages and currents than the ones which is available in a PV panel. In order to obtain higher voltages and current, PV panels must be connected into arrays. When PV panels are connected in series higher voltages are obtained, while parallel connections result in higher currents. The number and configuration of the elements of a PV array vary depending on the overall system's requirements [8].

1.2.2. PV Inverters

PV inverter systems connected to the low voltage grid have an important role in distributed generation systems. In order to keep up with the current trends regarding the increase in PV installations, PV inverters should have the following characteristics [9]:

- Low cost
- Small weight and size, due to residential installations
- High reliability to match with that of PV panels
- High efficiency
- Be safe for human interaction

The following section gives a brief account of the classification of grid interactive inverter topologies as available in literature [6] [3][5]

1.2.2.1. Central Inverters

Centralized inverters interface a large number of PV modules to the grid which is shown in Figure 1.2 (a). The PV modules are divided into series connections (called a string), each generating a sufficiently high voltage to avoid further amplification. These series connections were then connected in parallel, through string diodes, in order to reach high power levels. At first, line commutated thyristor based inverters were used for this purpose. These were slowly replaced by force commutated inverters using IGBT's [11]. However, there are disadvantages associated with central inverter scheme. There is a need for high-voltage DC cables between PV panels and inverter [12]. There are power losses due to common MPPT and module mismatch. Moreover there are losses in the string diodes and the reliability of the whole system depends on one inverter [14][6] [2][10]

1.2.2.2. String Inverters

The present technology consists of the string inverters and the modules. The string inverter which is shown in figure 1.2 (b), is a reduced version of the centralized inverter shown in figure 1.2 (a), where a single string of PV modules is connected to the inverter. The input voltage may be high enough to avoid voltage amplification. The possibility of using lesser number of PV modules in series also exists, if a dc–dc converter or line-frequency transformer is used for voltage amplification. There are no losses associated with string diodes and separate MPPT's can be applied to each string. This increases the overall efficiency compared to the centralized inverter, and reduces the price, due to mass production [10].

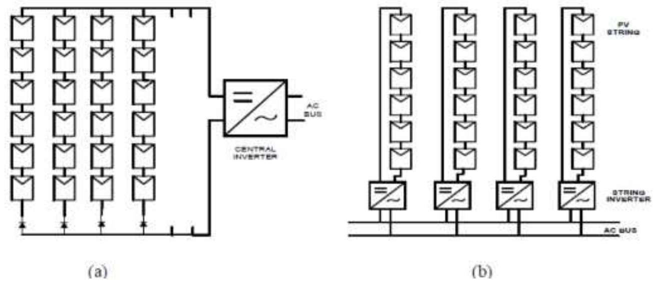

Figure 1.2 (a) central inverter and (b) string inverter

1.2.2.3. Module integrated inverters

A Module integrated has been shown in figure 1.3 (a). It removes the mismatch losses between PV modules since there is only one PV module, as well as supports optimal adjustment between the PV module and the inverter and, hence, the individual MPPT. It includes the possibility of an ease of enlarging the system, due to its modular structure [10]. On the other hand, the necessary high voltage-amplification may reduce the overall efficiency and increase the price per watt, because of more complex circuit topologies. On the other hand, the module integrated inverter is intended to be mass produced which leads to low manufacturing cost and low retail prices. The present solution is to use dc–ac inverters using IGBT or MOSFET [10].

1.2.2.4. Multi-string inverters

Multi-string inverters have recently appeared in the PV market. They are an intermediate solution between String inverters and Module inverters. A Multi-String inverter has been shown in figure 1.3 (b), which has the advantages of both String and Module inverters. It consists of many DC-DC converters with individual MPPT's, which feed energy to a common DC-AC inverter. This way, no matter the nominal data, size, technology, orientation, inclination or weather conditions of the PV string, they can be connected to one common grid connected inverter. The Multi String concept is a flexible solution, having a high overall efficiency of power extraction, due to the fact that each PV string is individually controlled [10].

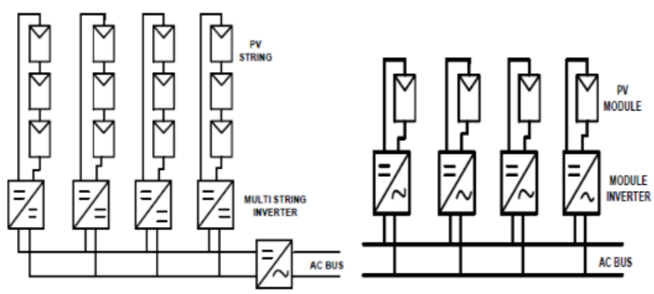

Figure 1.3 (a) Module integrated inverter and (b) string inverter

1.2.2.5. Multi stage inverters

Off late multi stage inverter topology has received attention for power conversion (dc-to-ac). Advantages of the multi stage inverter (MSI) includes

A. The multilevel structures can ensure even voltage sharing, both statically and dynamically, among the active switches while it is difficult for a two-level inverter with a series connection of switches to do so.
B. A substantial reduction in size and volume is possible due to the elimination of the bulky coupling transformers or inductors.
C. Multi stage inverters can offer better line current waveforms with less harmonic content and thus can significantly reduce the size and weight of passive filter components [15][2] [9].

1.3. Maximum power point tracker

Maximum power point tracking techniques are used in photovoltaic systems to maximize the PV array output power by tracking continuously the MPP which depends on panel's temperature and irradiance conditions. PV array under uniform irradiance exhibits a I- V characteristic with a unique point called the maximum power point (MPP), where the array produces maximum output power. Since the I-V characteristic of a PV array and hence its MPP changes as a consequence of the variation of the irradiance level and of the panel's temperature, it is necessary to track continuously the MPP in order to maximize the power output from a PV system, for a given set of operating conditions. MPPT is not a mechanical tracking system that physically moves the modules to make them point more directly at the sun. It is a fully electronic system that varies the electrical operating point of the modules so that the modules are able to deliver maximum available power. MPPT can be used in conjunction with a mechanical sun tracking system, but the two systems are completely different [7]. The issue of maximum power point tracking has been addressed in different ways in the literature. The conventional MPPT methods [10] are generally categorized into the following groups:

A. perturbation and observation (P&O) methods;
B. incremental conductance methods;
C. microcontroller-based methods;
D. miscellaneous.

2. METHODOLOGY

2.1. System Design

Recently, many countries of all over the world have paid a lot of their attention to the development of a renewable energy against depletion of fossil fuels in the coming future. The renewable energy means that the energy density is as high as fossil fuel or higher than that and the clean energy does not emit any polluted substances such as nitrogenous compounds, sulphate compounds, and dust. Hydrogen, as a future energy source, is thought as an alternative of fossil fuels in view of environment and energy security, because hydrogen itself is clean, sustainable, and emission-free. Hence, there are many ongoing active studies on the production and application of hydrogen in our society.

