A Three-Phase Three-Level NPC Inverter Based Grid-Connected Photovoltaic System With Active Power Filtering

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***Abstract*—This paper presents a three-phase three-level neutral point clamped (NPC) inverter based single-stage grid-connected photovoltaic (PV) system with shunt active power filter (APF) functionality. The proposed system can perform both the maximum real power injection with the perturb and observe (P&O) maximum power point tracking (MPPT) algorithm from the PV panels into the grid and active power filtering to compensate the load current harmonics. Thus, the PV system operates more efficiently compared to the conventional PV systems and can be useful for power system applications. Control of the proposed system is based on synchronous reference frame control algorithm and hysteresis band current control technique. The effectiveness of the proposed system is demonstrated with Matlab/Simulink simulations and validated through dSPACE DS1103 real-time control platform based laboratory experimental results.**

***Keywords*—photovoltaic system; active power filter; grid connected; multilevel inverter; maximum power point tracking.**

I. INTRODUCTION

Photovoltaic (PV) systems are becoming increasingly popular as a renewable source. The PV systems can be grouped into stand-alone systems and grid-connected systems [1]-[3]. Grid-connected PV systems are having more interest recently because they do not need physical storage systems (batteries) and so the investment cost is reduced. In grid-connected PV systems, maximum power point tacking (MPPT) techniques are used to deliver maximum power into the grid [4]. Because of having low implementation complexity Perturb&Observe method is widely used in PV systems [5]. Single-stage and two-stage grid-connected systems are commonly used topologies in PV applications [6], [7]. Two-stage system, has some disadvantages what are less efficient, being larger and more costly disadvantage. Therefore single-stage structure is widely used today due to small size, low cost, high efficiency and high reliability. Higher power equipments require higher voltages, which limit the maximum DC voltage level. Therefore a new family of multilevel inverters has emerged as the solution for solar applications, as the PV array is directly connected to each level of the DC link. NPC topology is popular since it has the advantages such as: DC-link capacitors are common to three phases, switching frequency can be low and reactive current and negative phase sequence current can be controlled [8]. Another benefit of using 3L NPC topology is the lower current THD; that reduces the filtering effort (less copper needed, lower losses in the filter) [9].

Also, the increasing use of power electronic devices and non-linear loads is known to cause serious problems in electric power systems. Therefore, the PV system combined with the function of a shunt active power filter (APF) can be useful for the application in the power distribution system [10]-[17]. The active filtering capability does not require modifications to the power stage. Also, single-phase or three-phase multilevel inverters for PV system grid integration have been suggested in order to improve the performance of the PV system [18]-[21].

In this study, the operation of a three-level neutral point clamped (NPC) inverter for the PV system including the function of APF, is investigated. The general diagram of grid connected PV system with APF function proposed in this work is shown in Fig. 1. The synchronous reference frame (*dq*) control strategy has been used for PV system active power injection and APF harmonic currents filtering. Hysteresis control technique has been applied for the switching pattern generation. The perturb and observe (P&O) MPPT technique is used and integrated with the dc-link controller. The feasibility of the proposed system is verified through Matlab/Simulink simulations and an experimental prototype with a dSPACE DS1103 real-time control board.

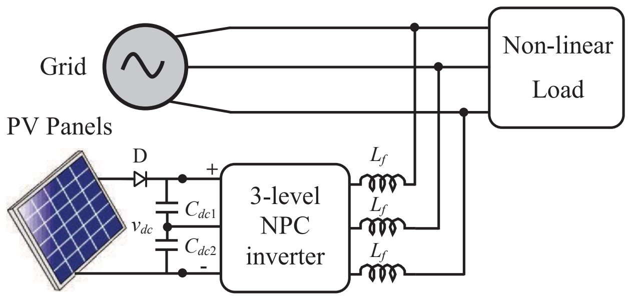

Fig. 1. General diagram of grid-connected PV system with APF function.

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II. Control of the PV system With APF function

The grid-connected PV system and shunt APF have similar topology and control strategy. The combined system can supply active power as well as current harmonics when irradiation is enough. In this study, the MPPT system is integrated with the DC-link controller so that a DC–DC converter is not needed and the output shows accurate and fast response. Fig. 2 shows the control block diagram of the single-stage grid-connected PV system with APF function.

