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The installed capacity of grid connected PV plants has increased significantly over the past few years and is expected to continue its growth over the next decade due to the continuous demand for renewable energy and distributed generation systems. This paper presents a seven-level flying capacitor (FC) based active neutral point clamped (ANPC) converter for the connection of utility-scale PV system to the electricity grid. The multilevel voltage output of the topology provides high quality waveforms while maintaining the operational characteristics of NPC based converters for PV systems. The converter topology together with a method to regulate the FC voltages to their reference values and an optimal third harmonic injection for utilization of the DC-link voltage are presented. Simulation results for the operation of the grid connected converter under steady state and transient operation are provided in order to demonstrate the operation and performance of the topology in grid connected applications. © 2012 IEEE.
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The Seven-level Flying Capacitor based ANPC Converter for Grid Intergration of Utility-Scale PV Systems

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***Abstract*—The installed capacity of grid connected PV plants has increased significantly over the past few years and is expected to continue its growth over the next decade due to the continuous demand for renewable energy and distributed generation systems. This paper presents a seven-level flying capacitor (FC) based active neutral point clamped (ANPC) converter for the connection of utility-scale PV system to the electricity grid. The multilevel voltage output of the topology provides high quality waveforms while maintaining the operational characteristics of NPC based converters for PV systems. The converter topology together with a method to regulate the FC voltages to their reference values and an optimal third harmonic injection for utilization of the DC-link voltage are presented. Simulation results for the operation of the grid connected converter under steady state and transient operation are provided in order to demonstrate the operation and performance of the topology in grid connected applications.**

***Index Terms*—Active neutral point clamped, Multilevel converters, Pulse-width modulation, SPWM, Grid connected converters, PV systems.**

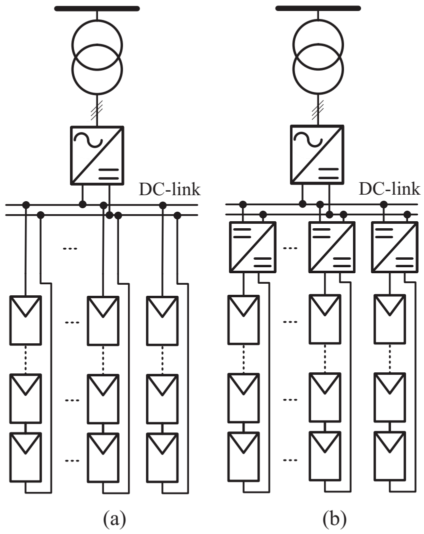

Fig. 1. PV system configuration (a) central inverter, (b) multistring inverter

I. Introduction

Solar PV is a fast growing market with the amount of installed capacity more than doubling from 7.2GW in 2009 to 16.6GW in 2010. The total global installed capacity is now above 40GW and continues to grow every year. The countries of the European Union lead the way in installed capacity accounting for more than 80% of the new installations for 2010. Global trends towards renewable and together with the climate change goals set by the countries are expected to sustain this growth for the coming years [1]– [3].

In Australia, the newly installed capacity for 2010 only was 383 MW (almost fivefold the installed capacity of 2009) and reaching a cumulative total solar PV capacity of 571 MW [2]. This growth is likely to be sustained in the future with state and country-wide policies and initiatives such as the Solar Flagships project aiming to support the construction and demonstration of large-scale, grid connected solar power stations in Australia [4].

Recent trends in the grid integration of large-scale PV systems utilize multi-string topologies which combine the advantages of string and module converters. This configuration provides multiple DC-DC converters that allows individual maximum power point (MPP) tracking of the different PV strings in the system and a central inverter (similar to that of the central concept of Fig. 1a) for connection to the low or medium voltage electricity grid. The concept of multistring configuration is demonstrated in Fig. 1b. The central inverter used in the configuration can be either a two-level voltage source converter (VSC) or a multilevel converter depending on the power and voltage ratings of the system.

