Modular Multilevel *MMI(HB)* Topology for Single-Stage Grid Connected PV Plant

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Keywords - Grid Connected Photovoltaic (PV), Single-stage, Modular Multilevel Inverter (MMI), Half Bridge (HB).

Abstract- A new topology for the single-stage grid connection of Photovoltaic (PV) system is proposed in this paper. PV inverters of various types have been proposed previously. Modular multilevel inverter, MMI(HB) using half-bridge submodules is recent and a potential candidate for PV application. Conventionally, the DC link of MMI has a centralized large DC source e.g. PV system connected across it. In the proposed topology, distributed PV system e.g. PV strings/ arrays are connected directly across dc link of MMI(HB) submodules (SMs). This allows easy expansion, independent monitoring of each PV string voltage and maximum power point optimization. The dynamics of PV generator is different from the conventional power generator, hence, a new combination of MPPT and decoupled dq controller is proposed to maximize the real power output from the PV strings and limit reactive power exchange with the grid as per the system requirements. In order to validate the proposed concept of new single-stage grid connected PV topology and its controller, simulations were conducted. A detailed model of the proposed 1800W, PV system consisting of 36 PV modules connected across a 13 level three phase MMI (HB) was established. The simulation results of new PV system during fast changes in solar irradiation and reactive power exchange has confirmed the feasibility of proposed MMI(HB) interface for single-stage grid connected high voltage, high power PV system and has verified the validity of the control strategy adopted.

I. INTRODUCTION

Globally, there is an environmental concern regarding fossil fuel power generation because of the emissions and green house effect. Renewable energy resources are a viable alternative and important among them is solar power. Photovoltaic (PV) is maintenance free, environmental friendly and has the advantage of being modular, but it is costly requires conditioning for interface [1]. Large PV plants with efficient interface using fewer components will enable cost reduction. Further, grid-connected high voltage, high power PV systems will have a pivotal role in achieving high penetration of renewable energy systems, providing real and reactive power support to meet system requirements and eliminate the need for storage. Large PV plants with capacity exceeding 100MWs have started to materialize. The voltage from PV strings/arrays is still low typically in the range of 1kV which in turn restricts the size of inverter to about 1MW. A PV plant generating hundreds of MW will require large number of similar inverter units for power conditioning. Further, the high capacity PV plants are required to comply with stringent inter-connection regulation at PCC i.e. control real and reactive power flow for frequency and voltage regulation ensuring grid integrity during various contingencies. It will not be an easy task to make a PV installation comprising of such a large numbers of inverters grid compliant at the PCC and to verify their collective response at site [2]. Conventional large centralized VSC inverter lacks modularity, suffers the drawback of poor expandability and higher harmonic levels. In addition conventional inverters require intermediate interface devices such as, dc-dc converters for maximum power point tracking (MPPT) and ac transformers for stepping up voltage which lowers the efficiency by 2-3%. The distorted output voltages generated in renewable system causes transformer core saturation, increased losses and in some cases even failure.

Therefore, research is focused on innovative solutions for the inverter configuration. Consequently, newer arrangements for interfacing PV to the grid have been proposed and evaluated [3][4]. Modular multilevel inverter, MMI(HB) is very promising for the high voltage, high power PV systems because of the requirement of isolated dc sources. Also the fact that the PV systems are modular in nature; PV strings can be easily integrated with modular multilevel inverters. Its advantages such as independent maximum power point tracking for distributed PV strings, transformerless topology, low harmonic content in the output, low PWM carrier frequency and hence reduced losses cannot be disregarded [5][6]. Multilevel topologies are also of interest because of less stressful conditions for semiconductor devices. The multilevel inverter with modularity and low number of components will be the next generation potential interface for grid connected PV system. The HV inverters that use MMI(HB) topology is rapidly increasing[7]. The DC link of conventional MMI has a centralized DC source across it and entire PV system connected across it has been explored previously [8] as well as PV strings using independent dc links in cascaded H-bridge configuration has been reported [9]. But configuration using submodule dc links of MMI(HB) for the connection of distributed PV strings has not been examined so far in PV systems which has the advantage of fewer components. The proposed topology has the advantage of integrating a large number of PV strings/arrays (hundreds) in a single three phase multilevel inverter which is modular in nature and can be easily made grid compliant as shown by the results. The other advantage from the conventional MMI(HB) topology is that no energy transfer from DC link source to submodule capacitor, hence inverter losses shall be lower. This paper discusses the detailed modeling of the new topology of distributed PV system connected to the dc links of submodules (SMs) of a modular 13-level inverter. The simulations were conducted to examine the response to the step changes in the solar irradiance and reactive power levels.

