A Novel Photovoltaic Power Generation System including the Function of Shunt Active Filter

Minwon Park*, Nak-Gueon Seong and In-Keun Yu****

Abstract - With significant development of power electronics technology, the proliferation of nonlinear loads such as static power converters has deteriorated power quality in power transmission and distribution systems. Notably, voltage harmonics resulting from current harmonics produced by the nonlinear loads have become a serious problem in many countries. Many photovoltaic power generation systems installed in building systems have harmonics that are the worst object for distribution systems as a utility interactive system, and it tends to spread out continuously. Proposed and implemented in this paper is a multi-function inverter control strategy that allows a shunt active filter function to the power inverter of the photovoltaic power generation system established on a building system. The effectiveness of the proposed system is demonstrated through the simulation of a hypothetical power system using PSCAD/ EMTDC.

Keywords: Active filter, Photovoltaic, PV-AF System, MPPT(Maximum Power Point Tracking) control, Harmonics

1. Nomenclature

i_o = zero-sequence current of dq transformation [A]
i_d = d-axis current of dq transformation [A]
i_q = q-axis current of dq transformation [A]
i_{nd} = d-axis current of negative dq transformation [A]
i_{nq} = q-axis current of negative dq transformation [A]
e_R, e_S, e_T = three-phase utility L-G voltage [Volt]
e_{TR}, e_{RS}, e_{ST} = three-phase utility L-L voltage [Volt]
i_R, i_S, i_T = three-phase utility current [A]
i_U = utility current [A]
i_{LR}, i_{LS}, i_{LT} = three-phase load harmonics current [A]
i_L = load harmonics current [A]
i_{OUT} = PV-AF system output current [A]
i_{OUT} * = reference current of PV-AF system [A]
i_{AFR}, i_{AFS}, i_{AFT} = three-phase AF compensation current [A]
i_{AF} = AF compensation current [A]
i_{PV} = output current of PV array [A]
i_r = command current level [A]
i_{out} = inverter output current of PV system [A]
i_{CAF} = command output current of AF [A]
i_{CPV} = command output current of PV array [A]
e_{dc} = output voltage of PV array [Volt]
e_{dc} * = reference voltage of PV array output [Volt]
d = d-axis component of load harmonics current
q = q-axis component of load harmonics current
nd = negative d-axis component of load harmonics current
nq = negative q-axis component of load harmonics current
d' = d-axis negative-phase-sequence component of load harmonics current
q' = q-axis negative-phase-sequence component of load harmonics current
$d\sim$ = d-axis harmonics component of load harmonics current
$q\sim$ = q-axis harmonics component of load harmonics current

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2. Introduction

Photovoltaic (PV) power generation systems are a promising source of energy for the future. With great interest in clean and renewable energy sources, PV generation systems have been extensively studied and implemented [1] and have also been established as not only stand-alone systems, but also utility interactive systems [2]. The utility interactive system, in particular, is being distributed rapidly due to its availability and high efficiency. Practical technologies, however, are required in PV generation systems [3]. From the system operation technology and effectiveness point of view, the power output of the PV generation system is directly affected by weather conditions, and when AC power supply is needed, power conversion using an inverter system and an MPPT control are necessary.

With significant development of power electronics technology, the proliferation of nonlinear loads, such as static power converters, has deteriorated power quality in power transmission and distribution systems. Notably, voltage harmonics resulting from current harmonics produced by the nonlinear loads have become a serious problem in many countries.

To compensate for harmonics in power systems, active filters (AFs) have been rapidly expanding with power electronics technology developed. Since their basic compensation principles were proposed around 1970, significant research has been performed on active filters and their practical applications [4–8]. The main purpose of active filters installed by individual consumers is to compensate for the current harmonics and current imbalance of the consumers themselves equipment's harmonic-producing loads.

The primary purpose of the AFs to be installed by utilities in the near future is to compensate for voltage harmonics and voltage imbalance, or to provide "harmonic damping" throughout power distribution systems.

