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NPC Photovoltaic Grid-Connected Inverter using Proportional-Resonant Controller

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Abstract—Multi-megawatt photovoltaic (PV) power plants are widespread in electrical power systems because of the drastic decrease in the PV panel prices. The multi-string structure is considered for high power PV systems due to the increase in the overall energy conversion efficiency and the modularity when compared to the centralized topology. High power conversion can be achieved easily using parallel connection of several grid-tied two-level voltage-source inverters (2L-VSIs). However, this configuration complicates the control designs. Thus, this issue can be overcome by replacing these 2L-VSIs with a single high power three-level neutral point clamped inverter (3L-NPC). Moreover, the 3L-NPC inherits several attractive merits such as improved power quality with reduced total harmonic distortion (THD), increased overall efficiency as well as lower costs. In addition to that, the voltage oriented control using proportional-resonant (VOC-PR) in conjunction with the adaptive space vector modulation (ASVM) technique is proposed for the large-scaled PV system with grid-tied NPC inverter. The feasibility of the proposed control for the high power system is validated through the simulation results under various environmental conditions. Besides that, the dynamic mance of the system under the proposed VOC-PR is greatly enhanced in comparison with the conventional method using PI controller.

Index Terms—Photovoltaic systems, adaptive space vector modulation, voltage oriented control, proportional-resonant controller, NPC inverter

I. INTRODUCTION

Renewable energy sources have produced large amount of energy in the last few years and reached a total share of 19.3% in 2009 [1]. Photovoltaic (PV) is one of the renewable energy resources that grows rapidly with its total installed capacity increased from 2GW in 2004 to 70GW in 2011. The rate of such growth is initiated mainly due to the drastic decreased of the PV panel cost from \$4.90/W_{pk} in 1998 to \$1.28/W_{pk} in 2011 and it is expected to remain high in the upcoming years. To date, there are more than 50 utility scaled PV plants with capacity of more than 30MW operating worldwide [2]–[5].

Large scale PV plants are usually designed based on two different structures which are the centralized topology and the multi-string topology. In the centralized structure, the PV power is injected directly into the grid through a single DC/AC inverter. The amount of current produced from each PV panel depends on the solar irradiance. If the same amount

of irradiance is received by all the PV panels, there will only be one maximum power point (MPP). However, the partial shading is most likely to happen in practice. Thus, different amount of current is produced from the PV panels and strings due to the dissimilar irradiance levels. Therefore, a blocking diode must be connected across each PV string to prevent any reverse current when any of the PV string current is lower than the others. Besides that, multiple MPPs are exhibited in the I-V characteristics. As a result, the global maximum power cannot be extracted directly by the single DC/AC inverter.

Similar configuration is found in the multi-string topology, but the only difference is that each of the PV strings is connected to a DC/DC converter instead. By doing so, the maximum power is extracted independently. Hence, the overall system output power is increased in this case compared to the centralized topology. These isolated DC/DC converters provide both boost capability as well as high frequency galvanic isolation to eliminate the common mode current. Thus, the bulky low frequency isolation transformer can be eliminated at the AC side. Besides that, high modularity is found in the multi-string topology as it allows different types of PV panels as well as different DC/DC converter topologies in the system. However, the implementation cost and the design complexity are higher than the centralized structure. Due to the optimization and increase in the power conversion efficiency, it is popularly chosen over the centralized topology and is considered as the state of art nowadays.

The classical two-level voltage source inverter (2L-VSI) is well-known for its low cost and simple design which is usually implemented in the low PV power applications [4], [6]. In the case of large-scaled PV plants, multiple 2L-VSIs must be connected in parallel in order to deliver such high power to the grid due to its limited semiconductor devices blocking voltage capability. However, this is not a promising solution as it complicates the control design and the complexity of the entire system. To avoid such complications, high-power multilevel grid-tied inverters are proposed for high power PV applications. Hence, the multilevel converters have emerged as the most viable solutions in this case due to their perceived merits such as delivering excellent power quality with low harmonic contents as well as achieving better efficiency compared

Fig. 1: Proposed multi-string PV system with grid-tied NPC inverter.

to the 2L-VSCs [7].

