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Research Article

Grid Tied MMC-Based Photovoltaic System by using Triple Active Bridge Converter

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Abstract – In the field of Multi-Terminal DC (MTDC) systems, Modular-Multilevel Converter (MMC) is a promising topology. The article analyzes the Grid-Connected Photovoltaic (PV) system by Triple Active Bridge (TAB) converter. No power mismatch occurs by connecting the TAB converter with the above arm and lower arm of MMC. This arrangement overcomes the problem of capacitor voltage profile by eliminating differential-mode component. A circulating-current controller is proposed to reduce the second-order harmonic capacitor voltage. In addition, the half-bridge circuit is being used in the TAB converter which reduces the overall components in the system, cost, and the volume of the system. The MATLAB/SIMULINK simulation shows the validity proposed topology.

Keywords – Modular Multilevel Converter (MMC), Photovoltaic (PV), Circulating Current, Triple Active Bridge (TAB)

I. INTRODUCTION

Nowadays, solar energy is an attractive solution to produce clean and sustainable energy. The installation of isolated and grid-connected large-scale photovoltaic (PV) power stations is thriving [1]. The division of power stations of photovoltaic is based on power converter setup namely: multi-string and centralized configurations. The centralized configuration consists of multiple series and parallel PV panels to fulfil the system's power requirements. But this structure fails to give the same output under the umbrella of partial shading [2]. Using the structure of a multi string, the DC-DC converter connects in each string and is separately controlled by Maximum Power Point Tracking (MPPT). It reduces the power loss [3] but still, the overall efficiency remains low. Traditionally, two and three-level Voltage Source Converters (VSC) was used to transmit solar energy at large levels. This large-scale transmission was unable to fulfill the requirements of high-power transmission due to the poor power quality, high switching losses and large DC link Capacitor required [4]. But still, the overall efficiency remains low. Traditionally, two and three-level Voltage Source Converters (VSC) was used to transmit solar energy at large levels. This large-scale transmission was unable to fulfil the requirements of high-power transmission due to the poor power quality, high switching losses and large DC link Capacitor required [5]–[7]. This structure is made up of multiple PV panels which are connected to a multi-port converter using an isolated dc-dc converter. An isolated transformer helps to reduce the leakage current of PV panels production which depends upon the parasitic capacitance. Hence, the number of photovoltaic panels reduces due to the high voltage gain. The highest efficiency can be achieved because MPPT can be implemented independently. The benefits of a Modular Multilevel Converter (MMC) consist of easy expansion, fewer output harmonics, and less voltage stress [8], [9]. It is highly used in medium-voltage transmission. Y.Zhiqing [10] proposed a system of the modular structure of a photovoltaic system, in which a photovoltaic converter is connected to each submodule. This system of framework can be able to achieve medium voltage direct current (MVDC) yield by super-imposing power units on one another. The drawback of the said topology is the power mismatch problem due to partial shading which was fixed by H. Bayat and A. Yazdani. They proposed a negative sequence circulating current strategy for power-mismatch elimination. The MMC-based structure has a high power balance capacity instead of CHB. However, the additional dc component of each leg of the MMC cause ripples in the system that increase the fundamental frequency of the system [10], [11]. To mitigate the ripples effect in the system, MMC requires several decoupling capacitances. These circuits cause to enhance the volume of the system along with the cost of the system. To reduces the ripples in the system, the circulating current strategy is adopted which also reduces the submodule capacitance. The ripple suppression amount is limited by using this method. Unique circuits of dc-coupling are added to the MMC the striving to increase the effectiveness of system [12]–[14]. The additional circuits used in these topologies increase the cost of the entire system.

Many topologies of modular converters have been proposed in recent years which were introduced in [15]–[17]. These topologies introduced the coupling transformers for power exchange in three-phase systems, which can reduce the low-frequency ripples among the submodule capacitance completely. The drawback of these topologies is the use of four winding transformer to send power from input to the load. This increases, complexity and the volume of the system. It can't fulfill the requirement of power mismatch in above and lower arm of modular multilevel converter. The three-phase MMC's fundamental structure is illustrated in Fig.1.