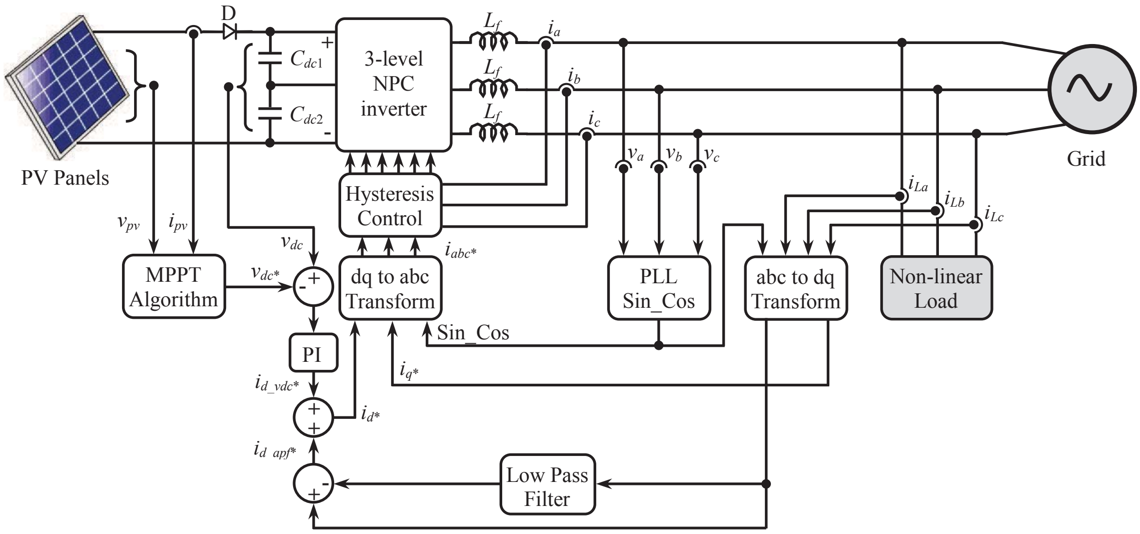

Fig. 2. Control block diagram of the single-stage grid-connected PV system with APF function.

In the control structure of the combined system one of active current reference components $i_{d\_vdc^*}$ is provided for active power injection, the dc-link voltage is set by a PI controller that compares the actual dc-link voltage and the reference generated by the P&O MPPT method. Also, in order to generate another active current reference component $i_{d\_apf^*}$, firstly, the measured load currents converted to general synchronous *dq* coordinates as in (1). Then the produced *d*-axis component is filtered through low pass filter (LPF) and extracted from the actual *d*-axis component. Thus the active current reference $i_{d\_apf^*}$ is provided to filter the load current harmonic components. Finally, active current reference is calculated shown in (2).

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \frac{2}{3}\begin{bmatrix} \sin(\omega t) & \sin(\omega t-\frac{2\pi}{3}) & \sin(\omega t+\frac{2\pi}{3}) \\ \cos(\omega t) & \cos(\omega t-\frac{2\pi}{3}) & \cos(\omega t+\frac{2\pi}{3}) \end{bmatrix}\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (1)$$

$$i_d^* = i_{d\_vdc}^* + i_{d\_apf}^* \quad (2)$$

The current reference on the *q*-axis i_q* is directly selected the actual i_q for power factor control. By applying the inverse *dq* transformation as in (3), the desired i_{abc^*} phase current references are obtained. These are passed to a hysteresis band current controller to generate the inverter gating signals needed to track the assembled current reference [22].

$$\begin{bmatrix} i_a^* \\ i_b^* \\ i_c^* \end{bmatrix} = \begin{bmatrix} \sin(\omega t) & \cos(\omega t) \\ \sin(\omega t-\frac{2\pi}{3}) & \cos(\omega t-\frac{2\pi}{3}) \\ \sin(\omega t+\frac{2\pi}{3}) & \cos(\omega t+\frac{2\pi}{3}) \end{bmatrix}\begin{bmatrix} i_d^* \\ i_q^* \end{bmatrix} \quad (3)$$

III. Simulation and experimental results

The performance of the combined operation of PV system with APF is analyzed and verified by simulations using Matlab/Simulink and experimental results with laboratory prototype. Harmonic currents were generated by a three-phase diode bridge rectifier as the non-linear load. The system parameters considered in this study are given in Table I. In this system, ten PV panels are connected in series to provide a 370V dc-link voltage and 5.4A dc-link current.

