Hybrid Modular Multilevel Converter Based Single-Phase Grid Connected Photovoltaic System

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Abstract- This paper presents a new single-phase Hybrid Modular Multilevel Converter (HMMC) topology with reduced number of sub-modules and its application in grid integration of Photovoltaic (PV) systems. This HMMC has reduced switch counts as compared to other existing multilevel topologies and so has potential advantages like reduction in converter losses and size, high efficiency, fewer circuit complexities, and the cost. The modified ripple correlation control (RCC) based maximum power point tracking (MPPT) is used to extract maximum power from the PV systems. A control strategy has been proposed for the control of the injected active and reactive power to the grid. The overall system has been simulated using MATLAB/Simulink platform, and the results are presented to support the theoretical concepts about HMMC with the control scheme proposed for the specific application.

Keywords Multilevel topology; modular multilevel converter; maximum power point tracking; photovoltaic system; single-phase grid integration.

1. Introduction

The interest on grid connection of renewable energy sources (RES) is increasing as the depletion of the conventional energy sources like oil and gas. As RES are freely, abundantly available and also pollution free, researchers across the world are trying to make these as alternate energy sources to tackle the forth-coming energy crisis. In last decade, there is a steep increase in installation of solar photovoltaic (PV) systems. In addition, the grid connected PV systems are of main concern of researchers. The primary goal of these systems is to extract maximum power from the PV panels and put this power into the grid through a power conditioning system (PCS). These PCS are actually power electronics based converters, which has to be more efficient, highly reliable, and the price should be low as the PV panel cost is reducing gradually. Therefore, many research works have been published in this domain in recent years. Currently, the state of the art technology is two-level multi string converter. This system has two stage conversion systems, DC-DC and then DC-AC having advantages like high scalability and high efficiency, but has high harmonic distortion and large size of the grid side filter [3].

In recent years multilevel converters have taken the interest of researchers in the application of grid integration of renewable energy sources. As compared to conventional two-level converters, they offer less total harmonic distortion (THD), higher efficiency and lower voltage stress to the switches. Various multilevel topologies have been proposed, such as neutral point clamped (NPC), cascaded H-bridge (CHB), modular multilevel converter (MMC) etc. Each has their own merits and demerits. It is very complicated to build NPC for voltage levels higher than five, as more will be levels so more will be clamping diodes and it is very difficult to control the dc-link capacitor voltage imbalance. Next developed simpler topology CHB has also a drawback like, it operates with isolated dc voltage sources which create difficulties in making voltages balanced. Therefore, the volume as well as the cost increases. Then the development of multilevel topologies brought modularity in the structure named as Modular Multilevel Converters (MMC) [1]. It has various advantages over other multi-level topologies, such as the modular design with sub-modules, scalability for ease in increasing the levels, less complicated design, etc [2]. The conventional single phase MMC is shown in Fig. 1 (a). It requires two voltage sources and 2N half bridge submodules (SM) for N level output voltage. This paper presents a new modified MMC topology as shown in Fig. 1 (b), where only one dc source can be used for producing both half-cycle of the voltage and need the half number of submodules and less number of switches.