The rest of the paper is organized as follows; section II, *MMI based PV System* introduces the new configuration. Section III

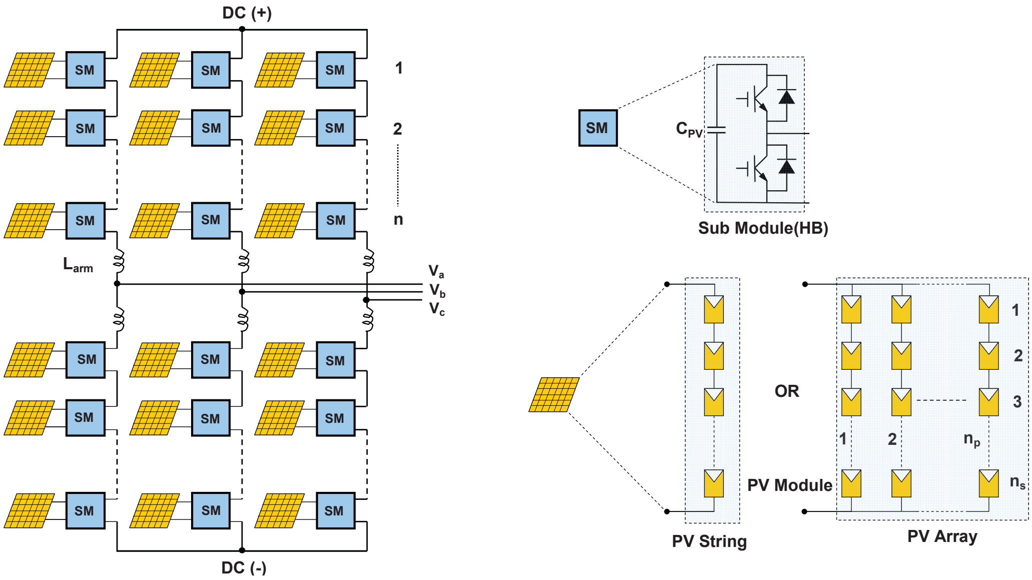


Fig.1. Three Phase Modular Multilevel Inverter (HB) PV System

,*PV System* discusses modeling of PV modules and its operating requirements; Section IV, *PV system* and *inverter Interface* presents the requirement for single-stage inverter for PV system. Section V, *Grid Interface* discusses the requirement for real and reactive power exchange with the grid. Section VI *P_{max} Q controller,* presents the working of the proposed controller for maximum active power transfer, Section VII presents the *Simulation Results* verifying the validity of proposed PV system and Section VIII concludes the paper.

II. MMI BASED PV SYSTEM

A new multilevel topology, modular multilevel converter suitable for voltage source converter (VSC) has recently gained attention in HV applications [10]. Its modular structure allows voltage scaling. In this topology the centre tapped converter arm acts as a controllable voltage source creating an approximate sine wave of adjustable magnitude and phase shift by using a large number of discrete voltage steps. The variable voltage sources are achieved with a number of identical but individually controlled SMs. MMI has better features; improved efficiency, low dv/dt and lower switching device rating resulting from smaller voltage steps. In conventional VSC, semiconductor devices are connected in series to provide the valve with required withstand rating. To ensure uniform steady-state and dynamic voltage distribution, all semiconductors devices connected in series have to turn on/off simultaneously and the parameters of all the devices should be perfectly matched which is not practical, hence elaborate grading circuits are required. In MMI there is no such requirement, switching of SMs in an arm does not take place simultaneously. The configuration of the proposed three phase modular multilevel inverter MMI(HB) PV system is shown in Fig.1. The three phase units of MMI are connected in parallel. Each phase unit consists of an upper and a lower arm made up of '*n*' SMs and an arm inductor L_{arm} connected in series. The mid point of phase unit feeds ac current to the load.

Each SM consists of IGBT based HB and a storage capacitor C_{pv} as shown in Fig.1. By different combinations of the two switches (T_1 & T_2) in each SM, two output voltage levels (*0* and V_c) are generated (Fig.2).

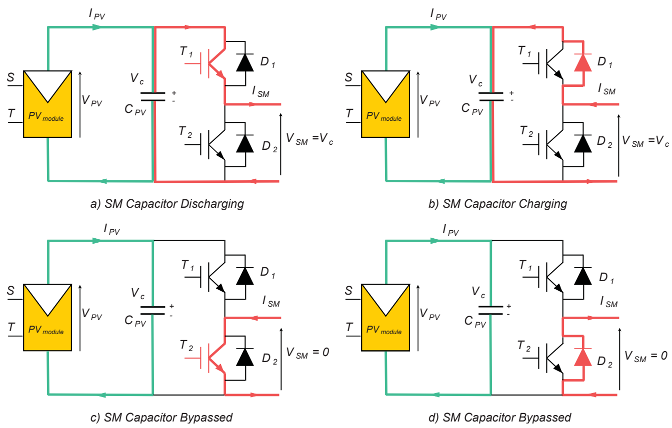


Fig.2. States of HB Submodule

A submodule is considered to be inserted if upper switch T_1 is closed and lower switch T_2 is open, Fig.2(a) and Fig.2(b). If the lower switch T_2 is closed and the upper switch T_1 is opened the submodule is considered to be bypassed, Fig.2(c) and Fig.2(d). The number of SMs inserted in each phase unit is always equal to '*n'*. It can be seen from the Fig.2(a) that during the time T_1 is conducting, the storage capacitor C_{PV} discharges to the inverter ac side and during the time T_2 is open and the diode D_1 conducts, the capacitor C_{PV} is charged by arm circulating currents, Fig.2(b). When T_2 or its antiparallel diode D_2 is conducting the capacitor C_{PV} is bypassed from the inverter ac side whereas it is charged by PV module, Fig.2(c) and Fig.2(d).