The output voltage waveforms of the multilevel converters are generally synthesized from several levels of DC voltages. Thus, the multilevel converter topologies can be constructed differently with multiple isolated DC-links [2], single DC-link configuration [8] or multiple series stacked DC-links [9]–[11]. Based on the multi-string structure in this case, the PV strings together with the DC/DC converters can be directly connected to these DC-links. Therefore, the number of series connected PV panels can be lesser since the DC-link voltage required is much lower. However, the voltage balancing and power sharing between these PV strings are of a great concern especially when partial shading condition is experienced. In the event of fault occurrence or partial shading, the output power of the DC/DC converters has to be reduced to the lowest in order to have a balanced system. As a result, there is a decrease in the overall efficiency when the PV power is not fully optimized.

In this paper, the grid-tied three-phase neutral-point-clamped (NPC) inverter is connected to multiple PV string modules via a common DC-bus. The maximum power of each PV string is extracted independently from the DC/DC converter using MPPT control. Based on the proposed configuration, the PV maximum power can be fully optimized even when partial shading condition is experienced. The three-phase NPC inverter will then deliver the maximum power to the grid by controlling the DC-link voltage (V_{dc}). A voltage oriented control structure using proportional-resonant (VOC-PR) is proposed to achieve better dynamic performance and low output current harmonic distortion. Besides that, the DC-link capacitor voltage balancing is achieved through the adaptive space vector modulation (ASVM) scheme. The performance of the proposed large-scaled multi-string PV system using grid-tied NPC inverter under VOC-PR control is evaluated under various dynamic operating conditions.

II. PROPOSED SYSTEM STRUCTURE

A comprehensive structure of the proposed large-scaled multi-string PV system is shown in Fig. 1. The system is

basically constructed with three distinct parts which are the PV strings, the DC/DC converters and the NPC inverter.

The number of series-connected PV panels required for each string can be determined based on the grid voltage characteristics and the DC/DC converter topologies. However, the proposed system structure is not restricted to any particular types of PV panels and DC/DC converter topologies as long as the desired minimum DC-link voltage is achieved. For simplicity sake, a simple boost converter is considered in this paper instead of an isolated DC/DC converter.

Each PV string is connected to an individual boost converter to form a single PV string module. Hence, multiple PV string modules are connected in parallel to the single DC-bus that consists of two series capacitors (C_1 and C_2). However, it should be noted that the number of PV string modules utilized in the system will affect the current ratings of the three-phase grid-tied NPC inverter design.

The grid-tied NPC inverter comprises two pairs of IGBT switches (S_{a1} and S_{a2}) including the complementary ($S_{a1'}$ and $S_{a2'}$) in each phase. The NPC operates with three different switching states to synthesize the three output pole voltage stepped levels at $V_{dc}/2$, 0 and $-V_{dc}/2$ with respect to the midpoint m of DC-link.

Despite the increasing demands of renewable energy resources, several regulations such as IEEE Std. 1547-2003 and IEEE Std. 929-2000 [12], [13] must be complied strictly to ensure the power quality of the renewable grid-connected system. Therefore, lower current harmonic distortion can be achieved with the aid of output filter inductors which are connected between the inverter and the grid. Due to the intelligent synthesis of three-level output voltage waveforms, the filter size can be much smaller compared to the conventional 2L-VSI.

III. PROPOSED CONTROL STRATEGY

There are two independent control strategies applied in the multi-string PV system as shown in Fig. 1 which are the boost converter control and the proposed grid-tied NPC control. The boost converter is controlled using a MPPT algorithm which adjusts the output voltage of each string (V_{st}) based on the

Fig. 2: Voltage oriented control using proportional integral (PI) controller.

voltage of the maximum power point. In this study, perturb and observe (P&O) algorithm is implemented for the MPPT control [8]. Meanwhile, the proposed NPC control maintains the DC-link voltage by regulating the inverter output power.