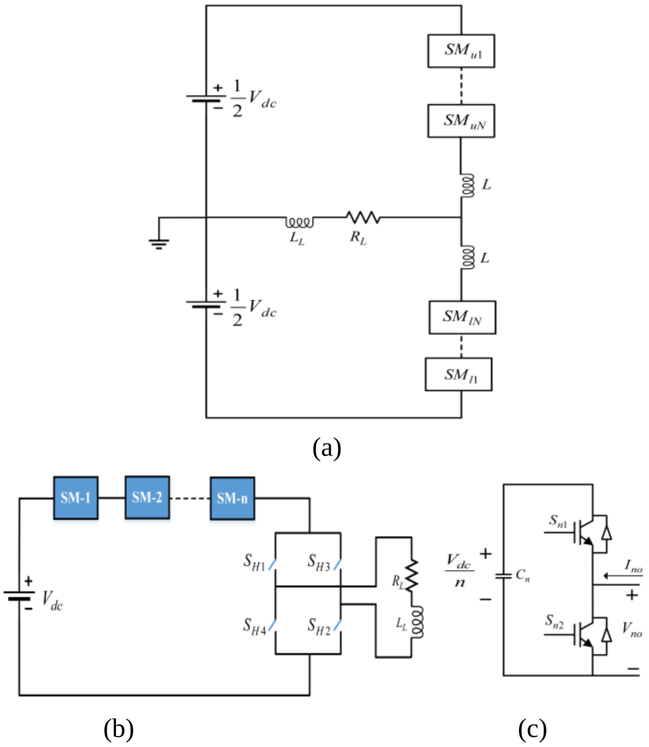

Fig. 1. Schematics of (a) Conventional single-phase MMC topology, (b) Hybrid MMC topology, (c) Half-bridge Sub-Module (SM)

The operation of HMMC and its application in grid integration of PV system with a suitable control scheme is presented in this paper. The overall system of application is shown in Fig. 2. The modified ripple correlation control (RCC) based MPPT is used to extract the maximum power from the PV system.

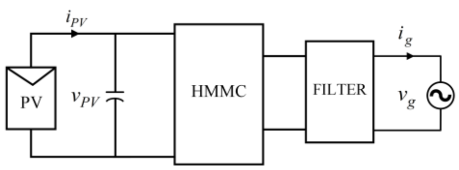

Fig. 2. Overall grid connected PV system

2. Topology Description and Control Scheme

The proposed HMMC topology as shown in Fig. 1 (b) is consists of N number of submodules and a H-bridge circuit across the load. In conventional MMC topology as shown in Figure 1(a) there are the equal number of upper arm and lower arm sub-modules, whereas in this HMMC only upper arm sum-modules are used to generate the N-level output voltage. The H-bridge circuit is the main part of this design, where it is used for the reversal of the load current as shown in Figure 1 (b). Also in comparison to the MMC, only one dc source is needed for generation of both positive and negative half cycle. The half bridge sub-modules are used as shown in Figure 1 (c). A comparative analysis of the number of submodules and switches between MMC and HMMC is presented in Table 1.

Table 1. Comparison between conventional MMC and HMMC

	MMC	HMMC
Number of sub-modules	$2N$	N
Number of switches	$2\times 2N$	$2N+4$
Number of Voltage Sources	2	1

2.1 Principle of operation

A seven level HMMC topology has been studied and implemented in this paper, where three submodules are needed along with H-bridge. The submodule switches are switched by phase-shifted carrier pulse width modulation (PS-PWM) scheme and the switches of H-bridge are switched at line frequency. Table 2 shows the switching sequences for different voltage levels.

The switching scheme for the switches of the sub-modules are done by using PS-PWM which has shown in Fig. 3.

Table 2. Switching sequence of seven-level HMMC

	S_{11}	S_{12}	S_{21}	S_{22}	S_{31}	S_{32}	S_{H1}	S_{H2}	S_{H3}	S_{H4}
$+V_{dc}$	0	1	0	1	0	1	1	1	0	0
$+2V_{dc}/3$	1	0	0	1	0	1	1	1	0	0
$+V_{dc}/3$	1	0	1	0	0	1	1	1	0	0
0	1	0	1	0	1	0	0	0	0	0
$-V_{dc}/3$	1	0	1	0	0	1	0	0	1	1
$-2V_{dc}/3$	1	0	0	1	0	1	0	0	1	1
$-V_{dc}$	0	1	0	1	0	1	0	0	1	1

Here the triangular carrier signals are phase shifted by $\frac{(N-1)f_c}{N}$ times for N submodules. The absolute value of the sinusoidal reference voltage v_{ref} has been taken as the reference signal for the comparison with the carrier signals v_{crn}. The condition for pulse generation for the SM switches is as follows

$$S_{n1} = \begin{cases} 1 & v_{ref} > v_{cr} \\ 0 & v_{ref} < v_{cr} \end{cases} \qquad (1)$$

And for the H-bridge switches

$$S_{H1}\,\&\,S_{H2} = \begin{cases} 1 & v_{ref} > 0 \\ 0 & v_{ref} < 0 \end{cases},\; S_{H3}\,\&\,S_{H4} = \begin{cases} 0 & v_{ref} > 0 \\ 1 & v_{ref} < 0 \end{cases} \qquad (2)$$