As the power level of the system increases, multilevel converters offer significant advantages over their two level counterparts such as lower harmonic distortion in the output waveforms, reduced electromagnetic interference (EMI) and reduced semiconductor stresses. Additionally, they minimize the need for series connection of power switched and lower the switching frequency of individual switch resulting in higher efficiency [5]. Multilevel topologies, due to the previously mentioned advantages, have been widely used in medium voltage drive applications and for the integration of wind turbines to the grid [5].

The main multilevel topologies include the neutral-point

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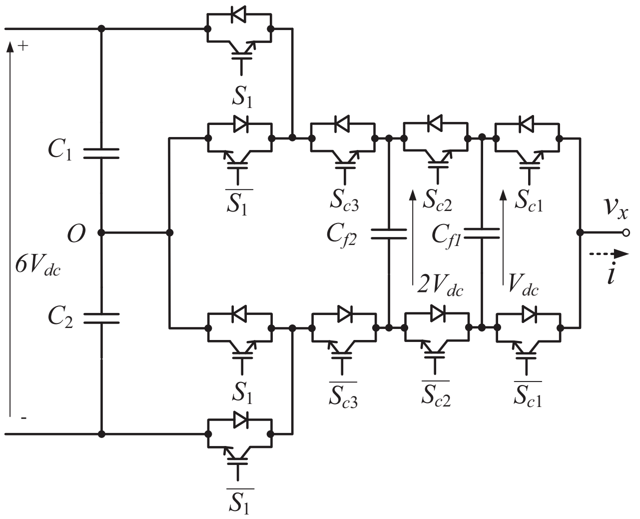

Fig. 2. Configuration of one phase of the seven-level flying capacitor based active NPC converter

clamped (NPC), flying capacitor (FC) and the cascaded H-bridges (CHB) converter. All three converters have been analyzed in the available technical literature identifying both the advantages and the challenges associated with each topology.

In order to utilize the advantages of each topology while minimizing the drawbacks as the number of voltage levels in the output increases, it is possible to combine the main toplogies and derive new converter configurations. These configurations, also known as hybrid multilevel converters, have attracted research interest in the last decade and certain technologies are already commercially available. Hybrid multilevel converters include topologies based on the cascaded connection of H-bridges to the output of typical converters [6], [7] as well as the active NPC family of multilevel converters [8]– [14].

This paper proposes the seven-level FC based ANPC converter (Fig. 2) for the grid integration of utility scale PV systems based on the multistring concept. The topology combines the advantages of the ANPC and FC converters, increasing the number of levels in the voltage output while reducing the filter requirements for the grid connection of the converter.

The paper is organized in the following way. Section II presents the circuit configuration, operating principles and modulation methods of the seven-level FC-based ANPC converter. Section III describes the configuration of the grid connected system and control structure while Section IV provides results based on simulations for the grid connected converter under steady state and transient operation. Finally the paper summarizes the conclusions in Section V.

II. Seven-Level FC Based ANPC Converter

The seven-level FC based ANPC (or seven-level ANPC) converter is the combination of a three-level ANPC converter with two FC cells at the output. The circuit configuration of one phase of the topology is given in Fig. 2. In order to derive the seven-levels at the output voltage waveform, the two

TABLE I
Switching States of the Seven-Level FC-based ANPC Converter

	S_1	S_{c3}	S_{c2}	S_{c1}	Output Voltage
V_1	0	0	0	0	$-3V_{dc}$
V_2	0	0	0	1	$-2V_{dc}$
V_3	0	0	1	0	$-2V_{dc}$
V_4	0	1	0	0	$-2V_{dc}$
V_5	0	0	1	1	$-V_{dc}$
V_6	0	1	0	1	$-V_{dc}$
V_7	0	1	1	0	$-V_{dc}$
V_8	0	1	1	1	$(-)0$
V_9	1	0	0	0	$(+)0$
V_{10}	1	0	0	1	$+V_{dc}$
V_{11}	1	0	1	0	$+V_{dc}$
V_{12}	1	1	0	0	$+V_{dc}$
V_{13}	1	0	1	1	$+2V_{dc}$
V_{14}	1	1	0	1	$+2V_{dc}$
V_{15}	1	1	1	0	$+2V_{dc}$
V_{16}	1	1	1	1	$+3V_{dc}$