The main method for capturing the sun's energy is the use of photovoltaic. Photovoltaic (PV) utilizes the sun's photons or light to create electricity. PV technologies rely on the photoelectric effect first described by a French physicist Edmund Becquerel in 1839. Solar cells and modules using this PV effect are ideal energy generators that they require no fuel, generate no emissions, have no moving parts, can be made in any size or shape, and rely on a virtually limitless energy source, namely, the sun. The photoelectric effect occurs when a beam of ultraviolet light, composed of photons, strikes one part of a pair of negatively charged metal plates. This causes electrons to be "liberated" from the negatively charged plate. These free electrons are then attracted to the other plate by electrostatic forces. This flowing of electrons is an electrical current. This electron flow can be gathered in the form of direct current (DC). This DC can then be converted into alternating current (AC), which is the primary form of electrical current in electrical power systems that are most commonly used in buildings. PV devices take advantage of the fact that the energy in sunlight will free electrical charge carriers in certain materials when sunlight strikes those materials. This freeing of electrical charge makes it possible to capture light energy as electrical current [1].

In general, photovoltaic (PV) arrays convert sunlight into electricity. DC power generated depends on illumination of solar and environmental temperature which are variable. It is also varied according to the amount of load. Under uniform irradiance and temperature, a PV array exhibits a current-voltage characteristic with a unique point, called maximum power point, where the PV array produces maximum output power. In order to provide the maximum power for load, the maximum-power-point-tracking (MPPT) algorithm is necessary for PV array. Briefly, an MPPT algorithm controls converters to continuously detect the instantaneous maximum power of the PV array [2].

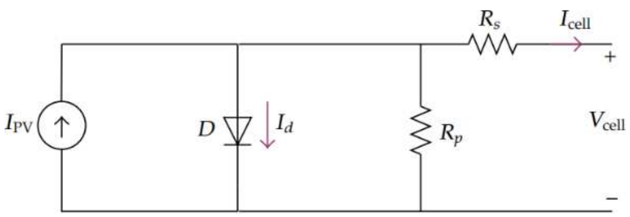

Figure 2.1: Equivalent circuit of PV model.

2.2. PHOTOVOLTAIC MODELLING

A. Ideal PV Cell Model

The equivalent circuit of the ideal PV cell is shown in Figure 2.1. The basic equation from the theory of semiconductors [3] that mathematically describes the I-V characteristic of the ideal PV cell is as follows:

$$I = I_{PV,cell} - I_{0,cell}\left[\exp\left(\frac{qV}{akT}\right) - 1\right] \quad (2.1)$$

$$I_d = I_{0,cell}\left[\exp\left(\frac{qV}{akT}\right) - 1\right] \quad (2.2)$$

where $I_{PV,\,cell}$ is the current generated by the incident light (it is directly proportional to the sun irradiation), I_d is the Shockley diode equation, $I_{0,cell}$ is the reverse saturation or leakage current of the diode, q is the electron charge ($1.60217646 \times 10^{-19}$ C), k is the Boltzmann constant ($1.3806503 \times 10^{-23}$ J/K), T (in Kelvin) is the temperature of the p-n junction, and "a" is the diode ideality constant [4].

B. Modeling the PV Array

Equations (2.1) and (2.2) of the PV cell do not represent the *V-I* characteristic of a practical PV array. Practical arrays are composed of several connected PV cells and the observation of the characteristics at the terminals of the PV array requires the inclusion of additional parameters to the basic equation [3, 4]:

$$I = I_{PV} - I_0\left[\exp\left(\frac{V + R_s I}{V_t a}\right) - 1\right] - \frac{V + R_s I}{R_p} \quad (2.3)$$

where I_{PV} and I_0 are the PV current and saturation currents, respectively, of the array and $V_t = N_s kT/q$ is the thermal voltage of the array with N_s cells connected in series. Cells connected in parallel increase the current and cells connected in series provide greater output voltages. If the array is composed of N_p parallel connections of cells, the PV and saturation currents may be expressed as $I_{PV} = N_p\ I_{PV,cell}$, $I_0 = N_p\ I_{0,cell}$. In (2.3), R_s is the equivalent series resistance of the array and R_p is the equivalent parallel resistance. Equation (2.3) describes the single-diode model presented in Figure 1 [4].

All PV array datasheets bring basically the following information: the nominal open- circuit voltage ($V_{oc,n}$), the nominal short-circuit current ($I_{sc,n}$), the voltage at the MPP (V_{mpp}), the current at the MPP (I_{mpp}), the open-circuit voltage/temperature coefficient (K_V), the short-circuit current/temperature coefficient (K_I), and the maximum experimental peak output power (P_{max}). This information is always provided with reference to the nominal condition or standard test conditions (STCs) of temperature and solar irradiation. Some manufacturers provide *I-V* curves for several irradiation and temperature conditions. These curves make easier the adjustment and the validation of the desired mathematical *I-V* equation. Basically, this is all the information one can get from datasheet of PV arrays [4].

Electric generators are generally classified as current or voltage sources. The practical PV device presents hybrid behavior, which may be of current or voltage source depending on the operating point. The practical PV device has a series resistance R_s whose influence is stronger when the device operates in the voltage source region and a parallel resistance R_p with stronger influence in the current source region of operation. The R_s resistance is the sum of several structural resistances of the device. R_s basically depends on the contact resistance of the metal base with the p semiconductor layer, the resistances of the p and n bodies, the contact resistance of the n layer with the top metal grid, and the resistance of the grid [5]. The R_p resistance exists mainly due to the leakage current of the p-n junction and depends on the fabrication method of the PV cell. The value of R_p is generally high and some authors neglect this resistance to simplify the model. The value of R_s is very low, and sometimes this parameter is neglected too.

The *V-I* characteristic of the PV array, shown in Figure 2.2, depends on the internal characteristics of the device (R_s, R_p) and on external influences such as irradiation level and temperature.