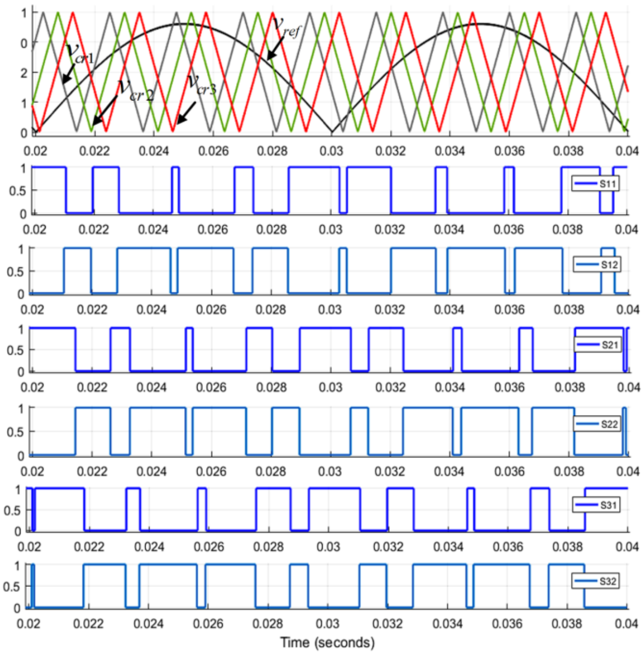

Fig. 3. Phase shifted PWM switching scheme

The detailed PWM scheme is shown in Fig. 3 for seven level output voltages.

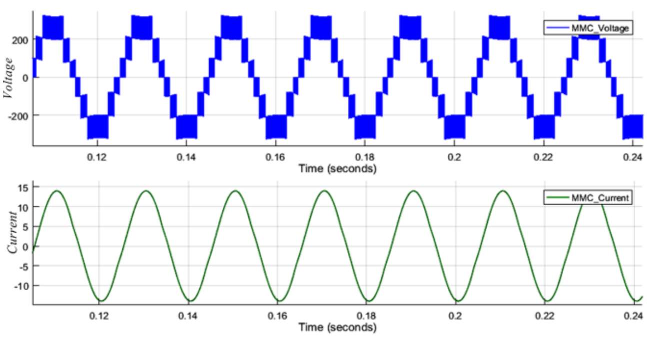

Fig. 4. Output voltage and current waveform of HMMC

The output voltage and current waveforms for input voltage $V_{in} = 340volts$ with load $R_L = 20\Omega$ and $L_L = 5mH$ is shown in Fig. 4. In this case The total harmonic distortion of the output current and the output voltage of the HMMC are 2.76% and 24% respectively. It is same as in case of the convensional MMC topology with same load condition. And more will be the levels in output voltage the less will be the THD.

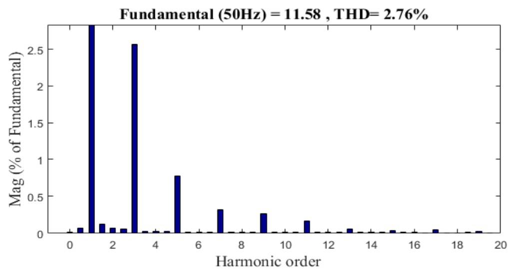

Fig. 5. Total harmonic distiortion (THD) of output current of HMMC

2.2 *Modified RCC MPPT*

The PV module has a characteristic to supply double frequency voltage $\tilde{p}(t) = \bar{v}(t).\tilde{i}(t) + \tilde{v}(t).\bar{i}(t) + \tilde{v}(t).\tilde{i}(t)$ and current i_{PV}. So the DC-link voltage and current also have inherent harmonic components in them.

The ripple content of any general time-varying signal $x(t)$ can be expressed as

$$x(t) = \tilde{x}(t) + \bar{x}(t) \qquad (3)$$

Where $\tilde{x}(t)$ represents the ripple content and $\bar{x}(t)$ represents the moving average component. As the PV array current and power contains ripple, these can also be represented as same as $x(t)$.