capacitors have to be maintained at V_{dc} and $2V_{dc}$ respectively while the two DC-link capacitors are maintained to $3V_{dc}$ for a total voltage of $6V_{dc}$ in the overall DC-link. Each of the switches S_{c1}, S_{c2} and S_{c3} has to withstand voltage equal to V_{dc} while the outer S_1 switches of the topology should be rated for three times this voltage. In order to limit the stress and the higher losses of the outer switches, the modulation scheme operates the outer switches with a switching frequency equal to the fundamental frequency of the output waveform.

The limitation of fundamental switching frequency in the outer S_1 switches of the topology limits the available states of the three-level ANPC from six to four and in combination with the two states of each FC cell, the converter offers a total of sixteen switching states for the seven voltage levels in the output. The switching states and voltage outputs of the seven-level ANPC converter are summarized in Table I. The voltage levels of $\pm V_{dc}$ and $\pm 2V_{dc}$ can be acquired with three different switching combinations and the redundant switching states to acquire these levels offers a way to balance the voltages across the FCs and the neutral point voltage. The two states that provide the zero voltage state, due to the fundamental switching frequency of the outer switches, provide the zero voltage level during the positive (V_9) and negative (V_8) half-period of the waveform, respectively.

The voltage of the FC cells and the neutral point voltage (defined as the difference between the upper and lower DC-link capacitor voltage $V_{C_1} - V_{C_2}$) is affected by the switching states selected in the converter. The effect of each switching state on these voltages base on the direction of the current at the output of the phase is shown in Table II. The voltage regulation of the FCs is based on selecting the proper state to maintain both FC cells to their reference values. It is necessary for the proper operation of the converter to actively control the FC voltages to the reference voltages of V_{dc} and

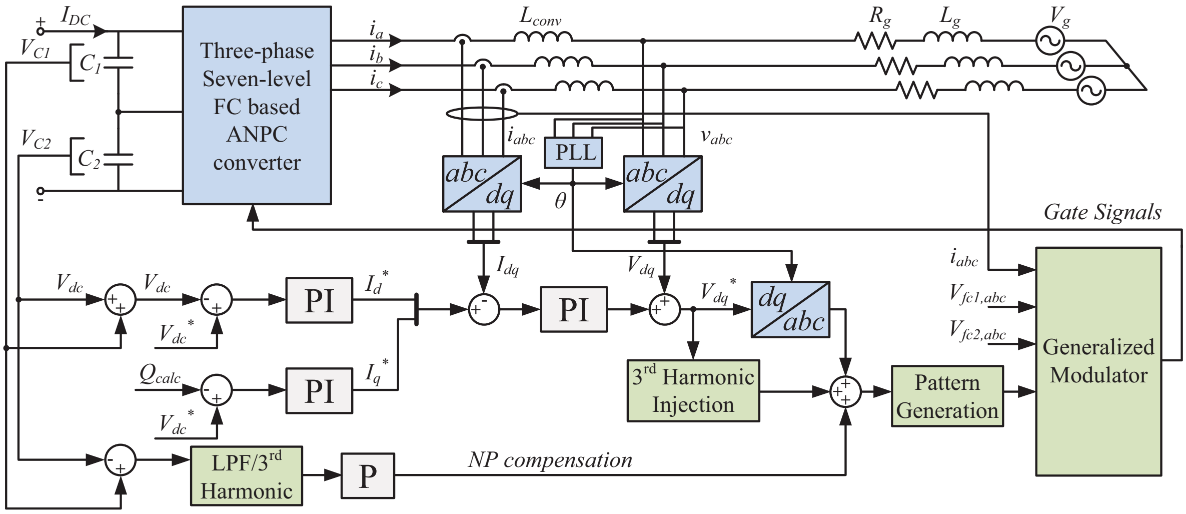

Fig. 3. Converter and controller configuration for the seven-level FC based ANPC converter