The proposed NPC control scheme consists of three parts: phase-locked loop (PLL), voltage oriented control (VOC) and adaptive space vector modulation (ASVM). The PLL calculates the phase voltage angle(θ) by measuring the three-phase grid voltages. The computed voltage angle is used to ensure that the frequency of the grid current is matched to the grid frequency. The implementations of VOC and ASVM for the grid-tied inverter are detailed in the following.

A. Voltage Oriented Control

The VOC is conventionally proposed in [14] using proportional-integral (PI) as shown in Fig. 2. The VOC-PI consists of outer and inner control loops. The outer loop maintains the DC-link voltage (V_{dc}) to its desired reference level by adjusting the inverter output power. The reference d-axis current is also computed by the outer loop to control the output active power while the amount of output reactive power is calculated using the reference q-axis current which is usually set to zero for unity power factor operation. The three-phase output currents (I_a , I_b and I_c) are transformed to the synchronous rotating frame (I_d and I_q) through park transformation. It can be seen that there are two separated PI controllers used for obtaining the reference dq voltage signals (V_d^* and V_q^*) based on the I_d and I_q errors respectively. Finally, an inverse park transform generates the reference stationary frame voltages (V_α^* and V_β^*) from the reference dq voltage signals and the grid voltage angle (θ). Hence, the ASVM block uses the reference stationary frame voltages to generate switching signals.

Despite the facts that PI is easy for implementation, but there are some drawbacks such as the need of multiple frame transformations and result high computational complexity, the presence of steady-state error in the stationary frame as well as the essential to decouple the phase dependency in the three phase systems. These disadvantages affect the dynamic response of the converter causing large transient inrush current and voltage across the DC-link.

In order to improve the dynamic performance and reduce the steady-state error of the controller, this paper proposes a proportional-resonant (PR) in the inner loop of the VOC

Fig. 3: Voltage oriented control using proportional-resonant (PR) controller.

instead of using PI. The dynamic performance is evaluated and compared between the conventional VOC-PI and the proposed VOC-PR in the following section IV.

The proposed VOC-PR control scheme is shown in Fig. 3. The DC-link voltage is tracked to its desired reference level, similarly as the conventional VOC-PI, using a PI to generate the reference d-axis current. In the case of achieving a unity power factor operation, the reference q-axis current is set to zero. Hereafter, the reference dq-axis currents (I_d^* and I_q^*) are converted to obtain their equivalent reference stationary frame currents (I_α^* and I_β^*) using inverse park transformation. The respective $\alpha\beta$ current errors are then obtained by subtracting the reference stationary frame currents with the stationary frame currents (I_α and I_β), obtained from the measured three-phase output inverter currents through inverse Clarke transformation. Lastly, the reference stationary frame voltages (V_α^* and V_β^*) can be acquired directly from the two independent PR controllers without inverse Park transformation. The PR controller transfer function is expressed as follow:

$$G_{PR} = K_P + \frac{K_I}{s^2 + \omega^2} \quad (1)$$

where K_P is the proportional gain term, K_I is the integral gain term and ω is the resonant frequency. The resonant term provides an infinite gain at the resonant frequency that minimizes the steady-state error. Therefore, the steady-state current error can be minimized by having the resonant frequency matching with the grid frequency.

Moreover, the ASVM can generate the gating switching signals directly from V_α^* and V_β^* without any frame transformations. Hence, the reduced of frame transformations decreases the computational complexity unlike the conventional VOC-PI method. In addition to that, the transformation errors are eliminated, thus enhancing the performance with better reference tracking and faster dynamic response [15], [16].

B. Adaptive Space Vector Modulation

The output voltage waveforms are synthesized using the adaptive space vector modulation (ASVM) technique. The space vector representation for the NPC inverter is shown in Fig. 4. It can be observed that there are several pairs of vectors (e.g. "100" and "211") in each internal voltage state which generate the same output voltage level. Conventionally, the classical SVM uses the pair of vectors during every switching cycle period. Therefore, an increase in the switching

Fig. 4: Space vector representation of the NPC inverter.

Fig. 5: Circuit diagram and current path for vectors of one vector pair.

loss is experienced with the classical SVM due to the high switching frequency operation. Thus, the ASVM technique is implemented in conjunction with the proposed VOC-PR in this paper to improve the inverter efficiency. The overall switching loss is decreased by reducing the switching frequency since one of the vector pairs is utilized in each switching cycle [17], [18]. This can be observed from the current flow based on the vector pair "100" and "211" as shown in Fig. 5.