The amount of incident light directly affects the generation of charge carriers and, consequently, the current generated by the device. The light-generated current (I_{PV}) of the elementary cells, without the influence of the series and parallel resistances, is difficult to determine. Datasheets only inform the nominal short-circuit current ($I_{sc,n}$), which is the maximum current available at the terminals of the practical device. The assumption $I_{sc} \approx I_{PV}$ is generally used in the modeling of PV devices because in practical devices the series resistance is low and the parallel resistance is high. The light-generated current of the PV cell depends linearly on the solar irradiation and is also influenced by the temperature according to the following equation (2.4), [2, 4, 6–8]

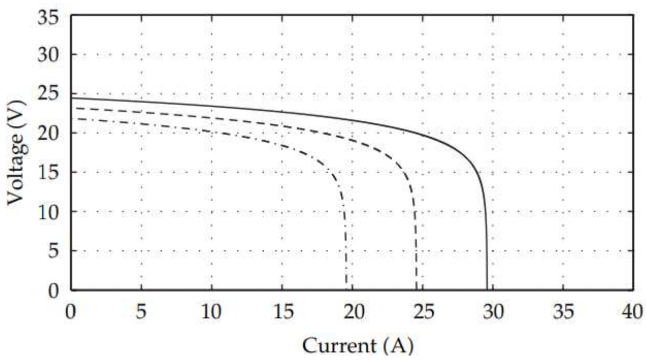

Figure 2.2: V-I characteristic of PV.

$$I_{PV} = \left(I_{PV,n} + K_I \Delta T\right) \frac{G}{G_n} \quad (2.4)$$

where $I_{PV,n}$ (in amperes) is the light-generated current at the nominal condition (usually 25°C and 1000 W/m^2), $\Delta T = T - T_n$ (T and T_n being the actual and nominal temperatures (in Kelvin), resp.), G (watt per square meter) is the irradiation on the device surface, and G_n is the nominal irradiation. $V_{t,n}$ is the thermal voltage of N_s series-connected cells at the nominal temperature T_n.

The saturation current I_0 of the PV cells that compose the device depend on the saturation current density of the semiconductor (J_0, generally given in [A/cm^2]) and on the effective area of the cells. The current density J_0 depends on the intrinsic characteristics of the PV cell, which depend on several physical parameters such as the coefficient of diffusion of electrons in the semiconductor, the lifetime of minority carriers, and the intrinsic carrier density [9]. In this paper the diode saturation current I_0 is approximated by the fixed value (6 mA).

The value of the diode constant "*a*" may be arbitrarily chosen. Many authors discuss ways to estimate the correct value of this constant. Usually, $1 \leq a \leq 1.5$ and the choice depends on other parameters of the *I-V* model. Some values for "*a*" are found in [6] based on empirical analyses. Because "*a*" expresses the degree of ideality of the diode and it is totally empirical, any initial value of "*a*" can be chosen in order to adjust the model. The value of "*a*" can be later modified in order to improve the model fitting, if necessary. This constant affects the curvature of the *V-I* curve and varying *a* can slightly improves the model accuracy [4].

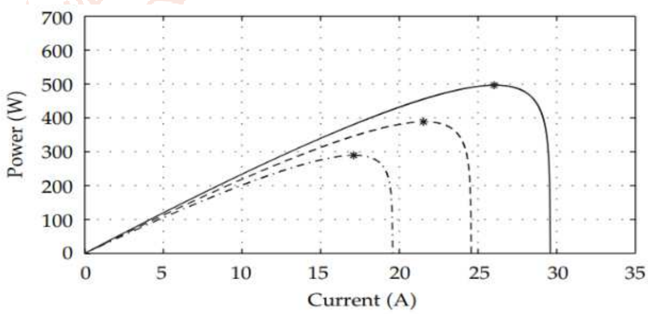

Figure 2.3: P-I characteristic of PV.

2.3. STAND-ALONE SOLAR POWER SYSTEM

The solar PV system consists of a PV module, the dc/dc boost converter, the maximum power point tracking algorithm and the load. Radiation (R) is incident on the PV module. It generates a voltage (V) and current (I) which will be fed into the load [3]. The voltage power characteristic of a photovoltaic (PV) array is nonlinear and time varying because of the changes caused by the atmospheric conditions. When the solar radiation and temperature varies the output power of the PV module also changes. In order to obtain the maximum efficiency of the PV module, it must operate at the maximum point of the PV characteristic. The most extreme power point relies upon the temperature and irradiance which are non-direct in nature. The greatest power point following control framework is utilized and work viability on the non-straight varieties in the parameters, such as temperature and radiations [4]. A MPPT is used for extracting the maximum power from the solar PV module and transferring that power to the load. A dc/dc converter (boost converter) serves the purpose of transferring maximum power from the solar PV module to the load. A dc/dc converter acts as an interface between the load and the module. The dc/dc converter with maximum power point tracking algorithm and the load is shown in Fig. 2.4. By changing the duty cycle, the load impedance as seen by the source is varied and matched at the point of the peak power with the source so as to transfer the maximum power. Therefore, MPPT techniques are needed to maintain the PV array's operating at its MPP [3]. In this paper, two most popular of MPPT technique (Perturb and Observe (P&O) methods and artificial neural network (ANN) methods and dc-dc converter will be involved in comparative study.

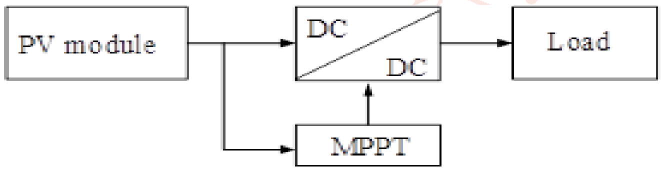

Fig. 2.4 Block Diagram of PV System with MPPT

2.4. MAXIMUM POWER POINT TRACKING

Most extreme Power Point Tracking (MPPT) is helpful apparatus in PV application. Sun oriented radiation and temperature are the primary factor for which the electric power provided by a photovoltaic framework. The voltage at which PV module can create greatest power is called 'most extreme power point (pinnacle control voltage). The primary rule of MPPT is in charge of separating the greatest conceivable power from the photovoltaic and feed it to the heap by means of dc-to-dc converter which steps up/ down the voltage to required size [5]. The operating point of a PV generator is located at the intersection of its current-voltage curve with the load-line. This operating point may be far from the maximum power point (MPP) of the generator wasting a significant part of the available solar power. To achieve optimum matching between the PV generator and the load, an MPP tracker, normally comprised of a simple dc-dc converter, is used. The duty ratio of the converter is controlled by an MPPT algorithm to maximize the power delivered to the load.

A number of different MPPT algorithms have been proposed [1-3], including the P&O algorithm. This simple algorithm does not require previous knowledge of the PV generator characteristics or the measurement of solar intensity and cell temperature and is easy to implement. The algorithm perturbs the operating point by increasing or decreasing a control parameter by a small amount and measures the PV array output power before and after the perturbation. If the power increases, the algorithm continues to perturb the system in the same direction; otherwise the system is perturbed in the opposite direction (Fig. 2.5).

There are two common approaches for implementing the P&O algorithm; reference voltage perturbation [4-10] and direct duty ratio perturbation [5, 7, 11-13]. For reference voltage perturbation, the PV array output voltage reference is used as the control parameter in conjunction with a controller (usually a PI controller) to adjust the duty ratio of the MPPT power converter. The PI controller gains are tuned while operating the system at a constant voltage equal to the standard test condition (STC) value of the MPP voltage. These gains are kept constant while the reference voltage is controlled by the MPPT algorithm. For direct duty ratio perturbation, the duty ratio of the MPPT converter is used directly as the control parameter.