The PV (string/array) which is connected across the SM coupling capacitor 'C_{pv}' feeds dc current to the multilevel inverter SM continuously depending on the weather conditions. The configuration can be easily expanded by adding SMs and PV strings in phase units. A modular multilevel inverter with '*n'* SM's/arm synthesizes *(2n+1)* level line voltage waveform. The multilevel voltage waveform enables the reduction of harmonics in the inverter output current. The arm inductors L_{arm} placed in series with the SM's reduces the fault currents. The distinctive characteristic of MMI is that its arm currents are continuous. The inverter arm current comprises of one part that flows out to the load is assumed to be equally shared between the two arms of phase unit and a second part that flows through the whole phase unit which controls the charging and discharging of the storage capacitors in the submodules. However, there are balancing currents which circulate within the individual phase units of MMI due to the inequalities of three generated phase voltages [11]. The circulating current does not affect ac side currents of the inverter and if these are uncontrolled it could increase the required rating of switching devices. In MMI topology there are additional control requirements than a conventional VSC. MMI needs a controller to balance individual SM storage capacitor voltages and elimination of the circulating currents. [12][13][14]

III. PV SYSTEM

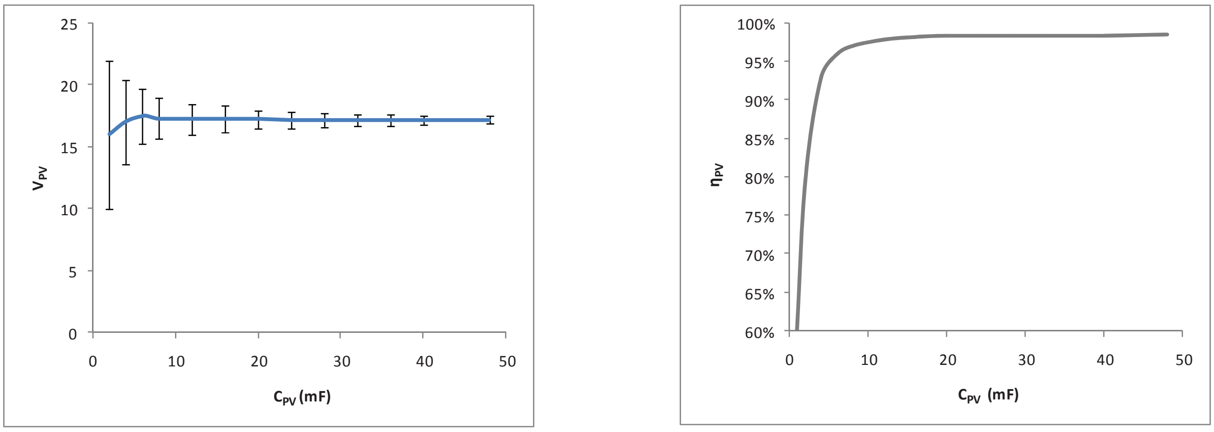
The PV cell is the basic building unit of a PV module. Usually large number of PV cells is combined to form low power PV module. The PV string/array is a matrix of PV modules connected in series and series/parallel combination (Fig.1). If n_p is the number of parallel PV strings in a array and n_s is the number of series connected PV modules in the string, V_c, I_c and P_c are the voltage, current and power output of each PV module, respectively, then their relationship is described as $V_a=n_sV_c$, $I_a=n_pI_c$, $P_a=n_sn_pP_c$. Where V_a, I_a and P_a are the output voltage, current and power of the PV array, respectively. The PV cell equivalent circuit model is expressed in two main types; single diode and double diode model. A simplified single diode mathematical model is generally used for grid-tied systems. In this paper, a single diode model suggested by [15] is used, which if required, can also be used to simulate PV strings/array under conditions of non-uniform irradiance. The input to the digital model of PV module is solar irradiance '*S'* and module temperature '*T'* and the output is voltage V_{PV} and current I_{PV} (Fig.2). PV module power output varies with operating conditions, it generates more power at higher solar irradiation and also when the temperature drops. A change in the temperature of solar panel has an impact on the output voltage of PV module. There is a nonlinear relationship between PV module voltage and its power output. The PV module has a *constant current* and a *constant voltage* operating region. In order to achieve maximum power output, the PV module voltage needs to be controlled. Hence an important requirement in a PV generating system is the means of continuously adjusting the PV module operating voltage so that maximum power output is achieved for any given operating condition. Various maximum power point tracking (MPPT) methods to fulfill this task have been developed and implemented [16]. The incremental conductance method has been used in this paper. V_{ref} is the reference voltage at which the PV module is made to operate by incrementing/decrementing it through a optimum voltage step. At MPP, V_{ref} equals to V_{MPP}. Once the MPP is achieved, the operation of the PV array is maintained at this point unless a change occurs. The incremental step size of voltage determines how fast the MPP is tracked. Separate dc levels in multilevel inverter makes possible independent tracking of each PV string and thus has the possibility of optimizing the output from each PV string.