TABLE I. System Parameters

Grid	Voltage	110 V_{rms}/L-N
	Frequency	50 Hz
PV Panel	Peak power Open Circuit Voltage Short Circuit Current Voltage at MPP Current at MPP	200 Wp 45.78 V 5.75 A 37.05 V 5.40 A
PV system with APF	DC-link voltage L_f, C_{dc1}, C_{dc2}	370 V 6.7 mH, 2200 µF
Load	Three-phase diode bridge rectifier with RL load	90 Ω 5.6 mH

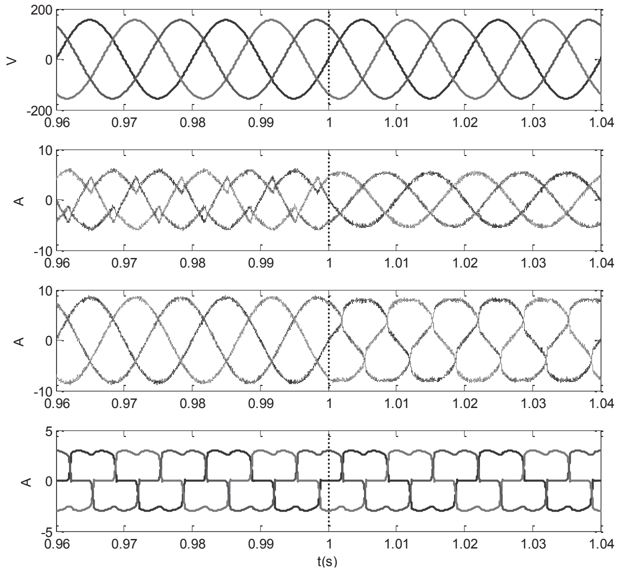

Fig. 3. Three-phase grid voltage, grid current, inverter current and load current waveforms, respectively.

The proposed system has tested two operation modes: PV system only and PV system with APF function. The system has operated as PV system without APF function during first second and as with APF function during last second. Three-phase grid voltage, grid current, inverter current and load current waveforms are shown in Fig 3. Grid current and inverter current THD waveforms are shown in Fig. 4. Also, in Fig 5, MPPT output reference voltage, dc-link voltage, PV panel power and current waveforms are illustrated. Simulation results show effectiveness of the MPPT and PV system with shunt APF function is able to inject real power and to compensate the harmonics currents.

A laboratory system has been designed and constructed to confirm the viability of the proposed system. The system is digitally controlled using a dSPACE DS1103 controller board. This hardware includes a real-time processor and the necessary I/O interfaces to allow the carrying out of the control operation and supports the real-time interface (RTI) tool that allows programming via Matlab/Simulink.

In the experimental system, load currents, inverter currents and source voltages are measured by utilizing hall-effect current and voltage sensors. The dc-link voltages are measured with an isolation amplifier. All of the measured signals are scaled in the signal conditioning board. This provides the measured signals at the required voltage level for the dSPACE ADC unit. Fig. 6 shows the experimental block diagram of the grid-connected PV system with APF function based on NPC inverter. The experimental results of the waveforms of grid voltage, grid current, inverter current and load current for phase-a are illustrated in Fig. 7. In the PV system only function mode, the PV system outputs a general sinusoidal current to inject an active power to the power system. Also, in PV system with APF function mode, it is observed that harmonics have been removed from the grid line, and the grid current is sinusoidal. In this study, the experimental waveforms were recorded with a Tektronix DPO3054 digital oscilloscope, and the harmonic analyses were done with a Fluke 434 power quality analyzer.