TABLE II
EFFECT OF THE SWITCHING STATES ON FC AND NP VOLTAGES

Switching states	Effect on FCs				Effect on NP		Output voltage
	$i>0$		$i<0$		$i>0$	$i<0$	
	C_{f1}	C_{f2}	C_{f1}	C_{f2}			
V_1	-	-	-	-	—	—	$-3V_{dc}$
V_2	⇓	-	⇓	-	—	—	$-2V_{dc}$
V_3	⇑	⇓	⇓	⇑	—	—	$-2V_{dc}$
V_4	-	⇑	-	⇓	↗	↘	$-2V_{dc}$
V_5	-	⇓	-	⇑	—	—	$-V_{dc}$
V_6	⇓	⇑	⇑	⇓	↗	↘	$-V_{dc}$
V_7	⇑	-	⇓	-	↗	↘	$-V_{dc}$
V_8	-	-	-	-	↗	↘	0
V_9	-	-	-	-	↗	↘	0
V_{10}	⇓	-	⇑	-	↗	↘	$+V_{dc}$
V_{11}	⇑	⇓	⇓	⇑	↗	↘	$+V_{dc}$
V_{12}	-	⇑	-	⇓	—	—	$+V_{dc}$
V_{13}	-	⇓	-	⇑	↗	↘	$+2V_{dc}$
V_{14}	⇓	⇑	⇑	⇓	—	—	$+2V_{dc}$
V_{15}	⇑	-	⇓	-	—	—	$+2V_{dc}$
V_{16}	-	-	-	-	—	—	$+3V_{dc}$

$2V_{dc}$ respectively. This process requires active balancing of the two capacitors by selecting the corresponding states that regulate the voltages towards the reference values. A number of methods have been proposed in the literature including natural balancing of voltage level modulation [13], nearest voltage level [14] and a generalized modulator suitable for SPWM and selective harmonic elimination PWM techniques [16].

III. Grid Connected System Configuration and Control

The seven-level ANPC converter is applied in the grid integration of a utility scale PV plant and depending on

TABLE III
PARAMETERS OF THE SIMULATED SYSTEM

Parameter	Value
Fundamental Frequency	50 Hz
Rated Power	1MVA
Carrier Frequency (LSC-PWM)	2 kHz
Flying Capacitors	2 mF
DC-link Capacitors	2 mF
DC-link Voltage ($6V_{dc}$)	5.5 kV

the voltage level, the converter can be connected to a low or medium voltage grid through a transformer at the point of common coupling (PCC). A rated power of 1 MW is considered as a typical value of a PV cluster for the system and simulations. Depending on the configuration of the PV plant, higher power could also be attained through the converter. Both the flying and the DC-link capacitors are selected to be 2 mF for a output switching frequency of 2 kHz. As the selection of the switching states is based on the generalized modulator presented in [16], the average switching frequency of each power device is approximately 800-900Hz.

The parameters of the overall system are presented in Table III and the simulation model together with the controllers are shown in Fig. 3. The control of the system is based on the well-known decoupled dq-control. The converter is used for the grid integration of the PV plant and the control variables of the system are the DC-link voltage and the reactive power at the PCC, that is maintained to zero.

In order to extend the operational range of the converter an optimal third harmonic injection is used in the modulation of the converter [17]. In order to facilitate the balancing of the neutral point in the DC-link, a feed-forward compensation is also used in the system [17]. The difference between the DC-link voltages is filtered so that the third harmonic and the switching frequency harmonics are removed and the deviation