IV. PV SYSTEM AND INVERTER INTERFACE

Inverters connecting PV systems to the grid have to ensure that the PV strings/arrays operate at MPP and at the same time sinusoidal ac currents are fed into the grid. In the single-stage configuration, inverter has to handle both the above requirements. In the proposed topology, PV strings interfaced to the individual dc links of SMs is by default a single-stage approach. The advantages of single-stage approach are the reduced component count and higher conversion efficiency [17] [18]. There are however drawbacks, any voltage ripple that may appear at the PV module terminals will cause deviation from the MPP, thereby diminishing the utilization of the PV module. In the SM(HB) the varying output voltage reflects back to the PV module and the power extracted from the module is reduced. Hence, storage capacitor which acts as a buffer between PV system and the inverter has to be large enough to decouple the PV module from the SM. For the topology used, the PV module voltage is same as that of SM storage capacitor V_c (Fig.2). The minimum required storage capacitor C_{PV} has to be optimised such that it maintains the advantage of the single-stage approach by avoiding inefficient utilization of the PV source. The utilization efficiency of a PV module indicates the actual power extracted from the PV module from its maximum possible power output. The PV module voltage ripple has a direct relation to the SM storage capacitor size and its nominal voltage. Also, there is a direct relation between the amount of energy that can be stored in the MMI and its power transfer capability. The minimum SM storage capacitance required for the PV module power transfer can be computed from the relationship [19].

$$C_{PV\,\min} = \frac{1}{3n.\varepsilon.(V_C)^2} \cdot \frac{P_S}{k.\omega_N} \cdot \left(1 - \left(\frac{k.\cos\varphi}{2}\right)^2\right)^{\frac{3}{2}}$$

Where P_S is the apparent power output of the inverter, n the number of SM's per arm, $\boldsymbol{\varepsilon}$, the relative voltage ripple, V_C, the average capacitor voltage, k, is modulation index the normalized amplitude of the phase voltage, ω the angular frequency of the output voltage and $cos\varphi$ the displacement factor. However, the optimum value of the storage capacitor



(a) $V_{mean}, \Delta V_C \;\; vs. \;\; C_{PV}$ (b) $\eta_{PV} \;\; vs. \;\; C_{PV}$

Fig.3. Optimization of Storage Capacitor, C_{PV}

required for the PV module was confirmed by carrying out simulations at different SM storage capacitance values. The relationship between ΔV_C, V_{mean} and C_{PV} is plotted and the results are shown in Fig.3(a) for the PV module power output, P_{pv} = 50W. The relationship between utilization efficiency η_{PV} and C_{PV} for the same PV module is plotted and results are shown in Fig.3(b). From the above plots it can be seen that η_{PV} of the PV module is as high as 98% for storage capacitor size of *12mF* and there is not much gain for selecting higher size storage capacitor. The storage capacitance C_{PV} sizing for the single-stage inverter is based on η_{PV} and voltage deviation ΔV_C is not a criterion [20]. The capacitance of *12mF* was selected for the simulations so as to maintain the SM voltage well within the acceptable range.

V. GRID INTERFACE

MMI acts as an interface between the distributed source PV plant and the ac grid. It must extract maximum power from the PV source, convert it to an ac of the required quality and feed it into the grid while controlling the reactive power exchange.

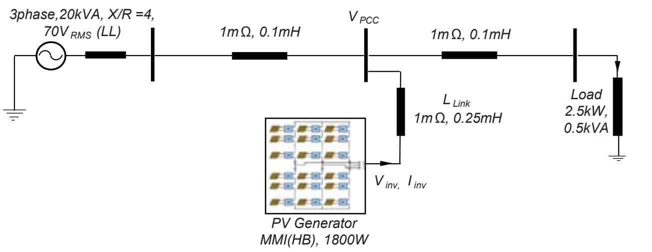


Fig.4. System Representation

The modular multilevel inverter is connected to the grid through a series inductance L_{Link} at the point of common coupling, *PCC* to reduce harmonics in the output current as depicted in Fig.4. The V_{PCC} is the *PCC* phase voltage while the inverter output phase voltage and line current are V_{inv} and I_{inv}, respectively. The real and reactive power exchanged by PV Inverter with ac grid at the point of common coupling is expressed by:

$$P = \frac{V_{PCC}.V_{inv}}{X_{arm} + X_{Link}}.\sin\delta$$

$$Q = \frac{V_{inv}.\cos\delta - V_{PCC}}{X_{arm} + X_{Link}}.V_{PCC}$$

For controlling reactive power exchange the inverter connected to the grid requires that the inverter output current, I_{inv} synchronizes with the fundamental component of the grid phase voltage, V_{PCC} even when the grid voltage is distorted, unbalanced or the grid frequency varies. The PLL helps to extract the fundamental component of V_{PCC}, which is used for determining voltage V_{inv} the inverter has to generate to ensure that the current fed into the grid, I_{inv} is in phase with the fundamental grid voltage V_{PCC} even during abnormal conditions. In this way, the reactive power fed to the grid is controlled. For modeling, all the ac variables are converted to the dc ones so that the active and reactive powers can be decoupled with each other for the ease of control [21]. The instantaneous relationship between the inverter output and grid phase voltages in time domain can be described by the following expression using *abc-dq* axis transformation:

$$v_{inv\_d} = \left(k_p + \frac{k_i}{s}\right)\left(i_d^* - i_{inv\_d}\right) - \omega.L_{Link}.i_{inv\_q} + v_{PCC\_d}$$

$$v_{inv\_q} = \left(k_p + \frac{k_i}{s}\right)\left(i_q^* - i_{inv\_q}\right) + \omega.L_{Link}.i_{inv\_d} + v_{PCC\_q}$$

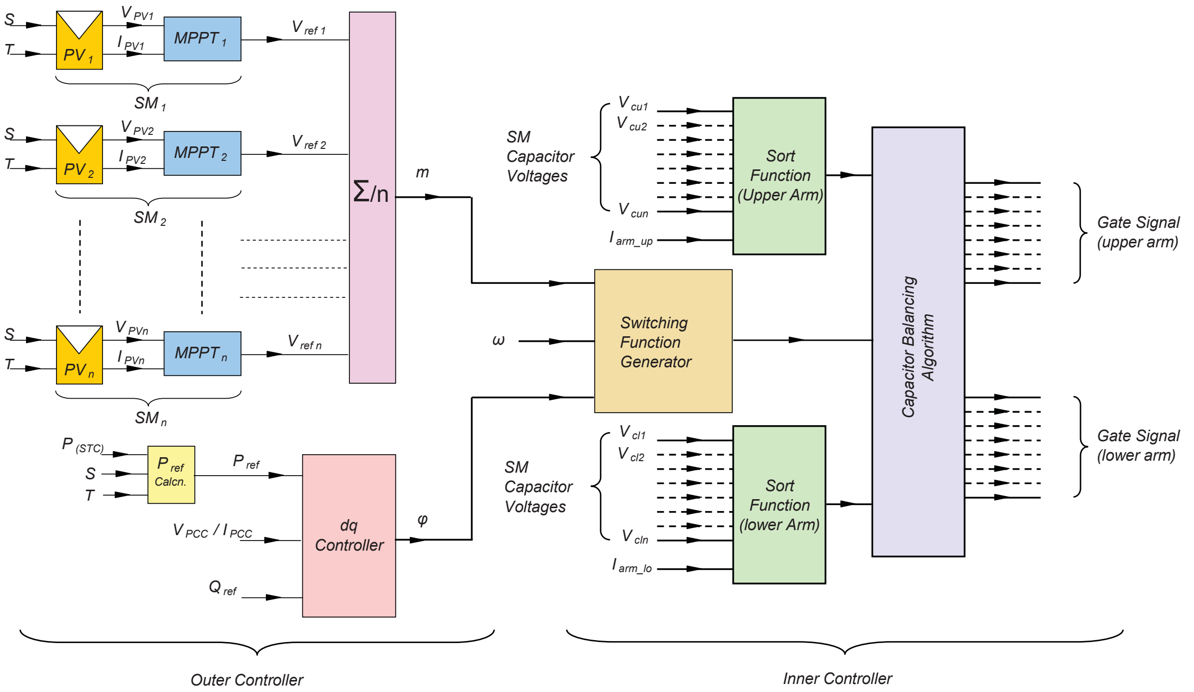


Fig.5. Control Hierarchy

Where v_{inv_d}, v_{inv_q} and i_{inv_d}, i_{inv_q} are the d and q-axis components of three phase inverter output voltages and currents respectively, ω is the fundamental angular frequency v_{PCC_d} and v_{PCC_q} are the are the d and q-axis components of three phase grid voltages at the point of common coupling. The current reference i_d^* and i_q^* are defined in terms of active power reference, p_{ref} and reactive power reference, q_{ref} by the following expressions :

$$p_{ref} = \tfrac{3}{2}\left(v_{PCC\_d}.i_d^* + v_{PCC\_q}.i_q^*\right)$$
$$q_{ref} = \tfrac{3}{2}\left(v_{PCC\_d}.i_q^* - v_{PCC\_q}.i_d^*\right)$$

VI. P_{MAX} Q CONTROLLER

The dynamics of PV generator is different from that of a conventional rotating power generator which needs special consideration. The power output of PV generator has a nonlinear relation with its output voltage. The control hierarchy for the proposed single-stage grid connected PV system is modeled considering two level control configurations, the higher level, *Outer Controller* and the lower level, *Inner Controller*. The function of *Outer Controller* is to regulate the real and reactive power delivered to the grid by the single-stage PV system. It comprises of two controllers – the *dc voltage controller* and the *reactive power controller*. The *dc voltage controller* regulates the real power exchange which is based on MPPT while the *reactive power controller* uses the decoupled *dq* controller for var exchange.