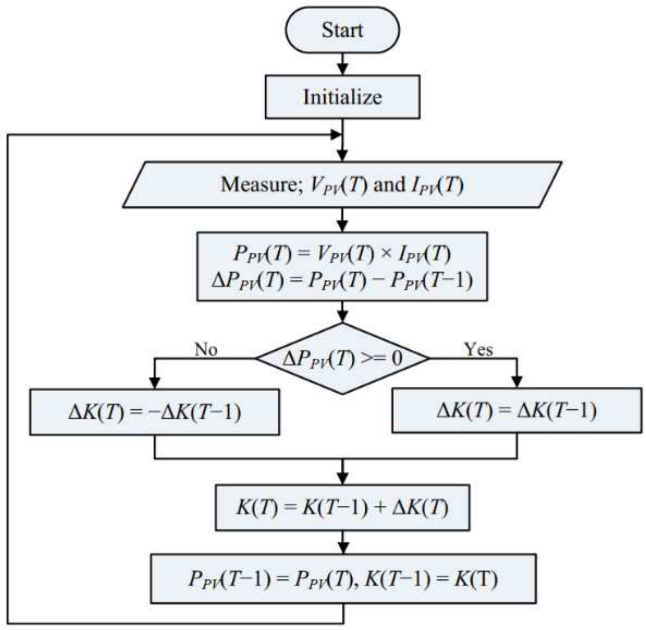

Fig. 2.5 Flowchart of P&O MPPT algorithm

2.5. CASCADE MULTILEVEL INVERTER

Although it is an enabling and already proven technology, multilevel converters present a great deal of challenges and even more importantly, they offer a wide range of possibilities that their research and development is still growing in depth and width. Researchers all over the world are contributing to further improve energy efficiency, reliability, power density, simplicity, and cost of multilevel converters, and broaden their application field as they become more attractive and competitive than classic topologies. Recently, many publications have addressed multilevel converter technology and stressed the growing importance of multilevel converters for high-power applications. By considering all this previous publications an in-depth verification is carried out on cascade multilevel inverter. In the previous chapter evaluation of high power converters are demonstrated. Moreover, concept of multilevel inverters is also introduced. In this chapter an in-depth investigation on cascade multilevel converters is carried out with experimental verifications. Later in Section 2.6 importance of cascade multilevel inverter is studied. Further, section 2.7 studies the applications of CMI. Section 2.8 provides the details of most important switching techniques which are adopted for CMI.

2.6. IMPORTANCE OF CASCADE MULTILEVEL INVERTER

In previous chapter a brief review is done on NPC-MLI, FC-MLI and CHB-MLI. However, on comparing these three commercial topologies of multilevel voltage-source inverters, cascade multilevel inverter reaches the higher output voltage and power levels (13.8 kV, 30 MVA) and the higher reliability due to its modular topology. Cascade multilevel inverters are based on a series connection of several single-phase inverters. This structure is capable of reaching medium output voltage levels using only standard low- voltage mature technology components. Typically, it is necessary to connect three to ten inverters in series to reach the required output voltage. These converters also feature a high modularity degree because each inverter can be seen as a module with similar circuit topology, control structure, and modulation [40]. Therefore, in the case of a fault in one of these modules, it is possible to replace it quickly and easily. Moreover, with an appropriated control strategy, it is possible to bypass the faulty module without stopping the load, bringing an almost continuous overall availability [41]. Numerous publications have been visible in the literature, particularly on this architecture. However, research on cascade multilevel inverter is a hot topic in multilevel based structures. So it's feasible to know the reason behind its significance.

In general inverters are compared in terms of feasibility of their utilization and applications. According to the MIL-HDBK-217F standards, the reliability of a system is indirectly proportional to number of its components, consequently less the components more reliable is the system [32]. Therefore, let's make the component verification of above mentioned inverters, so that it would be clear about the issues like; switching losses, reliability and cost factor. Compared to m-level DC-MLI, FC-MLI uses m-1 capacitors on the dc bus, the CMI uses only (m-1)/2 capacitors for same m-level. Clamping diodes are not required for FCMI and CMC. But balancing capacitors are must for FCMI. But for CMI such balancing – capacitors are completely absent. However, this is summarized in Table 2.1. After comparing CMI with DC-MLI, and FC-MLI, CMI requires least number of components and its dominant advantage is circuit layout with flexibility and outstanding availability due to their intrinsic component redundancy. Due to these features, the cascade multilevel inverter has been recognized as an important alternative for power market.

TABLE 2.1 Comparison of Traditional Multilevel Topologies

Converter Type	DC-MLI	FC-MLI	CMI
Main switching	(m-1)*2	(m-1)*2	(m-1)*2
Main diodes	(m-1)*2	(m-1)*2	(m-1)*2
Clamping diodes	(m-1)* (m-2)	0	0
Balancing capacitors	0	(m-1)* (m-2)/2	0
DC Bus Capacitors	(m-1)	(m-1)	(m-1)/2

2.7. APPLICATIONS OF TRADITIONAL CASCADE MULTILEVEL INVERTER

Although traditional cascade multilevel inverter suffers with separate dc sources but the applications of traditional CMI's are vast. In fact this is the only architectures which have been noticed in every application. Fig.2.6 presents complete details of applications and for the sake of simplicity some of the prominent applications are mentioned below.

2.7.1. Traction

Traction systems need a rectification stage of a high voltage low-frequency ac power from the catenary and a fully controllable inversion stage to feed the traction motors. MMCs have been proposed to be used as an interface between the catenary voltage and low-voltage motor drives. The configuration used in [33] connects a single-phase line of 15 kV/16.7 Hz to three- phase 600 V induction motor drives using an MMC and a medium-frequency transformer. Classical cascade multilevel inverters have also been proposed as a part of a power-quality compensator to reduce harmonics, reactive power, negative sequence, and the volatility of the load [34]. Applications of cascade inverters on electric vehicles have been found in [35], where a back-to-back multilevel cascade topology is proposed, and in [46-47], where a cascade inverter with floating dc link is used as an inductor less boost inverter.