Even though both vectors generate the same output voltage level, but there are different effects on the DC-link capacitor voltages. For instance, when the state vector is "100", the DC-link capacitors C_1 and C_2 are in charging and discharging states respectively, according to the voltage potentials. Hence, the DC-link capacitor voltage balancing is achieved based on the state vector selection principle as described in (2) and (3). The vector selection principle is applicable for other vector pairs as well.

$$\left. \begin{array}{l} V_{c1} \leq V_{c2} \ \& \ I_a \geq 0 \\ V_{c1} > V_{c2} \ \& \ I_a < 0 \end{array} \right\} \Rightarrow (100) \quad (2)$$

$$\left. \begin{array}{l} V_{c1} \geq V_{c2} \ \& \ I_a \geq 0 \\ V_{c1} < V_{c2} \ \& \ I_a < 0 \end{array} \right\} \Rightarrow (211) \quad (3)$$

TABLE I: SIMULATION PARAMETERS

Parameter	Symbol	Value
Grid Voltage	V_{ab}	$400V_{l-rms}$
Grid Frequency	f	50Hz
Line Inductor	L_f	5mH
DC-link Capacitor	C_1, C_2	2200 μ F
DC-link Voltage	V_{dc}	770V _{dc}
NPC Switching Frequency	$f_{s,inv}$	7.2kHz
DC-DC Switching Frequency	$f_{s,boost}$	10kHz
Boost Inductor	L	1mH

Fig. 6: DC-link capacitor voltage in steady state condition under VOC-PR.

IV. EVALUATION RESULTS

The proposed multi-string PV system with NPC grid-tied inverter is co-simulated between Matlab/Simulink[®] and PSIM environment based on the detailed settings given in Table I. Three parallel connected PV string modules (which consist of the PV string and the boost converter) are considered here to evaluate the system dynamic performance using the proposed VOC-PR control scheme under various environmental conditions. Hence, these three independent PV string modules are set with different solar irradiation and temperatures. The PV panels are simulated using the SHARP NU-U235F1 model. Each PV panel produces the maximum power of 235W (30V and 7.84A) at 25°C and 1kW/m². Since the grid voltage is 400V_{l-rms}, the nominal DC-link voltage can be calculated according to (4) which is equal to 770V_{dc}, considering a normal modulation index of 0.85 m_a .

$$V_{l-rms} = \frac{\sqrt{3}}{\sqrt{2}} \times m_a \times \frac{V_{dc}}{2} \quad (4)$$

In this case, the nominal input voltage of the boost converter is 600V_{dc}. Therefore, a total of 20 PV panels are connected in series for each PV string.

The result in Fig. 6 has verified the DC-link capacitor voltage balancing performance based on the implementation of the ASVM technique together with the VOC-PR control scheme. It is clearly observed that the DC-link capacitor voltages are balanced at around 385V which is half of the DC-link voltage (770V_{dc}). Besides that, this result also concludes that the DC-link voltage is well-tracked to its reference.

TABLE II: DYNAMIC OPERATING CONDITIONS OF PV STRING

Time (s)	String I	String II	String III
0 - 6.1	Irra=1* Temp=25*	Irra=1 Temp=25	Irra=1 Temp=25
6.1 - 6.26	Irra=0 Temp=25	Irra=1.2 Temp=25	Irra=0.6 Temp=25
6.26 - 6.4	Irra=1 Temp=25	Irra=1.2 Temp=35	Irra=0.6 Temp=35

* Irrad: Irradiance (kW/m²) and Temp: temperature (°C)

Fig. 7: Dynamic performance of PV grid connected inverter under various temperature and irradiance states: (a) grid currents and phase voltage (scaled down by 10), (b) NPC line-line voltage and (c) inverter output power.

Fig. 8: Three phase transient grid currents under (a) VOC-PI and (b) VOC-PR.