The *dc voltage controller* is used to maximize the real power transfer of distributed PV source depending on the operating conditions (*S, T*). Ideally, its function will be to maintain the dc link voltage of submodules as required by their individual MPPT's. However, the *dc voltage controller* used, normalizes the summation of individual PV module voltage references generated by individual MPPT's (Fig.5) and provides a modulation index *m* for the reference voltage signal which the inverter should generate at its terminals. The *reactive power controller* has a feedback loop which continuously monitors the difference between the measured reactive power *Q* and its set point Q_{ref}. The error is used to generate the output signal *φ* for lower level controls which adjusts phase shift of the reference signal. The *dq* based *reactive power controller* decouples reactive power control from the active power in the link. The input to the *dq* controller is Q_{ref} and the P_{max} which is the maximum power available from PV source. P_{max} is decided based on the operating condition (*S* and *T)* for the PV source at any instant. The phase locked loop (*dq* controller) detects the grid phase voltage, V_{PCC} for *dq* axis coordinated transformation. And with the help of PLL the frequency and phase angle of the inverter output current I_{inv} can be kept same as that of grid voltage V_{PCC}. The control signals *φ* and *m* are used by lower level controller to generate the appropriate inverter switching pattern so that desired output is maintained. (Fig.5)

The *Inner Controller* function is to generate gate pulse for various SM switches and balancing of the voltage distribution across SM storage capacitors in the various arms of the phase units. In MMI to synthesize a multilevel voltage with the fundamental component as per the reference, the required SM gating signals are generated by pulse width modulation (PWM) technique. There are two main categories of multicarrier PWM technique, carrier disposition method wherein the carrier signals are shifted in magnitude and the sub-harmonic method where carrier signals are shifted in phase [22]. Carrier disposition PWM has been widely used in multilevel modulation and Phase disposition (PD) carrier strategy was used to generate SM gating signals. In this *(2n+1)level* MMI needs *n* triangular carriers at the multiple frequency of the fundamental and the amplitude is adjusted within -1 to 1. The reference signal generated by the *inner controller* is a sinusoidal wave of grid frequency whose peak is decided by modulation index m and phase by φ which is then compared to these shifted triangular waveforms and generates stepped phase voltage. Based on the voltage level the number of submodules to be inserted or bypassed in the upper and lower arm is decided. This number is generated by the switching function generator (Fig.5). However, the insertion and bypassing of submodules is done in such a way that capacitor voltage remains close to their nominal values by a robust capacitor voltage balancing strategy. Many capacitor voltage balancing strategies have been proposed since the introduction of MMI. In the present control strategy the capacitor balancing is achieved by sending periodic feedback signals of the individual SM capacitor voltages V_C to a control unit Sort Function (Fig.5) where these are sorted based on voltages in ascending or descending order. SMs in upper/lower arm are selectively inserted/bypassed based on their storage capacitor voltage and the arm current flow direction [13].