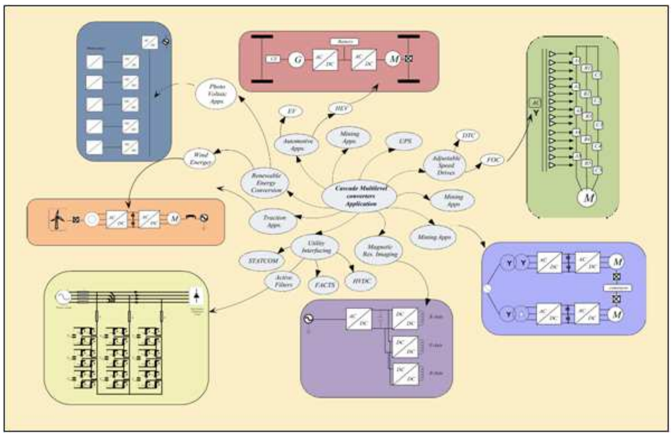

Fig. 2.6 Cascade multilevel converter applications

2.7.2. LNG Plant

The Liquid Natural Gas (LNG) plant presents a cyclic behaviour during the year, monitoring the turbine from the energy station in summer and reversing the power direction in winter when the energy consumption is higher. The use of a compressor directly connected to a gas turbine leads to an efficiency of 25%, due to the low efficiency of the turbine (approximately 30%). In fact combination of synchronous motor and a cascade multilevel regenerative converter, the efficiency has been improved to 36%. Due to the high power involved in this system (45 MW) and the bidirectional power flow, it is necessary to use a high-power converter with regeneration capability [22]. The cascade multilevel inverter emerges as the appropriate choice, considering also its extremely high availability. Cascade inverters can minimize the maintenance effect in the production cycle, increasing the mean time between failures and, at the same time, reducing the maintenance work duration.

2.7.3. Pumps and Fans

Pumps and fans are intensively used in almost all industry sectors. High-voltage high- power pumps and fans are used in water plants, oil and gas plants, cooling systems, geothermal and nuclear power plants, underground mining, furnaces and boilers, and so on. The use of cascade inverters to drive these devices could lead to an important efficiency improvement, because they typically run with variable speed at partial load. The use of variable speed drives, instead of dampers and throttling valves, to control the flow speed can reduce drastically the amount of power required. Fig. 2.5 shows an industrial fan application, where a 1-MW, 13.8-kV induction motor is driven by a converter connected directly to the distribution system. The distance from the drive and the motor is about 800 m. The configuration shown in [50] presents the problem of voltage resonances at the motor terminals due to high-voltage variations over the long cables, requiring an LC filter between the converter and the load. However, if a CHB inverter is used, the voltage variations are greatly reduced, and the filter is also smaller if any.

2.7.4. STATCOM

One of the best suited applications for cascade multilevel inverters is the power quality devices, like STATCOMs and universal power quality conditioners [58]. These devices are connected directly to medium-voltage networks, as shown in Fig.2.6, and do not require the injection of active power in a nominal operating point. To accomplish with the first requirement, it is possible to connect as many inverters as required to reach the operating voltage, without the use of a transformer. The second requirement determines a simplification of the cascade topology, which does not require a rectifier and input transformer stage, significantly reducing its costs. A combination of modulation and control techniques can provide floating and balanced dc voltages [59], [60]. Another alternative shown in [51] is to use photovoltaic cells to provide the floating dc voltages. The mentioned topology requires additionally a maximum power point tracker strategy to optimize the use of photovoltaic cells. However, in this case, it is possible to temporarily inject active power to the load. Additionally, according to recent survey CMI are extensively used in compressors (82%), synchronous motors (92%), converters (98%) and power generation plants (47%), in addition it is best suited for the power quality devices, like STATCOMs and universal power quality conditioners [42 - 43].

Recently, some new topologies of cascade multilevel inverters have also emerged. This includes asymmetric/hybrid cascade circuit topologies, cascade circuit topology with floating dc link, Cascade inverter with variable multilevel dc-link, MMC based cascade modules, Regenerative cascade inverter topologies, high frequency transformer-based power modules and finally low frequency transformer base multilevel inverters [34]. These multilevel inverters can extend rated inverter voltage and power by increasing the number of voltage levels. They can also increase equivalent switching frequency without the increase of actual switching frequency, thus reducing ripple component of inverter output voltage and electromagnetic interference effects. In over all, the application of cascade multilevel inverters (CMI) was prominent for motor drives and utility applications. Thus, the cascade inverter has drawn great interest due to the great demand of medium-voltage high-power inverters.

However, one of the major parts in the CMI operation is switching strategy. Indeed, a perfect switching can improve CMI performance dramatically.

2.8. Modulation Techniques and Control Strategies for Multilevel inverters

As discussion is confide to only cascade multilevel inverters, so switching techniques which are suitable for CMI are mentioned herein. However, in literature numerous modulation techniques have been proposed for cascade multilevel inverters. Some of the prominent switching techniques are demonstrated in Fig.2.7 While, a high number of power electronic devices and switching redundancies bring a higher level of complexity compared with a two-level inverter counterpart. This complexity could be used to add additional capabilities to the modulation technique, namely, reducing the switching frequency, minimizing the common-mode voltage, or balancing the dc voltages. Modulation techniques for cascade multilevel inverters are usually an extension of the two- level modulations [55].

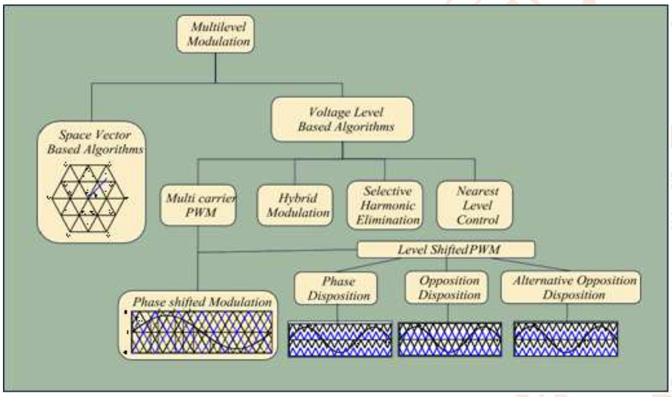

Fig. 2.7 Details of PWM techniques

According to their switching frequency, they can be classified as follows [56]: 1) fundamental switching frequency, where each inverter has only one commutation per cycle, for example, multilevel selective harmonic elimination (SHE), space vector control, and nearest voltage level, and 2) high switching frequency, where each inverter has several commutations per cycle, for example, multilevel PWM and space vector modulation (SVM).

2.8.1. Multilevel SHE

SHE techniques can be applied to cascade multilevel inverters using two approaches. The first one is to consider one commutation angle per inverter; thus, the number of harmonics that can be eliminated is Ninv – 1. The switching pattern of multilevel SHE can be obtained by solving a similar set of equations to two-level SHE [37]. Numeric mathematical methods used to solve these equations are Newton-Raphson, resultant theory [38], and genetic algorithms [39]. The typical waveform obtained by this technique is shown in Fig. 2.7 In these waveforms, it is possible to note that there exists a high difference among the conducting times, which produces an unbalanced power distribution. If a multipulse transformer is used, this power unbalance can lead to a distorted input current. In [36], this effect is reduced by a simple change of conducting angles. This modulation technique can be applied to symmetrical inverters, when the number of output voltage levels is high or when the inverter has unequal dc links [40]. The second approach is to combine the original SHE with the multilevel version [41], as it can be seen in the waveform of Fig. 2.8, where there are a number of switching angles per voltage level. Mostly, in SHE, the Fourier coefficients or harmonic components of the predefined switched waveform with the unknown switching angles are made equal to zero for those undesired harmonics, while the fundamental component is made equal to the desired reference amplitude. This set of equations is solved offline using numerical methods, obtaining a solution for the angles.