The dynamic performance of the proposed system is evaluated in Fig. 7 under the three different conditions listed in Table II. The proposed system is operated initially with the three PV string modules having the same parameters between $t=0s$ to $t=6.1s$. During the second condition (from $t=6.1s$ onwards), different amount of irradiance is experienced by String I (complete shading $Irrad = 0kW/m^2$), String II (increase in $Irrad = 1.2kW/m^2$) and String III (partial shading $Irrad = 0.6kW/m^2$). The irradiance in String I is changed back to its initial value while there is an increase in the temperature for String II and String III during $t=6.26s$ to $t=6.4s$.

The unity power factor operation is maintained throughout the different environmental conditions as shown in Fig. 7(a). Besides that, an output five-level line-line voltage waveform is synthesized by the grid-tied NPC inverter in Fig. 7(b). Thus, better power quality is achieved with the reduced THD profile as compared to the 2L-VSI.

However, it can be observed that there is a decrease in the magnitude of the three-phase grid current in Fig. 7(a) and the

DC-link voltage based on the magnitude of the output voltage waveform in Fig. 7(b). This is due to the sudden decreased in the total extracted PV power at $t=6.1s$. As a result, the output power of the grid-tied NPC inverter is also decreased in Fig. 7(c). During this period, the proposed VOC-PR controls the output inverter power accordingly to the extracted PV power by reducing the amount of current injected to the grid. Despite of such extreme shading conditions, there are no voltage and current spikes experienced at the ac grid side with the implementation of the proposed VOC-PR control scheme.

The performance of the conventional VOC-PI and proposed VOC-PR control algorithms are compared in Figs. 8 and 9. In Fig. 9, the DC-link voltage is rapidly tracked to its reference level under the proposed VOC-PR control. On top of that, the maximum transient DC-link voltage is greatly reduced from 2000V (VOC-PI) to 1200V (VOC-PR). In addition to that, the three-phase transient grid current under the proposed VOC-PR control scheme reach the steady-state condition with less than 0.1s in Fig. 8 (b) as compared to the performance under

Fig. 9: DC-link voltage under (a) VOC-PI and (b) VOC-PR.

VOC-PI control in Fig. 8(a).

The results in Figs. 7, 8 and 9 have validated the dynamic response of the multi-string PV system using the proposed VOC-PR control scheme. Moreover, the rated ratings of the components can be reduced as well due to the decrease in the DC-link voltage and the magnitude of the three-phase current during the transient period.

Moreover, the total harmonic distortion (THD) of the grid current under conventional VOC-PI and proposed VOC-PR are 4.4% and 3.8% respectively. Thus, these comparison results have evidently proven that the excellent performance and dynamic response are achieved for the proposed large-scaled multi-string PV system with NPC grid-tied inverter under VOC-PR control scheme.

V. CONCLUSION

This paper proposed a voltage oriented control using proportional-resonant (VOC-PR) in conjunction with the adaptive space vector modulation (ASVM) technique for large-scaled multi-string PV system with grid-tied NPC. The multi-string structure increases the overall energy conversion efficiency as well as the modularity of the PV plant. Several advantages such as improved power quality, reduced losses and lower implementation costs are found in the high-power grid-tied NPC inverter compared to the parallel-connected conventional 2L-VSIs for large-scaled PV system.

The feasibility of the proposed large-scaled multi-string PV system using the VOC-PR control scheme is validated with the simulation results under various extreme environmental conditions. Lower current THD is achieved with the elimination of the steady-state error due to the infinite gain characteristic of the PR at the selected resonance frequency which is matched to the grid frequency in this case. Despite the reduced computational efforts due to lesser frame transformations required, the dynamic performance of the system using proposed VOC-PR is greatly enhanced compared to the conventional VOC-PI as proven in the comparative results.

Moreover, the DC-link voltage and the three-phase grid current are significantly reduced during the transient period. Thus, the ratings of the components are not required to be oversized. Besides that, losses are reduced due to the lower

switching frequency operation of the ASVM technique while ensuring that the DC-link capacitor voltages are balanced. These perceived advantages make the proposed VOC-PR control scheme together with the ASVM technique becoming more attractively for the large-scaled high power PV system.

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