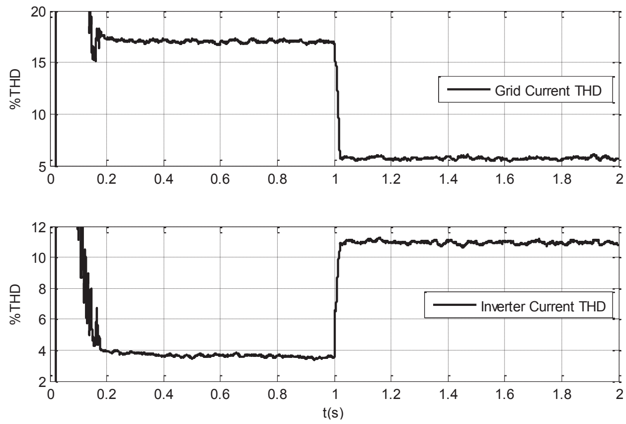

Fig. 4. Grid current and inverter current THD waveforms.

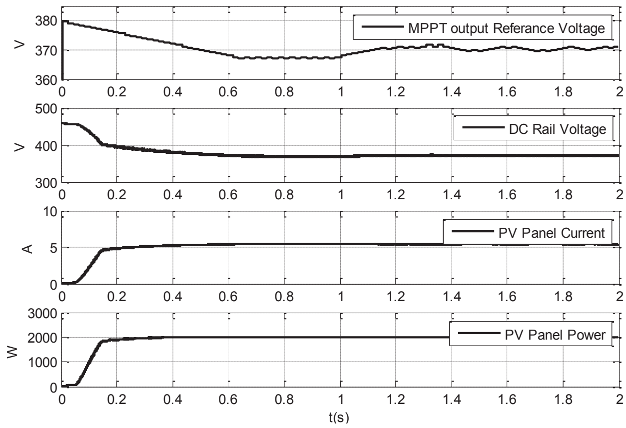

Fig. 5. MPPT output reference voltage, dc-link voltage, PV panel power and current waveforms.

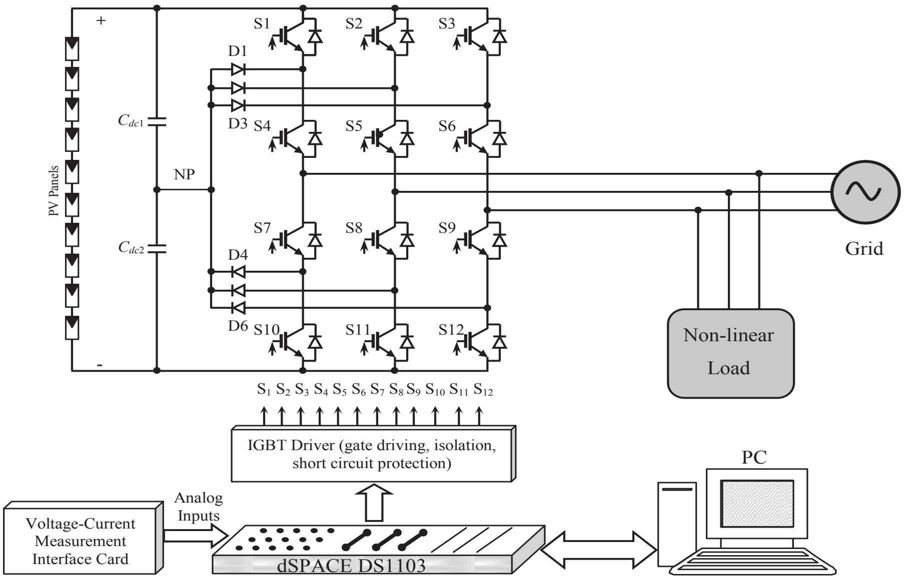

Fig. 6. The experimental block diagram of the PV system with APF function.