However, in all these cases, the number of harmonics eliminated is independent from the number of output voltage levels, and the switching frequency is higher than the fundamental. It is possible to note that there are several different possibilities to synthesize the output voltage, allowing a further optimization in terms of switching frequency. For converters with a higher number of levels, like CHB, SHE is also known as staircase modulation because of the stair-like shape of the voltage waveform. The basic idea is identical to SHE; the difference is that each angle is associated to a particular cell. The operating principle of this technique is to connect each cell of the inverter at specific angles to generate the multilevel output waveform, producing only a minimum of necessary commutations.

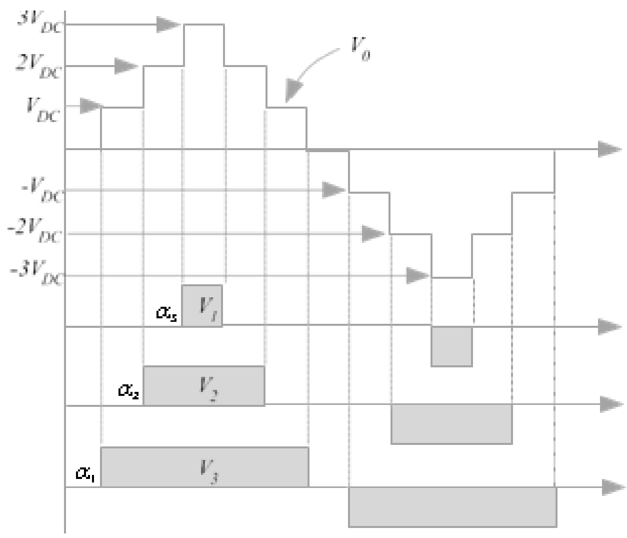

Fig 2.8 One angle per voltage level with multilevel selective harmonic elimination technique

The main advantage, like in SHE, is that the converter switches very few times per cycle, reducing the switching losses to a minimum. In addition, low-order harmonics are eliminated, facilitating the reduction of output filter volume, weight, and cost.

2.8.2. Multilevel SVM

The space vector modulation (SVM) algorithm is basically also a PWM strategy with the difference that the switching times are computed based on the three-phase space vector representation of the reference and the inverter switching states rather than the per-phase in time representation of the reference and the output levels as in previous analyzed methods. However, multilevel converters enclose a large number of vector states which can be used to modulate the reference [52,53]. Moreover, each state vector has a number of redundancies, as shown in Fig. 2.9. Multilevel SVM must take care of this behaviour to optimize the search of the modulating vectors and to apply an appropriate switching sequence [54], [55].

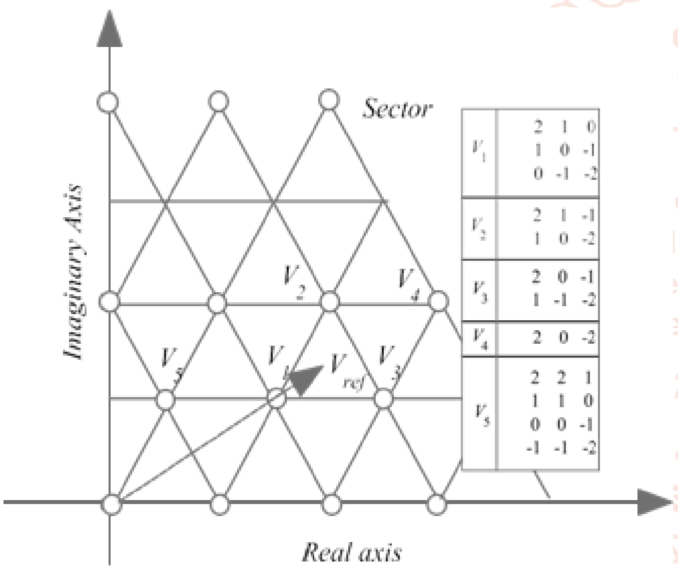

Fig. 2.9 Multilevel Space Vector Modulation

On the other hand, the same properties of state and switching redundancy allow the improvement of the modulation technique to fulfill additional objectives like, reducing the common mode output voltage [54], reducing the effect of over modulation on the output currents [45], improving the voltage spectra and minimizing the switching frequency [46], and controlling the dc-link voltage when floating cells are used [37], [38]. In general, one of the advantages of SVM techniques for multilevel converters is the reduction of computation and implementation complexity compared to carrier-based PWM algorithms because the number of carriers does not increase as the number of converter levels increases. This advantage makes the digital implementation of the algorithms easier. In addition, the vector redundancies and the switching sequences can be used for other control purposes and can be designed according to a specific criterion depending on the application. It has to be noticed that in order to achieve a proper time average, the modulation period Ts is small, leading to high switching frequencies, comparable to carrier-based PWM (above 1 kHz), and therefore not useful for very high-power applications.

2.8.3. Multilevel Carrier-Based PWM

Multilevel carrier-based PWM uses several triangular carrier signals, which can be modified in phase and/or vertical position in order to reduce the output voltage harmonic content. There are two common carrier modifications applied to these multilevel inverters. In fact, Level-shifted PWM is widely noticed in NPC inverters and can also be used in cascade inverters. In [49], it is shown that this modulation technique is applied to a five-level inverter. This modulation technique produces an uneven distribution of power among cells, which further results in high harmonic content in the input current. In [40], this drawback is avoided using a rotating carrier, which balances the power of each cell. In [50], the level- shifted modulation is used inside each CMI inverter and synchronized with the other cells to produce the multilevel output voltage. Phase-shifted PWM is the most commonly used modulation technique for cascade multilevel inverters because it offers an evenly power distribution among cells and it is very easy to implement independently of the number of inverters [51], [52]. This modulation shifts the phase of each carrier in a proper angle to reduce the harmonic content of the output voltage. Moreover, it is possible to work in the over modulation region when a common-mode term is added to the reference.

2.8.4. Phase Shifted (PS-PWM)

Phase-shifted PWM (PSPWM) is a natural extension of traditional PWM techniques, specially conceived for FC [43] and CHB [44] converters. Since each FC cell is a two- level converter, and each CHB cell is a three-level inverter, the traditional bipolar and unipolar PWM techniques can be used, respectively. Due to the modularity of these topologies, each cell can be modulated independently using the same reference signal.