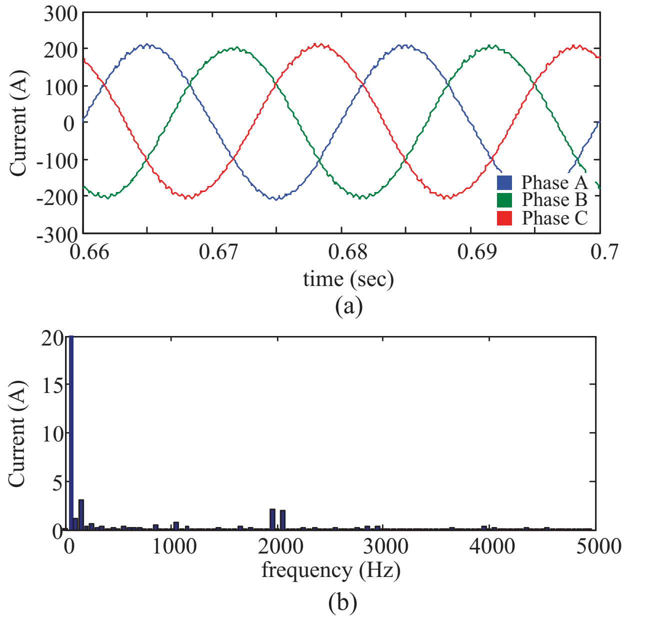

Fig. 4. Grid connected seven-level ANPC converter, (a) Grid currents, (b) Corresponding harmonic spectrum

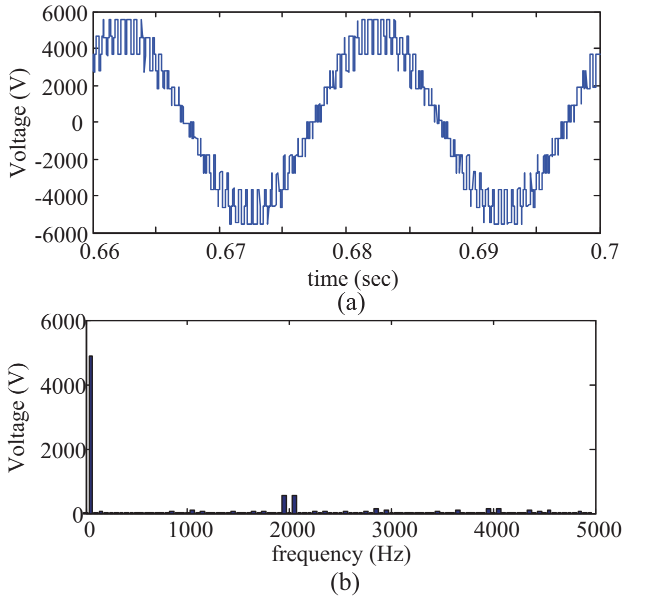

Fig. 5. Grid connected seven-level ANPC converter, (a) Line-to-line voltages, (b) Corresponding harmonic spectrum

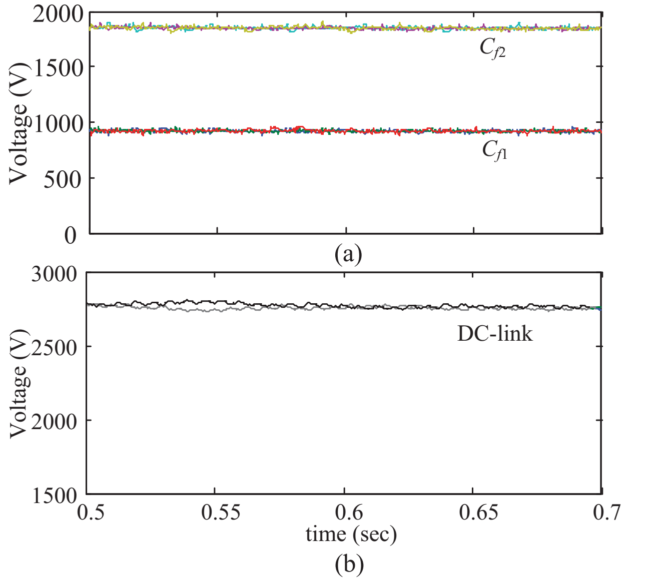

Fig. 6. Grid connected seven-level ANPC converter, (a) Flying capacitor voltages, (b) DC-link capacitor voltages

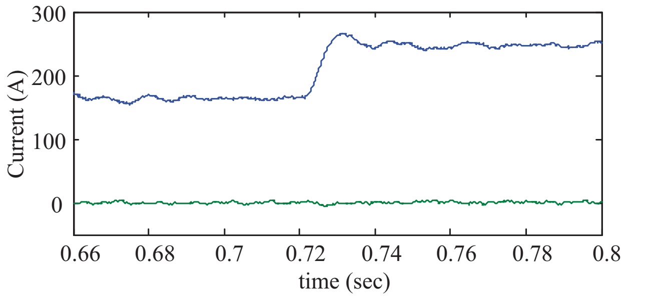

Fig. 7. d and q components of the grid currents for a step change in the active power of the converter

of two DC-link voltages is added, after it has been scaled through the proportional gain, to the modulation index used by the generalized modulator.