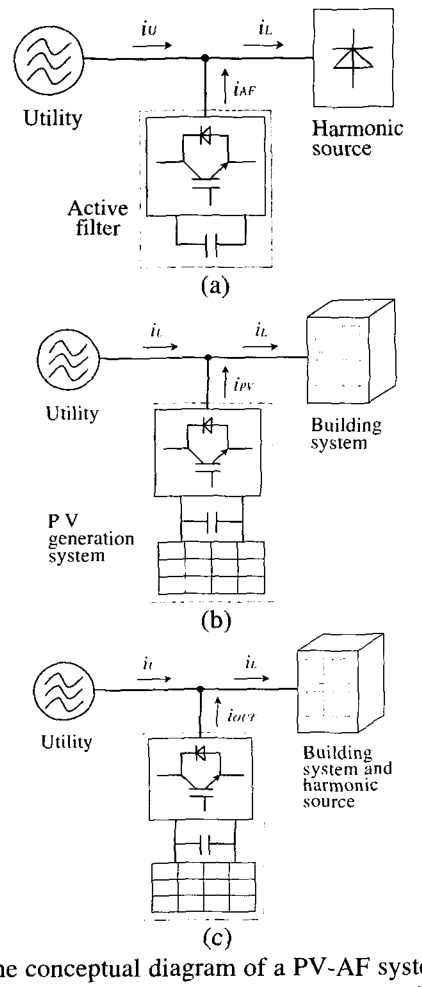


Fig. 1 The conceptual diagram of a PV-AF system: (a) the AF system, (b) the PV power generation system established in a building system, (c) the PV-AF system established in a building system.

The authors propose the possibility of adding the AF function into the power inverter of the PV power generation system. Many PV systems are already established in building systems with harmonics that are the worst object for distribution systems.

Fig. 1 explains the conceptual diagram of the PV-AF system. Figs. 1 (a) and (b) show the AF system and the PV power generation system, respectively, established in the building system. Fig. 1 (c) describes the PV-AF system. As shown in Fig. 1, the PV power generation system is physically adequate for achieving the PV-AF system and, thus, is proposed in this paper. The authors propose a multi-function inverter control strategy that adds the function of a shunt AF to the power inverter of the PV power generation system established in the building system using the reference voltage MPPT control.

3. AF systems

The shunt AF is used in this paper to compensate for the inverter's current harmonics and to stabilize utility power quality. The merit of the AF is its compensation ability with various changes of the utility condition. Compensation current is generated continuously from the AF. In general, two kinds of control strategies exist for extracting current or voltage harmonics from the corresponding distorted current or voltage. One is based on the Fourier analysis in the frequency domain [9,10], and the other, called the "p-q theory," is based on the theory of instantaneous reactive power in the three-phase circuit [11]. The concept of the p-q theory in the time-domain has been applied to the control strategy of almost all AFs by individual high-power consumers.

The general dq transformation is used in this paper to compensate for the negative component and the harmonic component. Using the dq transformation as described in Equation (1), the positive-phase-sequence component, the negative-phase-sequence component, and the harmonic component are shown as dc component, $2fHz$ component, and $6kfHz$ component, respectively (f = fundamental wave, k = 1, 2, 3,..). also In addition, in the case of ndq (negative dq) transformation, Equation (2), the negative-phase-sequence component, is shown as dc component.

$$\begin{bmatrix} i_o \\ i_d \\ i_q \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ -\sin\theta & -\sin\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} i_o \\ i_{nd} \\ i_{nq} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ \cos\theta & \cos\left(\theta + \frac{2\pi}{3}\right) & \cos\left(\theta - \frac{2\pi}{3}\right) \\ -\sin\theta & -\sin\left(\theta + \frac{2\pi}{3}\right) & -\sin\left(\theta - \frac{2\pi}{3}\right) \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \tag{2}$$

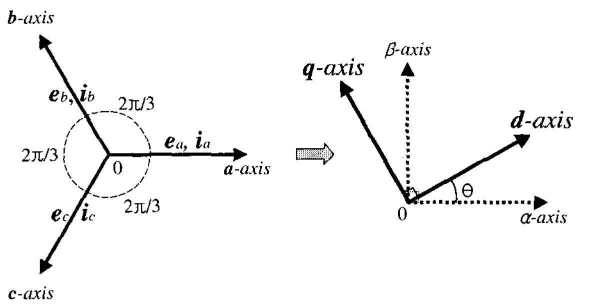


Fig. 2 Relation between three-phase and dq component.