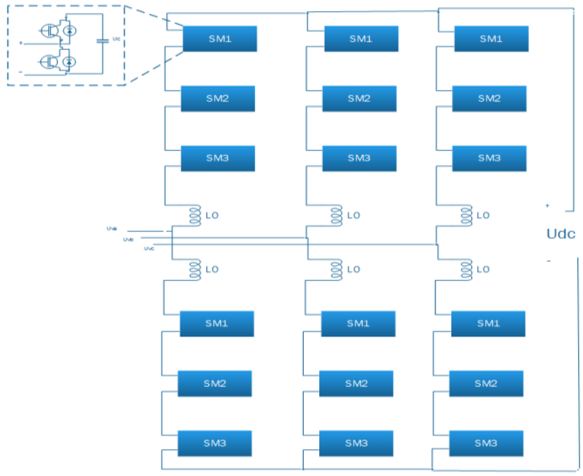

Fig. 1 Fundamental Structure of Three-phase MMC

II. PROPOSED TOPLOGY

The paper proposes an improved grid-connected photovoltaic system which is based upon the MMC, to solve the issues described above. In which, upper and lower arm of an isolation transformer can be connected to a three-port transformer (see Fig.2).

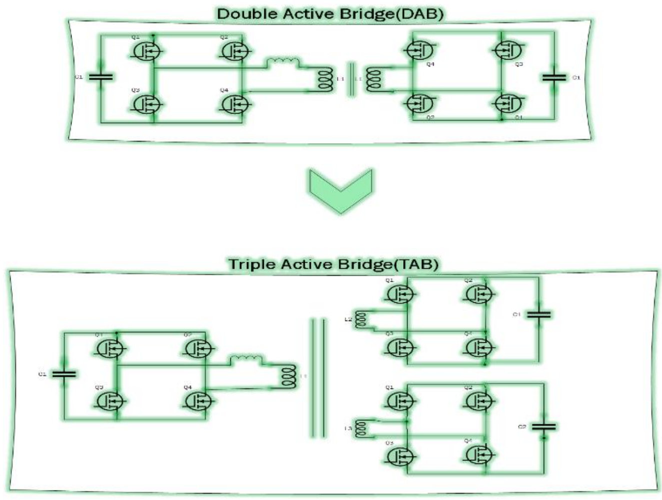

Fig. 2 Topology Improvement from DAB to TAB

The output power from the PV module can be equally divided into the above and lower leg of the MMC, which solves the power mismatch problem between the above and lower leg of the MMC. It equally balances the power in above and lower arms of the MMC. The proposed topology eliminates the power mismatch in the system. In the proposed topology, the triple active-bridge (TAB) converter is utilized instead of the dual active-bridge (DAB) converter, which reduces the components of the system resulting in the reduction of cost and volume of system. The strategy of circulating-current control is also proposed to cancel out voltage profile of capacitor.

III. CAPACITOR VOLTAGE PROFILE CANCELLATION

In previous topologies, the capacitor-voltage ripples of MMC submodule are fully analyzed [18], [19] and only difference between the MMC-Based grid-connected Photovoltaic system and previous topologies comes out to be the magnitude, so the analysis of the model is similar. Define the above-arm voltage V_{tu} and lower-arm voltage V_{tl} and I_g is the system output current. Where $(t = 1,2\ and\ 3)$ take a phase as an example that can be expressed as

$$\begin{cases} V_{1u} = \dfrac{1 - m.sin\omega t}{2} V_{dc} \\ V_{1l} = \dfrac{1 + m.sin\omega t}{2} V_{dc} \end{cases} \tag{1}$$

$$I_{g1} = i_g \sin(\omega t - \varphi_v) \tag{2}$$

Where m represents the modulation ratio, V_{dc} describes the output DC bus voltage and φ_v justify the power factor angle.

The current of above arm and lower arm can be express as [20]

$$\begin{cases} I_{1u} = \dfrac{I_{g1}}{2} + \dfrac{I_{dc}}{3} + I_{2f}\sin(2\omega t - \Theta_2 f) \\ I_{1l} = -\dfrac{I_{g1}}{2} + \dfrac{I_{dc}}{3} + I_{2f}\sin(2\omega t - \Theta_2 f) \end{cases} \tag{3}$$

In equation (3) I_{2f} shows the Amplitude of the second harmonics current and $\Theta_2 f$ describes the starting phase of the circulating current. I_{dc} Represents dc current of each arm. Let P_{dc} be the power flowing in the MVDC bus so the Current I_{dc} will be

$$I_{dc} = \frac{P_{dc}}{V_{dc}} \tag{4}$$

Let PV output power is constant and submodule capacitor output ripple voltage of upper and lower arms is

$$\tilde{v}_{cu1,ave} = \frac{\int P_{1u}|AC}{N\bar{v}_{cu1,ave}C} = \frac{v_{1u} i_{1u}|AC}{N\bar{v}_{cu1,ave}C} \tag{5}$$