IV. Simulation Results

In order to demonstrate the operational characteristics of the topology, the seven-level FC based ANPC converter is simulated in MATLAB/SIMULINK using the PLECS toolbox. Under steady state operation, the converter is capable of providing high quality output waveforms, minimizing the requirements for filters in the output. The three-phase currents at the output of the converter for 0.85p.u. active power at the output are given in Fig. 4a. The corresponding FFT is shown in Fig. 4b, where all the harmonics are well below the requirements of IEEE Std 519 [18]. The line-to-line voltage at the output of the converter and the corresponding harmonic spectrum at the output of seven-level topology are given in Figs. 5a and b, respectively.

The voltages of the flying and DC-link capacitors during ten periods of operation of the converter under steady state are given in Figs. 6a and b respectively. All the voltages are regulated to the respective references as required for the correct operation and in order to derive the seven levels in the voltage output of the converter. The deviation of each capacitor voltage is below 3% (higher deviation is expected in the first cell capacitor as it is maintained to a lower voltage than cell two) and the voltages of the FCs for all three-phases are tightly regulated.

The performance of the converter under a step change in the

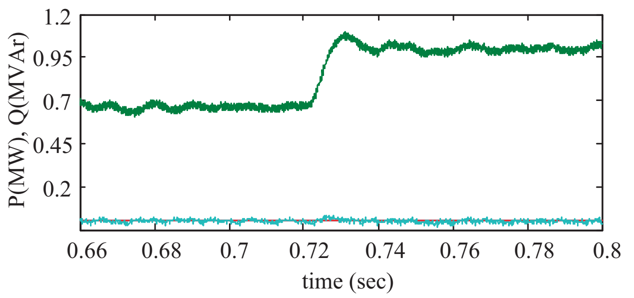

Fig. 8. Active and reactive power at the point of common coupling

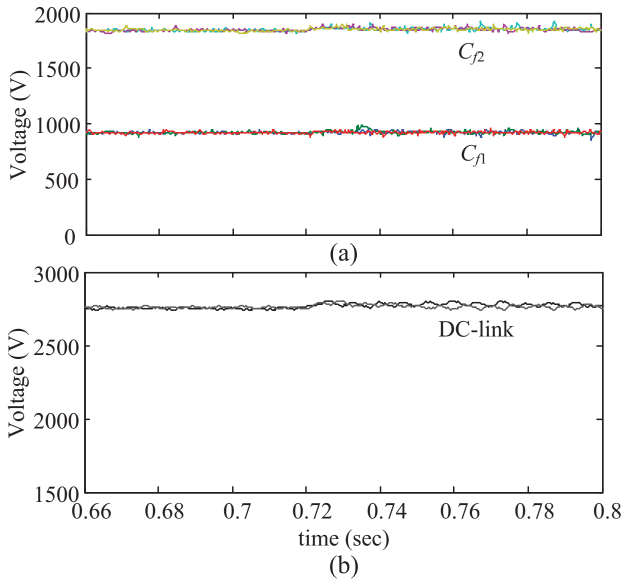

Fig. 9. Step change in the active power, (a) FC voltages, (b) DC-link capacitor voltages