Using equation (1), the power of the PV panel can be expressed as

$$p(t) = v(t).i(t) = \bar{v}(t).\bar{i}(t) + \bar{v}(t).\tilde{i}(t) + \tilde{v}(t).\bar{i}(t) + \tilde{v}(t).\tilde{i}(t) \quad (4)$$

The expression having only ripple content is

$$\tilde{p}(t) = \bar{v}(t).\tilde{i}(t) + \tilde{v}(t).\bar{i}(t) + \tilde{v}(t).\tilde{i}(t) \qquad (5)$$

The product of $\tilde{p}(t)$ and $\tilde{v}(t)$ is expressed as

$$\tilde{p}(t)\tilde{v}(t) = \tilde{v}^2(t)\left[\bar{i}(t) + \bar{v}(t).\frac{\tilde{i}(t)}{\tilde{v}(t)}\right] + \tilde{v}^2(t).\tilde{i}(t) \qquad (6)$$

Finally the $\tilde{p}(t)\tilde{v}(t)$ can be expressed after linearizing as

$$\tilde{p}(t)\tilde{v}(t) = \tilde{v}^2(t)\left[\frac{dp(t)}{dv(t)}\right] + \tilde{v}^2(t).\tilde{i}(t) \qquad (7)$$

The average value of $\tilde{p}(t)\tilde{v}(t)$ can be termed as the magnitude of error signal $e(t)$, where the average value of $\tilde{v}^2(t).\tilde{i}(t)$ over a cycle is zero. So this relation $\tilde{p}(t)\tilde{v}(t)$ is directly proportional to the magnitude of dp/dv, and can be represented as the distance of the operating point from maximum power point (MPP). As the average value of error signal represents the distance of the operating point from MPP, the operatig point can be controller by passing the average error signal through a PI controller. The detailed information regarding this MPPT scheme can be found at [6]. Fig. 6 shows the implementation of this scheme.

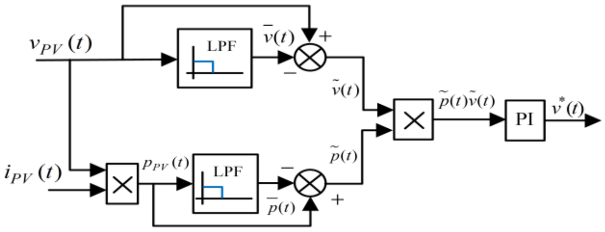

Fig. 6. Modified RCC MPPT controller

2.3 Proposed Control System

Figure 6. shows the overall control scheme for the HMMC based grid-connected PV system. The control loop utilizes the grid frequency generated through phase locked loop (PLL) block. The PV parameters are sensed for ensuring the operating point near to the maximum power point by MPPT scheme. The reference DC-link voltage is generated is compared with the actual sensed voltage and the error is passed through a PI controller. Then with the help of sensed PV current i_{PV}, a power reference P_{ref} is calculated. This scheme has both active and reactive power control loops as shown in Fig. 7. Then finally the v_{ref} is calculated for the pulse generation.

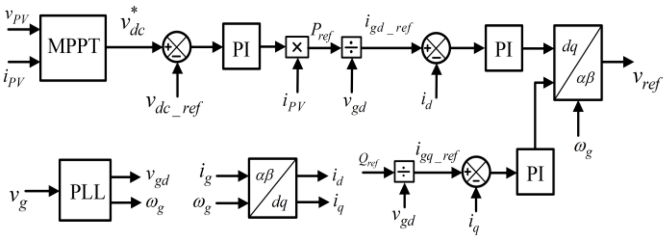

Fig. 7. Proposed voltage and current control scheme for the HMMC based grid connected PV system

3. Simulation Results

To verify the above theoretical concepts of the proposed control scheme, the simulation was carried out in MATLAB/SIMULINK. The parameters are shown in Table 3. The Suntech power STP250 PV module has been selected and 1 string of 10 modules are used. So the PV panel of rating 2.5 kW is used to feed the grid through seven-level HMMC. The irradiance profile changes from $500\,W/m^2$ to $1000\,W/m^2$ at 0.4 sec as shown in Fig. 8. The grid is maintained at rms voltage of 230 volts.