From eq. (1),(3) ,and (5) we can get the average ripple voltage of the submodule capacitor shown in eq. (6) and (7)

$$\tilde{v}_{cu1,ave} = \underbrace{\frac{mI_{dc}}{6\omega C}\cos\omega t - \frac{I_g}{4\omega C}\cos(\omega t - \varphi_v) - \frac{mI_{2f}}{4\omega C}\sin(\omega t - \Theta_{2f})}_{\text{Differential mode component}} \tag{6}$$

$$\underbrace{-\frac{I_{2f}}{4\omega C}\cos(2\omega t - \Theta_{2f}) + \frac{mI_g}{16\omega C}\sin(2\omega t - \varphi_v)}_{\text{Common mode component}} + \underbrace{\frac{mI_{2f}}{12\omega C}\sin(3\omega t - \Theta_{2f})}_{\text{Differential mode components}}$$

$$\tilde{v}_{cl1,ave} = -\underbrace{\frac{mI_{dc}}{6\omega C}\cos\omega t + \frac{I_g}{4\omega C}\cos(\omega t - \varphi_v) + \frac{mI_{2f}}{4\omega C}\sin(\omega t - \Theta_{2f})}_{\text{Differential mode components}} \tag{7}$$

$$\underbrace{-\frac{I_{2f}}{4\omega C}\cos(2\omega t - \Theta_{2f}) + \frac{mI_g}{16\omega C}\sin(2\omega t - \varphi_v)}_{\text{Common-mode component}} - \underbrace{\frac{mI_{2f}}{12\omega C}\sin(3\omega t - \Theta_{2f})}_{\text{Differential-mode components}}$$

The differential and common mode components of above and lower arm capacitor voltage can be obtained using

$$\begin{cases} v_{ct,com} = \frac{v_{cut} + v_{clt}}{2} \\ v_{ct,diff} = \frac{v_{cut} - v_{clt}}{2} \end{cases} \tag{8}$$

According to eq. (6) and (7), the common mode components can be reduced by injecting the circulating current [20].

$$\begin{cases} I_{2f} = \dfrac{mI_g}{4} \\ \theta_{2f} = \varphi_v + \dfrac{\pi}{2} \end{cases} \quad (9)$$

Here the I_{2f} is circulating current which is injected to the system to elimination of common –mode components. Fig.3 shows the controller used to inject the circulating current is system.