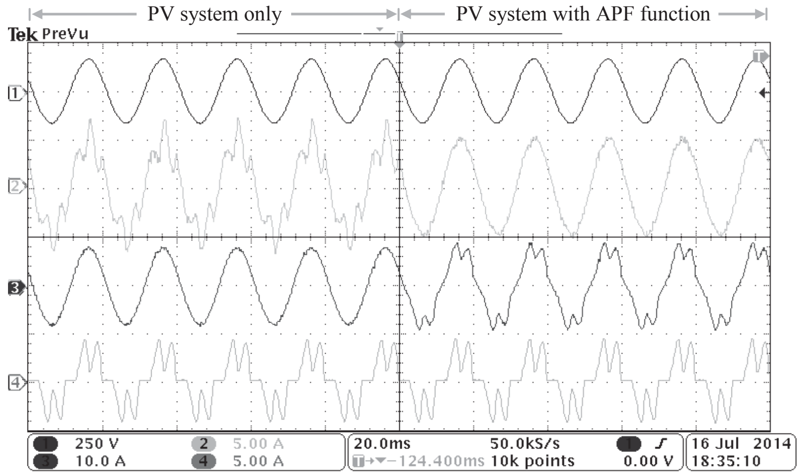

Fig. 7. The experimental results of the PV system with and without APF function.

The harmonic spectrum of inverter currents with PV system only operation mode is shown in Fig. 8. The inverter current THD values are well within the IEEE 519-1992 recommended limits. Fig. 9 and Fig. 10 show the harmonic elimination capability of the system with a non-linear load connected to the grid. The harmonic spectrum of source currents before and after APF function is shown in these figures, respectively. It can be seen that the THD value of the grid current can be reduced from 32.6% to 4.4% which is less than 5% requirement of the harmonic limit imposed by the IEEE 519 standard.

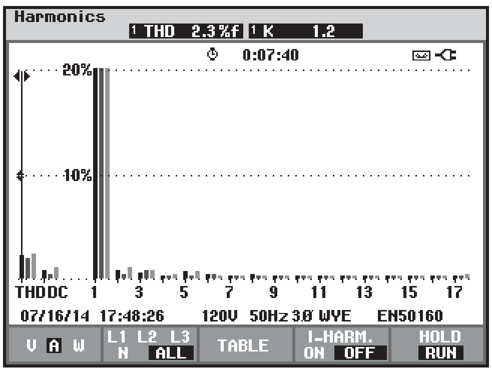

Fig. 8. The harmonic spectrum of inverter currents with PV system only.

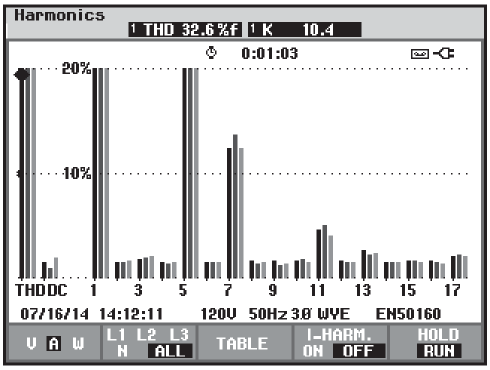

Fig. 9. The harmonic spectrum of source currents before APF function.

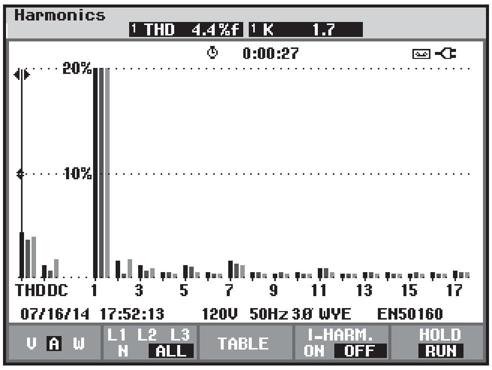

Fig. 10. The harmonic spectrum of source currents after APF function.

IV. Conclusions

In this paper, the performance of a three-phase single-stage grid-connected PV system with shunt APF function based on three-level NPC inverter is presented. This system can inject the maximum available PV power to the grid while simultaneously compensating harmonic currents drawn by non-linear loads. So, the combined system contributes to the enhancement of grid power quality. The effectiveness of the proposed system has been verified in simulations and experimentally using a dSPACE DS1103 controller based laboratory prototype. The results show that the proposed system is capable of injecting maximum PV power to grid while compensating load harmonic currents. After compensation, the grid current THD values are well within the IEEE 519-1992 recommended limits.

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