VII. SIMULATION RESULTS

A *1800W* single-stage distributed PV plant comprising of *36nos.* of PV modules of *50W* each is taken as a case study for detailed modeling as shown in Fig.1, wherein $n=6$. The PV generator is connected to the grid at PCC (Fig.4). The grid has connected load of *2500W, 500Var* at $70V_{rm\ L\text{-}L}$. It is assumed that all PV modules (*36nos.*) have the same operating conditions i.e. uniform irradiance (S) and temperature (T) and initially for all simulations, irradiance as $1000W/m^2$ and module temperature as 25^0C is assumed. The results of the simulations conducted are shown in Figs.6 to 9. Each figure shows waveforms in the following order, the irradiance level (S), grid phase voltage (v_{PCC_a}), inverter line current ($i_{inv\text{-}a}$), real power (P) and reactive power (Q) injected at PCC in the grid, PV module power output at SM level and lastly the SM capacitor voltage (V_C). Simulation results shown in the Fig.6 is for a step increase in solar irradiance from the initial level of $1000W/m^2$ to $1500W/m^2$ at time *0.4sec* and then restored back to the initial value at *0.8sec*. The *dc voltage controller* has increased the PV panel power output and simultaneously the *reactive power controller* restricts the reactive power flow to zero as desired. The graph shows that the mean capacitor voltage V_{mean} remains the same. The capacitor voltage variation ΔV_C remains within a band at the nominal PV module power output ($S=1000W/m^2$ and $T=25^0C$). However the capacitor voltage variation ΔV_C increases marginally when the power output of PV module increases at $S=1500W/m^2$ as the capacitor size is optimized for nominal power. Similarly, the Fig.7 is for the simulation results for step reduction in the irradiance level from $1000W/m^2$ to $500W/m^2$. The power output of the inverter drops at *0.4sec* which is restored to the initial level at *0.8sec*. The reactive power exchange has been restricted to zero by the controller. The results show that the mean capacitor voltage V_{mean} remains the same. The above results show that MPPT tracks the new maximum power point and maintains stable current output when the irradiance changes in step. It can be noticed that a sudden increase in the irradiance is not causing voltage rise at the point of common coupling (PCC). The reactive power reference is set to zero although it can be controlled at different values, if required. The power processed by PV module of *phase 'a'* of inverter is illustrated and the effect of MPPT on step change in solar irradiance is seen. The MMI(HB) can be used for generation/absorption of reactive power at inverter's full capacity when PV arrays are not generating any real power at night or on a overcast day. The reactive power support or voltage regulation potential of PV inverter could greatly benefit power system stability. Accordingly, simulations were carried out at *nil* solar irradiance, the reactive power exchange was increased to $\pm1500Var$. The results are shown in the Fig. 8 and 9. Initially the PV generator was operated at zero reactive power exchange at *0.4sec* there is a step reduction in irradiance level of $1000W/m^2$ and simultaneously the reactive power exchange is increased to $\pm1500Var$ and at 0.8sec the initial conditions were restored. From the SM voltage plot in Fig. 8 and 9 it can be seen that mean storage capacitor voltage is higher than the nominal mean value when the inverter is consuming reactive power hence higher energy storage is required and mean storage capacitor voltage is lower than the nominal mean value when inverter is generating reactive power and lower energy storage is required.

VIII. CONCLUSION

In this paper a modular multilevel HB inverter has been proposed as feasible alternative topology for a single-stage high voltage, high power grid connected PV application. The inverter features several advantages such as generation of high quality waveform, the capacity to operate a low switching frequency and the modularity concept. The results confirm the suitability of multilevel converter MMI(HB) interface for renewable power plants using solar energy. Multi-MW range PV plants will demand large number of inverters and two level VSC topologies will not be able to fulfill the quality and efficiency requirements. These large number of PV inverters running in parallel will have difficulty in complying with the stringent grid requirements. The need for step-up transformers for the conventional inverters reduces the performance ratio of the PV plant. The modular multilevel topology will be best suited for large utility PV generation which will reduce the requirement of power conditioning inverter to just a unitary one and at the same time maintain the modularity of PV plant. It will provide better harmonic spectra, facilitate low filtering requirements, low losses and eliminate heavy interconnecting transformer. The proposed new topology for high voltage, high power PV plant based on MMI(HB) can be easily integrated with the grid to ensure compliance to the system requirements.

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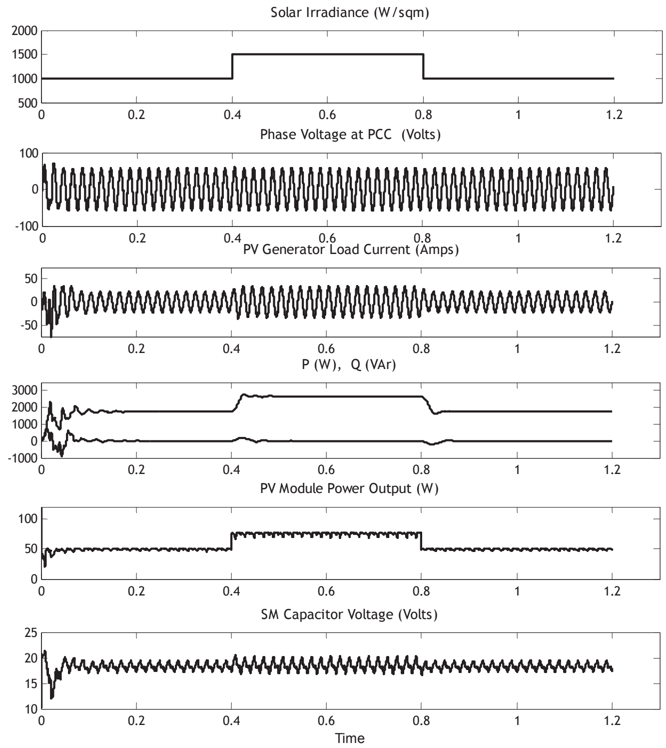

Fig.6. Simulation showing the effect of a step increase in solar irradiance at 0.4sec.