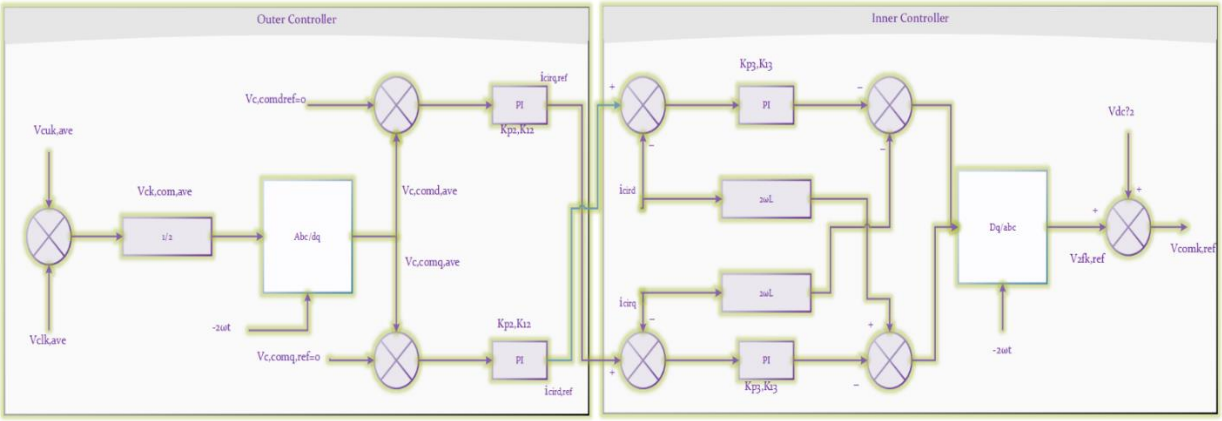

Fig. 3 Control Structure of MMC

The control structure is depicted in Fig. 3. The controller composed of an outside controller and an inside controller. The common mode element of arm capacitor average voltages (i.e.$V_{ccomj,ave}$) is converted into dq elements (i.e.,$V_{ccomd,ave}$and $V_{ccomq,ave}$) . Because the control goal is to reduce the second harmonic capacitor voltage and eventually reduce the capacitor voltage fluctuation, the values of V_{comd,ave_ref} and V_{comq,ave_ref} are both zero. The reference values for the second harmonic rotating currents, i_{cird} and i_{cirq}, are acquired by PI controllers at the end of the outside controller. With the exception of the fact that the reference values for the rotating current come from the outside controller, the inner controller is built to have a similar structure to the rotating current suppressing controller. The dc side voltage reference value is V_{dc_ref}. The output current controller determines the reference values for the differential mode element of the arm voltages, v_{diffj}.

IV. Maximum Power Point Tracking (MPPT)

In the proposed topology, differential-mode element of voltage has minimal impact on the power transmission of TAB. So, the photovoltaic panel output can be made correct by modifying the phase angle between input and output ports of TAB. Hence, the MPPT can be able to achieve by using the conventional MMPT control topology. Perturb and Observation algorithm adopted in this research for controlling the MPPT of each PV module as shown in Fig 4.

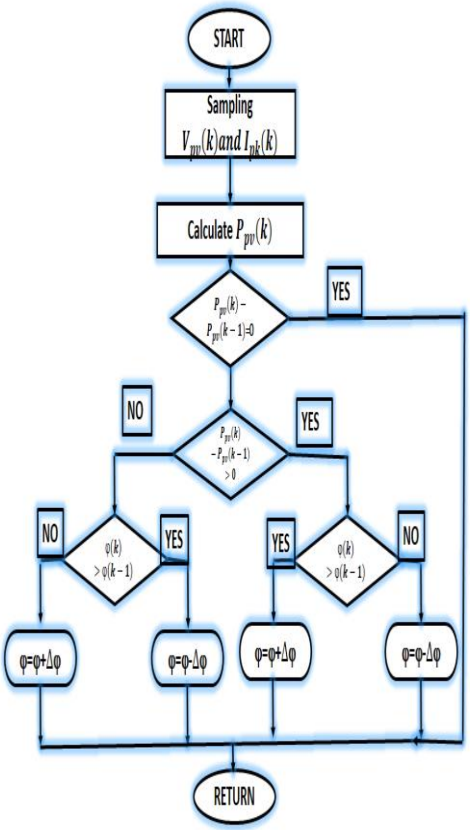

Fig. 4 Block diagram of MPPT

V. DISCUSSION

The proposed topology improves the function of, traditional Dual-Active Bridge (DAB) converter. It integrates two DAB converter into one TAB converter which reduces the components in the system. . Hence, the cost and volume of system reduces. It also improves the voltage ripple profile in the system by self-power balancing in the bridge arms. As compared to previous papers, the half-bridge circuit is used that further reduces the components in the system (see fig.5). The comparison of components used in the previous proposed topologies is shown in (Table.1).

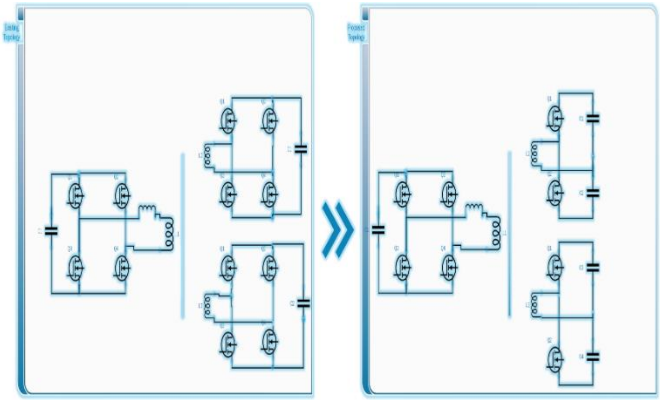

Fig. 5 Block diagram of MPPT

Table 1. Comparison Table

Topology/Core Technology	Proposed	[17]	[18]-[19]
Capacitor Ripple improvement	Y	Y	Y
MTDC Coupling	Y	N	Y
Self-balancing power in phase units	Y	Y	N
Converter winding	Three	Four	Four