Therefore, with a high pass filter (HPF), the harmonic component can be extracted using dq transformation, and with a low pass filter (LPF), the negative-phase-sequence component can also be extracted using ndq transformation [12].

Fig. 2 shows conceptual diagram of dq transformation. The α and β axes shown in Fig. 2 are the orthogonal coordinates that converted from three-phase coordinates. And the dq coordinate system results from rotation of the α-β coordinate system.

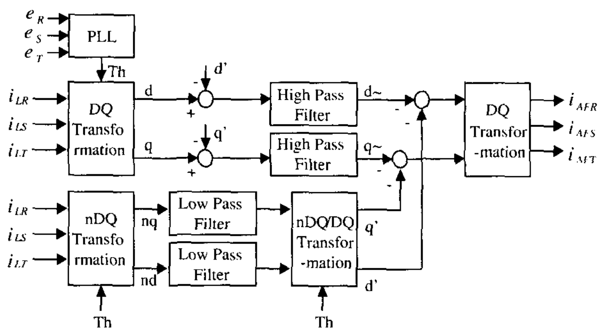


Fig. 3 Control block diagram of AF system.

The block diagram of the AF system is shown in Fig. 3.

Feedback load harmonic currents (i_{LR}, i_{LS}, i_{LT}) are transferred to dq and ndq values. ndq values are filtered by an LPF and remain as the negative-phase-sequence component (d', q'). The harmonics component ($d\sim$, $q\sim$) are obtained by the HPF. With these filtered components, the compensation current is determined.

4. PV-AF system

Individual consumers and end-users are responsible for keeping the current harmonics produced by their own equipment within the specified limits. Including the function of the AF in the PV power generation system connected up to utility system would be very helpful for the improvement of power quality for individual consumers rather than for the utility system. The main circuit diagram of the PV-AF system proposed in this work is shown in Fig 4. For the purpose of stable MPPT control, a novel reference voltage MPPT control is applied.

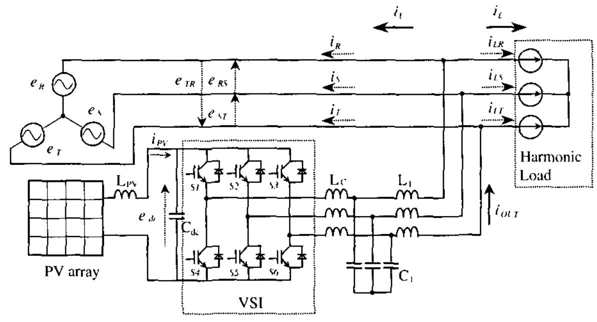


Fig. 4 Main circuit diagram of the PV-AF system.

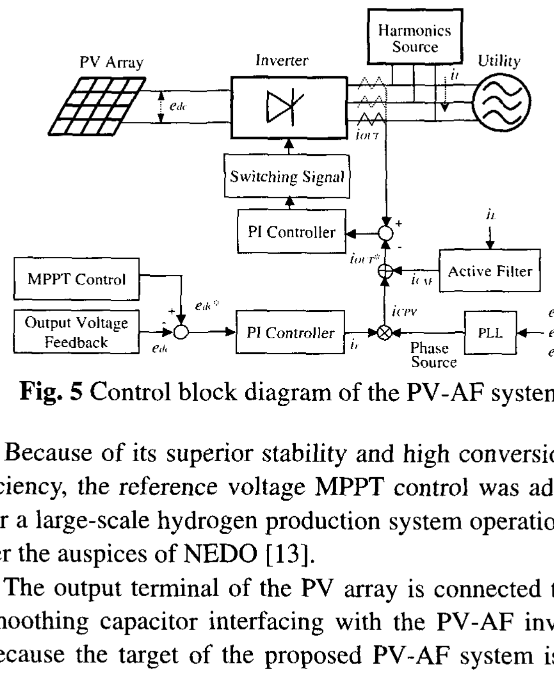


Fig. 5 Control block diagram of the PV-AF system.