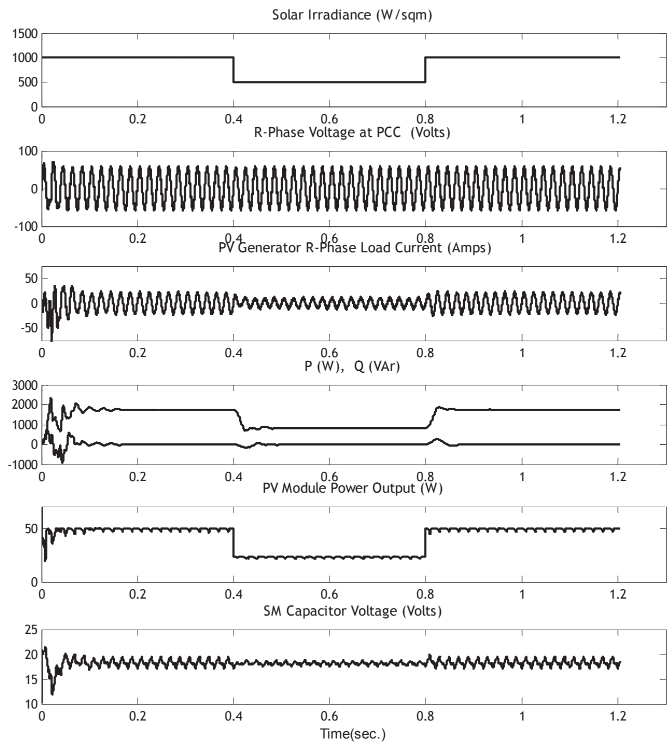

Fig.7. Simulation showing the effect of a step decrease in solar irradiance at 0.4sec.

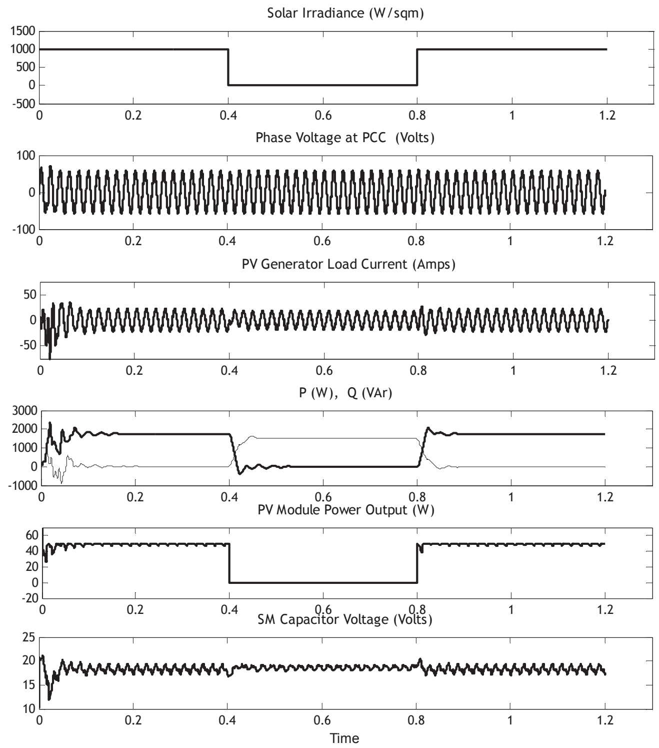

Fig.8. Simulation showing the step decrease in solar irradiance (-1000W/m^2) and increase in absorption of vars (0 to 1500) at 0.4sec.

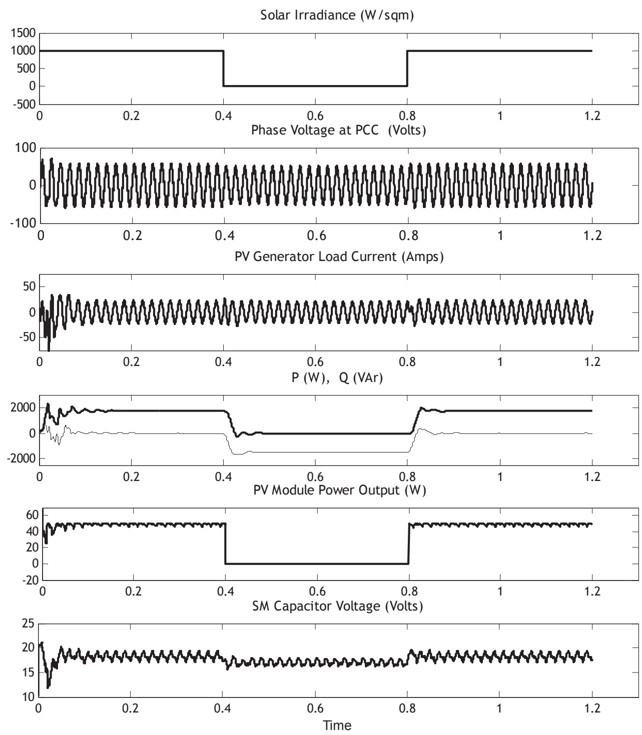

Fig.9. Simulation showing the step decrease in solar irradiance (-1000W/m^2) and increase in generation of vars (0 to 1500) at 0.4sec.