VI. SIMULATION RESULTS

To verify the proposed model a system is set up in MATLAB/Simulink. It consist of Three Phase units. In which each unit has above arm and lower arm, each arm consist of three submodules. Each MMC phase unit consist of three TAB units. Each Tab unit connect with PV unit. Each PV unit supplied 100kw power under the temperature of 25° and irradiance of $1000\ w/m^2$. Table.2 shows the all other parameters. Figure 6 shows the power imbalance under partial shading of MMC. The MMC has three phase unit and each phase unit have two arms (Above arm and lower arm). The output shows the six level because of six arms. The levels can be increased or decreased by changing the submodule in each phase units. It demonstrates the power imbalance under partial shading which is tested at $800\ w/m^2$ and $600\ w/m^2$. Fig.7 shows that TAB arrangement can achieve the self power balance at MMC arms. Figure.8 describes the three phase Grid side current which is imbalance at start. But after some time it is balanced by self-balancing of MMC. System required the balance current for smooth operation.

Table 2. Simulation Parameters

Simulation Parameters	Rated value
Rated power of TAB	100kw
Grid frequency	60Hz
DC bus voltage	3kv
String power	700kw
Capacitor: C	1.1mf
Inductance: L	5mH
Grid voltage	1kv

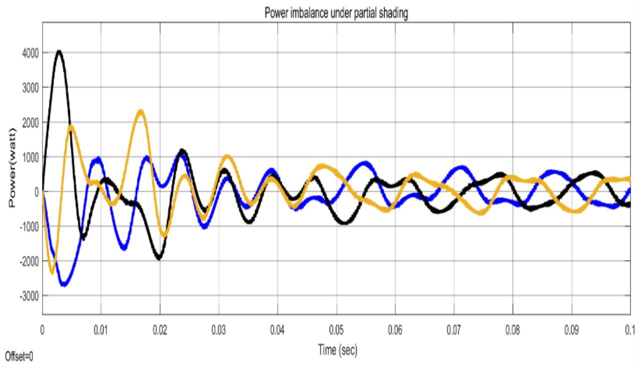

Fig. 6 Power imbalance under partial shading

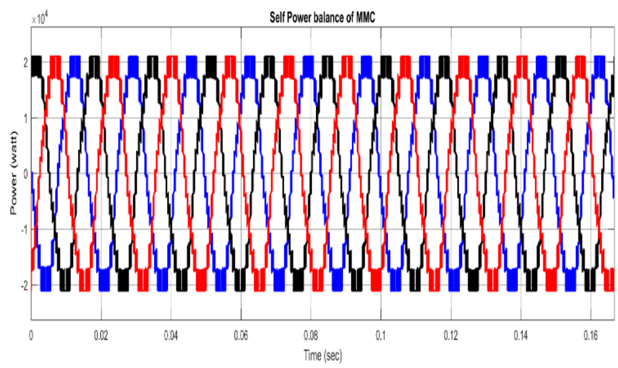

Fig. 7 Self power balance of MMC

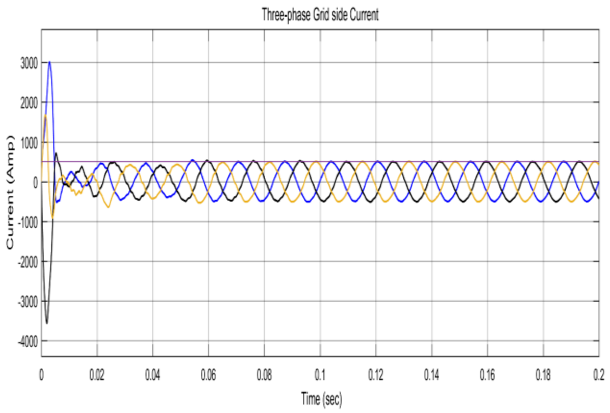

Fig. 8 Three-phase Grid side Current

VII. CONCLLUSION

The paper proposes an improved version of MMC, which is based on Grid-Connected photovoltaic system with TAB converter. It solves the power mismatch problem and contain self-power balance ability. The arrangement of TAB converter cancel out differential-mode component of capacitor-voltage ripple present in the system. Therefore, submodule-capacitance of MMC can be reduced multiple times which also reduces volume along with cost of the system. The circulating-current controller strategy is proposed to eliminate common-mode component of capacitor-voltage ripple. The proposed topology of TAB consists of half-bridge converter which also reduces the volume and cost of the system. The simulation results, shows the effectiveness of our proposed topology.

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