Because of its superior stability and high conversion efficiency, the reference voltage MPPT control was adopted for a large-scale hydrogen production system operation under the auspices of NEDO [13].

The output terminal of the PV array is connected to the smoothing capacitor interfacing with the PV-AF inverter. Because the target of the proposed PV-AF system is that the conventional PV system also plays the AF system role, the fundamental circuit diagram is almost the same as the conventional three-phase PV system connected up to utility. Its control block diagram is shown in Fig. 5. The reference voltage calculated from the module surface temperature is compared with the feedback voltage of the PV array.

5. Simulation and analysis

5.1 Simulation conditions

To confirm the availability of the PV-AF system, a hypothetical simulation using PSCAD/EMTDC [14] is perpothetical simulation using PSCAD/EMTDC [14] is performed. The fundamental circuit and control diagram are the same as in Figs. 4 and 5, respectively. The voltage source PWM converter is controlled by the feedback loops of the output current of the inverter. Optimal values of PI gains and filter constants are tuned to obtain proper responses. General PI gains are selected in this simulation. Selected proportional gain is 0.01 and integral time constant is 1 sec. Table 1 represents the rates of the PV array and utility system, and the simulation conditions are given in Table 2.

Real weather conditions are used in this simulation. Fig 6 shows the real weather conditions used in the simulation. For more adequate simulation results, two kinds of weather conditions are used. The simulation method for the PV system using real weather conditions is described in [15]. During simulation, harmonic current is supplied to the utility by harmonic load. The 5th and 7th harmonics having two kinds of magnitudes are used in this simulation. Source voltage is, however, assumed as sinusoidal wave because the proposed PV-AF system inverter is shunted and can compensate for only the source current.

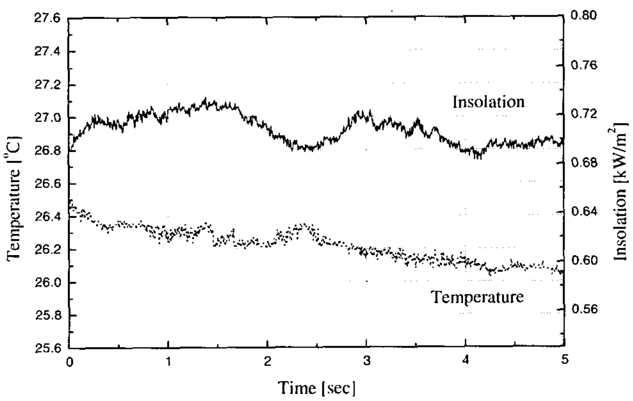
Table 3 shows three cases of simulation conditions. Each case has different weather and harmonics conditions.

Table 1 PV-AF system conditions

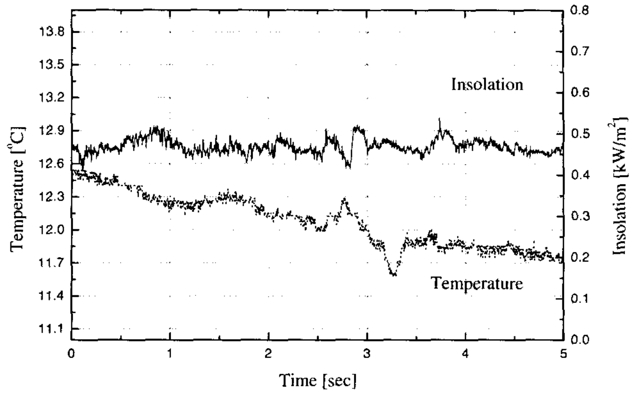
PV array	Rated Power	10.8 kW
	Rated Voltage	750 V
	Rated current	7 A
Utility	Rated Voltage	380 V
	Frequency	60 Hz

Table 2 Simulation conditions

Simulation Time	5.0 sec
Simulation Sampling Time	10 μs
Simulator	PSCAD/EMTDC



(a) Sunny condition



(b) Cloudy condition

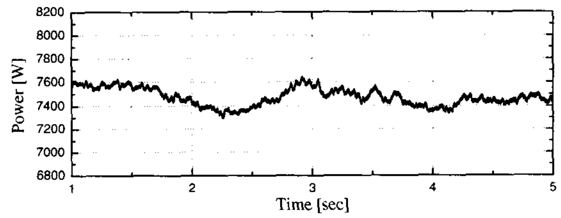
Fig. 6 Real weather conditions.