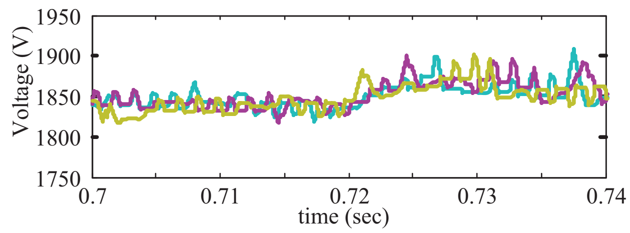

Fig. 10. Variation of cell two capacitor during a step change in active power

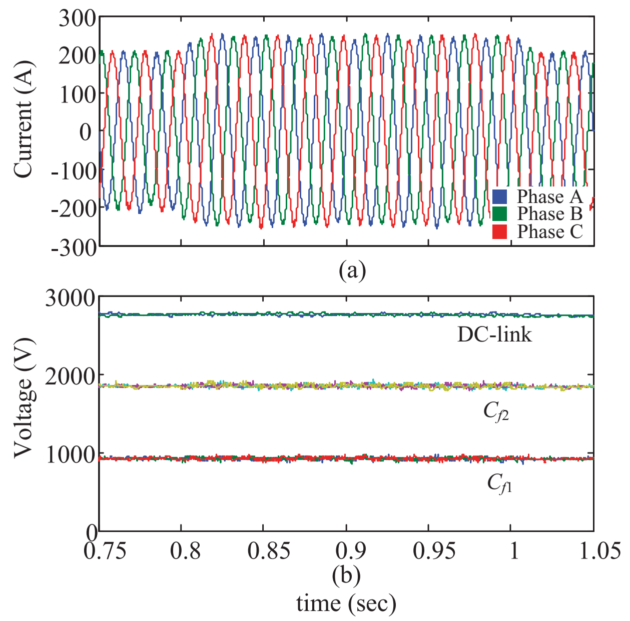

Fig. 11. Converter performance during a voltage sag at the PCC (a) Phase currents, (b) DC-link and flying capacitor voltages

output power is also investigated through simulations. Fig. 7 shows the d and q components of the current for a step change from 66% to 100% of the rated active power of the system while Fig. 8 shows the output active and reactive power of the converter at the PCC. The intermediate stages in the modulator and the selection of switching states in the converter in order to regulate the FC voltages affect the both the response and settling time of the converter during transients. The internal dynamics of the converter, especially those dealing with the balancing of the capacitors and which are the main priority of the modulator, affect its transient performance and may pose certain limits to the steps imposed on the references of the converter or the rate that the converter can follow transient changes.

During the step in the active power, the voltages of the FCs and DC-link capacitors are again tightly regulated as shown in Fig. 9a for the FCs and Fig. 9b for the DC-link capacitors. Fig. 10 shows the voltages of cell 2 capacitors during the step change in the active power. The capacitor voltages require one period to settle to the reference values while the higher current through each phase increases the ripple across each of the capacitors.

Finally, the performance of the converter during a voltage sag (type A [19]) of 20% at the PCC for 0.2 sec (0.8 to 1 sec) is also investigated. The converter maintains the power delivered to the PCC constant while again regulating the FC and DC-link voltages to the corresponding reference values. Fig. 11a shows the three-phase currents at the PCC during the voltage sag while Fig. 11b shows the DC-link and FC capacitor voltage, before during and after the voltage sag at the PCC.

V. Conclusions

In this paper, the seven-level FC based ANPC converter (or seven-level ANPC) is proposed for the grid integration of utility scale PV plants. The multilevel waveform at the output provides high quality voltages and currents at the PCC, minimizing the filtering requirements for the topology.

The paper presents the operating principles of the topology and the grid connected system under investigation. Simulation results of the system under steady state and dynamic changes both on the DC and AC side demonstrate the operation of the converter. The flying capacitor and DC-link voltages are tightly regulated to the reference values while the switching frequency of the individual power switches is maintained low. Although the internal dynamics, due to the regulation of the DC-link and FC voltages, affect the transient response of the converter, the results obtained are satisfactory for the proposed application of the converter.