A phase shift is introduced between the carrier signals of contiguous cells, producing a phase-shifted switching pattern between them. In this way, when connected together, a stepped multilevel waveform is originated. It has been demonstrated that the lowest distortion can be achieved when the phase shifts between carriers are 180 or 360°/k for a CHB Inverter. (where k is the number of power cells). This difference is related to the fact that the FC and CHB cells generate two and three levels, respectively.

A Five-level CHB example of the operating principle is illustrated in Fig. 2.9. Since all the cells are controlled with the same reference and same carrier frequency, the switch device usage and the average power handled by each cell is evenly distributed. For the case of the CHB, this means that multipulse diode rectifiers can be used to reduce input current harmonics. It is noticed in the FC, the advantage of the even power distribution is that once the flying capacitors are properly charged (initialized to their corresponding values), no un--balance will be produced due to the self-balancing property of this topology [55], hence there is no need to control the dc-link voltages. Another interesting feature is the fact that the total output voltage has a switching pattern with k times the frequency of the switching pattern of each cell. This multiplicative effect is produced by the phase-shifts of the carriers.

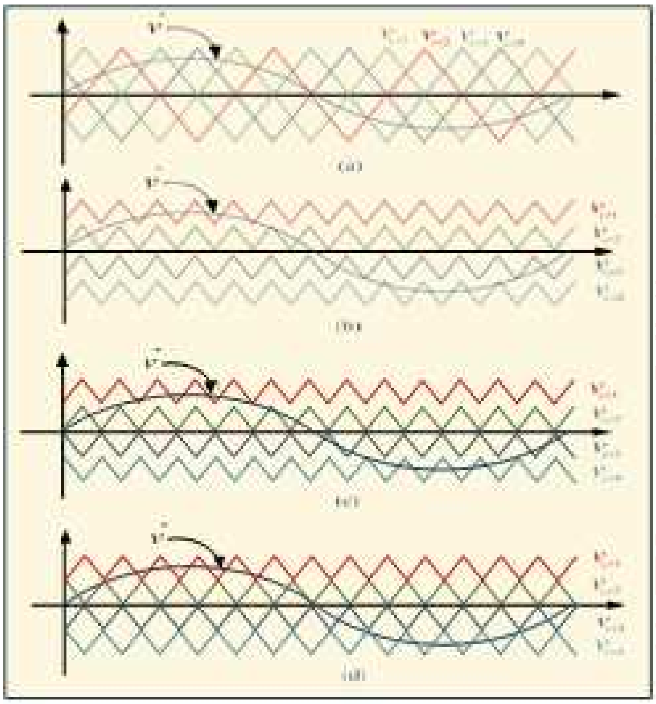

Fig. 2.10 Phase shifted and Level shifted PWM carrier arrangements (a) Phase shifted PWM (b) PD, (c) POD, (d) APOD

Hence, better total harmonic distortion (THD) is obtained at the output, using k times lower frequency carriers.

2.8.5. Level Shifted PWM (LS-PWM)

Level-shifted PWM (LSPWM) is the natural extension of bipolar PWM for multilevel inverters. Bipolar PWM uses one carrier signal that is compared to the reference to decide between two different voltage levels, typically the positive and negative busbars of a VSI. By generalizing this idea, for a multilevel inverter, m−1 carriers are needed. They are arranged in vertical shifts instead of the phase-shift used in PS-PWM. Each carrier is set between two voltage levels; hence the name B level shifted. Since each carrier is associated to two levels, the same principle of bipolar PWM can be applied, taking into account that the control signal has to be directed to the appropriate semiconductors in order to generate the corresponding levels. The carriers span the whole amplitude range that can be generated by the converter. They can be arranged in vertical shifts, with all the signals in phase with each other, called phase disposition (PD-PWM); with all the positive carriers in phase with each other and in opposite phase of the negative carriers, known as phase opposition disposition (POD-PWM); and alternate phase opposition disposition (APOD-PWM), which is obtained by alternating the phase between adjacent carriers [56-57]. An example of these arrangements for a five- level inverter (thus four carriers) is given in Fig. 2.10, respectively.

In brief, rather than level shifted PWM, phase shifted PWM technique has finite merits like, no rotation in switching, less switching losses and easy to implement. Indeed, in present article all productive topologies are implemented with sinusoidal PWM approach. Next sections provide the details of conventional CMI topology and performance verifications and challenging aspects to resolve.

3. SIMULATION RESULTS & ANALYSIS

3.1. Results

To evaluate the performance of the proposed Simulink Model – Dual Diode PV Model with Cascaded T-Bridge Multilevel PV Inverter_ Phase-shifted SPWM (PS-SPWM) switching scheme is then applied to control the switching devices of each T-bridge. and the control system, MATLAB/Simulink software has been utilized. Table 3.1 shows the characteristics of the simulated system.

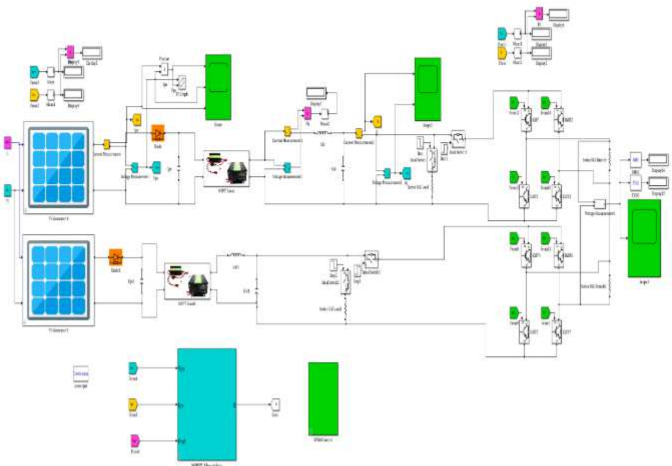

Fig. 3.1 MPPT Algorithms & Cascaded T-bridge 3 Level Inverter

TABLE 3.1: PV PARAMETERS

PV Paramters

Pmax (W)	200	n	1.3417
Isc (A)	8.21	Rs (ohm)	0.2172
Voc (V)	32.9	Rsh (ohm)	951.9317 (951.93)
ki (%/º)	3.18e-3/8.21 (0.00038733)	Ns	3
kv (%/º)	-0.123/32.9 (-0.0037386)	Np	3
Ncs	54		

Figure 3.2 shows Experimental power extracted from PV panels with MPPT_ The harvested solar power waveform of each phase with MPPT Booster Algorithms