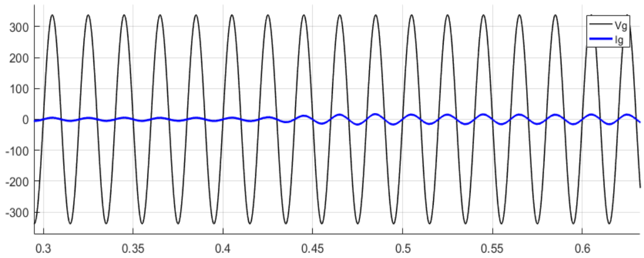

Fig. 8. Simulation results for step change in irradiation at 0.4 sec

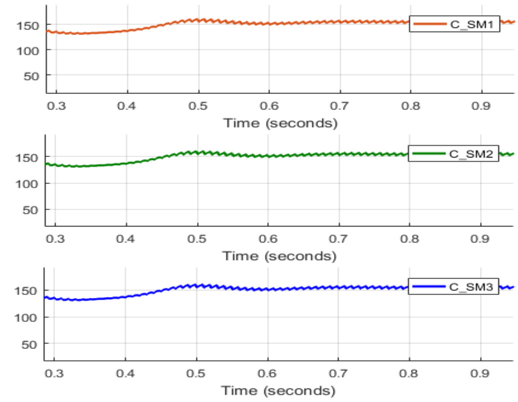

Fig. 9. Voltages across sub-module capacitors

The voltages across each sub-module capacitors of HMMC are shown in Fig. 9. The active and reactive power are controlled by adjusting the active current component i_{gd_ref} and reactive current component i_{gq_ref} respectively. The Fig. 10 shows the result for injected reactive power at +500 $Vars$ and Fig. 111 shows the at -500 $Vars$ respectively. The design parameter of the whole system is provided in Table 3.

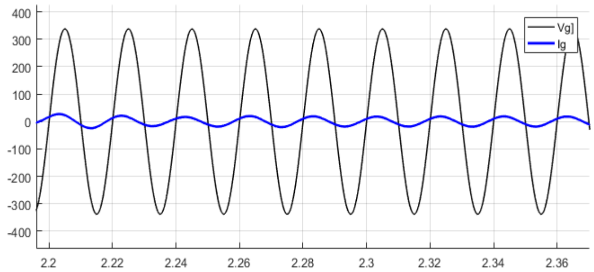

Fig. 10. Results of supplying +500 $Vars$ of reactive power

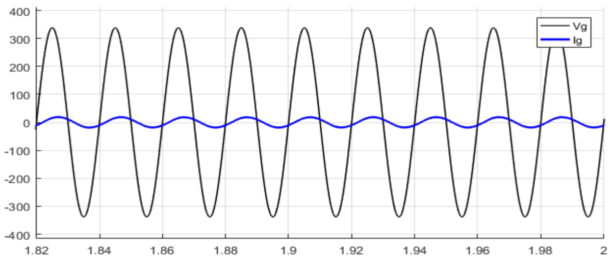

Fig. 11. Results of supplying -500 Vars of reactive power

4. Conclusion

This paper has presented a new Hybrid Modular Multilevel (HMMC) topology and its application in grid-connection of PV systems. This topology has the benefits of lower switch counts, simpler circuitry, and improved performance. The control scheme for the overall system is validated through simulation. From the results, it can be realized that this topology can be beneficial in the field of grid connected renewable energy sources.

Table 3. Design Parameters

Parameters	Symbol	Value
PV module MPP voltage	v_{MPP}	30.7 V
PV module MPP current	i_{MPP}	8.15 A
Nu. of modules per string	n_m	10
PV panel rated power	P_{rated}	2.5 kW
DC-link capacitor	C_{dc_link}	2200 μF
Sub-module capacitor	C_{SMn}	5000 μF
PWM carrier frequency	f_c	4 kHz
Single-phase utility grid	v_g	230 Vrms
Line frequency	f_l	50 Hz
Filter inductor	L_f	10 mH
DC-link voltage controller: PI	K_D, K_I	30, 200
Grid current controller: PI	K_D, K_I	15, 50
Ambient temperature	T	25^oC

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