REFERENCES

[1] European Photovoltaic Industry Association (EPIA) Report 2011, available at www.epia.org

[2] International Energy Agency Photovoltaic Power System Report 2011, available at http://iea-pvps.org/

[3] Blaabjerg, F.; Iov, F.; Kerekes, T.; Teodorescu, R.; Ma, K.; "Power electronics - key technology for renewable energy systems " in *Power Electronics, Drive Systems and Technologies Conference (PEDSTC), 2011 2nd* , 2011 , pp. 445 - 466

[4] Solar Flagships Program, Available online: http://www.ret.gov.au/energy/clean/sfp/Pages/sfp.aspx

[5] S. Kouro, M. Malinowski, K. Gopakumar, J.Pou, L. G. Franquelo, B.Wu, J. Rodriguez, M. A. Perez, and J. I. Leon, "Recent advances and industrial applications of multilevel converters," in *IEEE Trans. on Ind. Electron.*, vol. 57, no. 8, pp. 2553–2580, Aug. 2010.

[6] M. Veenstra and A. Rufer, "Control of a hybrid asymmetric multilevel inverter for competitive medium-voltage industrial drives," in *IEEE Trans.on Ind. Appl.*, Vol. 41, No.2, pp.655-664, Mar./Apr. 2005.

[7] G. Konstantinou, S. R. Pulikanti, and V. G. Agelidis, "Harmonic elimination control of a five-level DC-AC cascaded H-bridge inverter," in *Proc. IEEE PEDG*, 2010 pp. 352–357.

[8] P. Barbosa, P. K. Steimer, M. Winkelnkemper, J. Steinke, and N. Celanovic, "Active-neutral-point clamped (ANPC) multilevel converter technology," in *Proc. of EPE Conf.*, 2005, pp.11–14.

[9] S. R. Pulikanti and V. G. Agelidis, "Five-level active NPC converter topology: SHE-PWM control and operation principles," in *Proc. of AUPEC*, Perth, Australia, 2007, pp.1-5.

[10] F. Kieferndorf, M. Basler, L. A. Serpa, J. H. Fabian, A. Coccia, and G. A. Scheuer, "A new medium voltage drive system based on ANPC-5L technology," in *Proc. of ICIT Conf.*, 2010, pp.605–611.

[11] F. Kieferndorf, M. Basler, L. A. Serpa, J. H. Fabian, A. Coccia, and G. A. Scheuer "ANPC-5L technology applied to medium voltage variable speed drives applications" in *Proc. of SPEEDAM 2010*, pp. 1718 - 1725.

[12] S. R. Pulikanti, G. Konstantinou, and V. G. Agelidis "An n-level flying capacitor based active neutral point clamped converter," in *Proc. of IEEE PEDG*, May 2010, pp.553-558.

[13] S. R. Pulikanti, G. Konstantinou, and V. G. Agelidis, "Generalization of flying-capacitor based active-neutral-point-clamped Multilevel Converter Using Voltage-Level Modulation" in *IET Power Electronics*, Vol. 5, 2012.

[14] J.I. Leon, L.G. Franquelo, S. Kouro, B. Wu, S. Vazquez, "Novel modulator for the hybrid two cell flying capacitor based ANPC converter," in *POWERENG 2011*, Malaga, Spain, May 2011, pp. 1–6.

[15] J. Li, S. Bhattacharrya, A.Q. Huang, "A new nine-level active NPC (ANPC) converter for grid connection of large wind turbines for distributed generation" in *IEEE Trans. Power Electr.*, Vol. 26, No. 3, 2011, pp. 961-972.

[16] G. Konstantinou, S.R. Pulikanti and V. G. Agelidis, "Generalized modulator for the seven-level flying capacitor based active neutral point clamped converter," in *IEEE PEDG 2012*, Aalborg, Denmark, June 2012, pp. 1-6.

[17] A. Yazdani and R. Iravani, *Voltage-Sourced Converters in Power Systems (Power Engineering Series)*, IEEE Press, Piscataway, NJ, 2010.

[18] IEEE Recommended Practices and Requirements for Harmonic control in Electrical Power Systems, IEEE Standard 519-1992.

[19] M.H.J. Bollen, *Understanding Power Quality Problems: Voltage Sags and Interruptions (Power Engineering Series)*, IEEE Press, Piscataway, NJ, 2000.