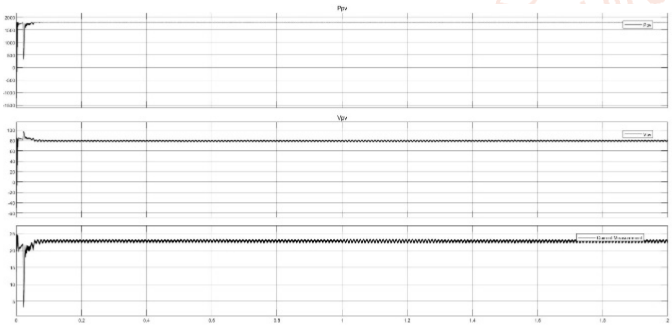

Fig. 3.2 PV Voltage, PV Current & PV Power Vs Time in (S)

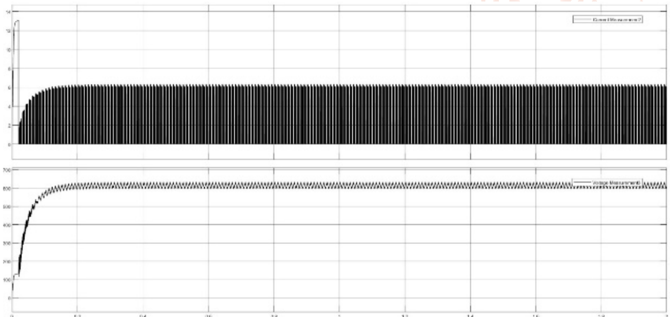

Fig. 3.3 Voltage & Current Vs Time in (S)

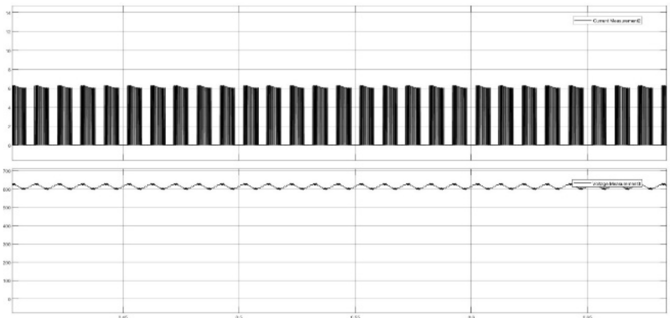

Fig. 3.3.1 Voltage & Current Vs Time in (S)

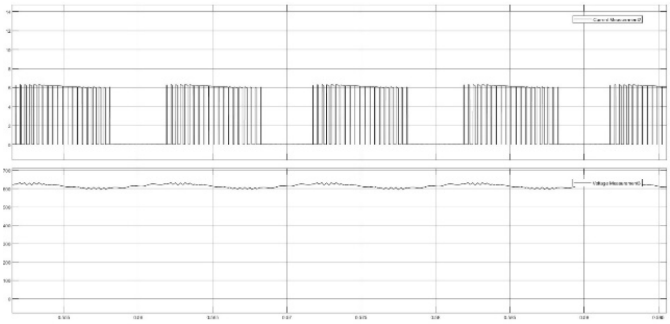

Fig. 3.3.2 Voltage & Current Vs Time in (S)

Figure 3.4 & 3.4.1 Shows Experimental inverter output voltages with modulation compensation _Cascaded T Bridge 3 Level Inverter output Voltage Wave form.

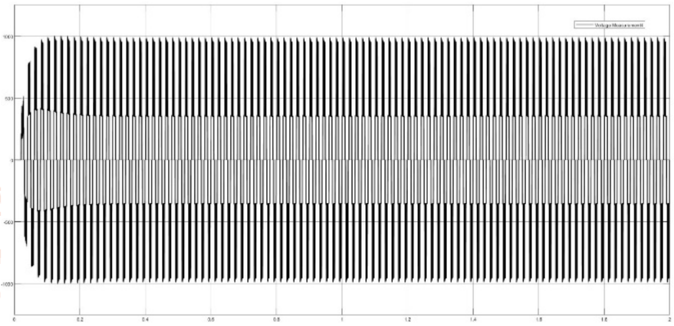

Fig. 3.4 PV Voltage, PV Current & PV Power Vs Time in (S)

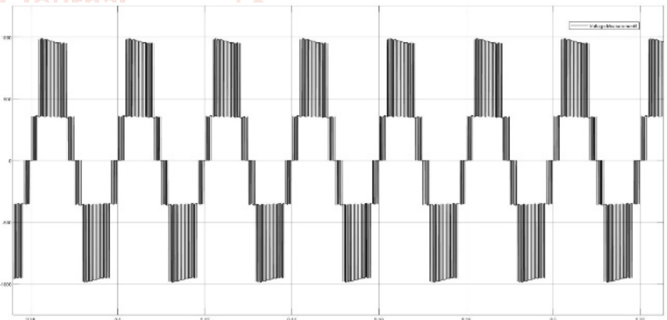

Fig. 3.4.1 PV Voltage, PV Current & PV Power Vs Time in (S)

4. CONCLUSION & FUTURE SCOPE

4.1. Conclusion

Dual Diode Photovoltaic Model Cascaded T-Bridge Multilevel PV Inverter with MPPT Booster Algorithms for Grid-Connected Applications presented in this work show that cascading T-bridge multilevel inverters are the most suitable inverter topologies for grid-connected applications. Three levels of MLI are performed, and a phase-shifted SPWM (PS-SPWM) switching scheme is then applied to control the switching devices of each T-bridge. The control scheme allows for high PV module utilisation and improves the overall efficiency of the PV system. The distorted grid current caused by PV mismatches is solved by modulation compensation without increasing the difficulty of the control system or causing extra power loss. Even though the capacity for balancing grid current is limited, the compensation scheme helps reduce the percentage of unbalanced grid current. And it also helps to avoid overmodulation. Hence, the findings indicate that the CTMLI produces the lowest THD contents and utilises fewer components. Moreover, the PS-SPWM produces less THD than SPWM.

4.2. Future Scope

- In the proposed multilevel inverter expansion for 3-phase applications, total number of transformers in the circuit can be reduced by using of cascaded 3-phase transformer circuit instead of single-phase transformer circuit. In the scheme, total number of switching components in the circuit is still a drawback to achieve lower cost and smaller size of the inverter compared with conventional multilevel inverter. This is a challenging issue and new modifications have to be carried out so as to reduce total switching components.
- The proposed inverter has been operated by only three control schemes, namely Fundamental switching, SHEPWM and sinusoidal PWM. Applying the improved switching techniques can still improve the output quality. So potential of proposed version could be explored by adopting different switching techniques.
- The proposed version of CMI is only adopted for active power filter applications. In fact, the merits of CMI can be used to build for photovoltaic/grid connected systems. So, it can extend to multiple applications like STATCOM, SSSC and UPQC etc.

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