Table 3 Simulation condition of each case

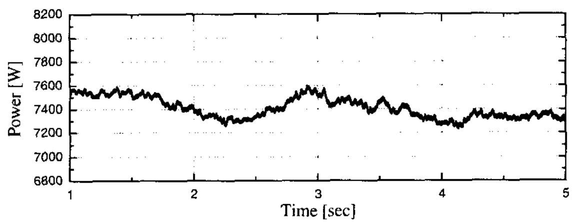
Case	Weather condition	Harmonics	
		5th	7th
Case 1	A of Fig. 5	4 [A] (5%) 1520 [W]	2.4 [A] (3%) 912 [W]
Case 2	A of Fig. 5	6.4 [A] (8%) 2432 [W]	4 [A] (5%) 1520 [W]
Case 3	B of Fig. 5	4 [A] (5%) 1520 [W]	2.4 [A] (3%) 912 [W]

5.2 Simulation results

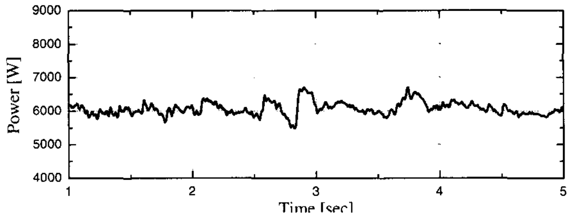
Fig. 7 shows the PV output power of each case. Differences of output power are caused by different weather conditions. Figs. 8 and 9 show the simulation results of the individual PV system. In this simulation, the function of the active filter is not activated. The output current of VSI flows in stably as expected but is unrelated with the harmonics of source current. Therefore, the harmonics current source deteriorates the utility current. . The utility harmonics current is confirmed through the Fast Fourier Transform (FFT) results of Fig. 10.



(a) Case 1

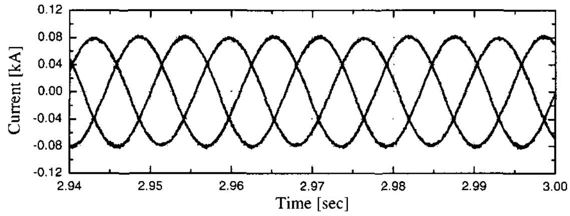


(b) Case 2

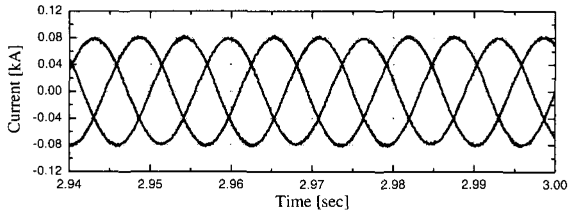


(c) Case 3

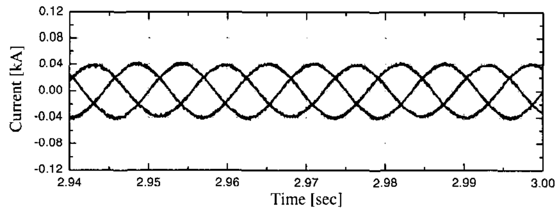
Fig. 7 Powers of each case.



(a) Case 1

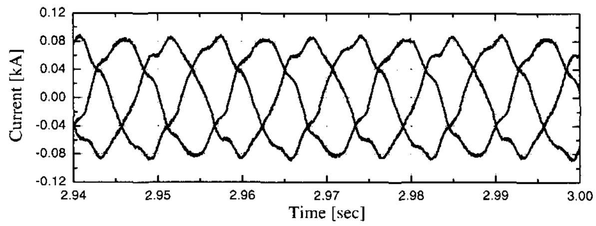


(b) Case 2

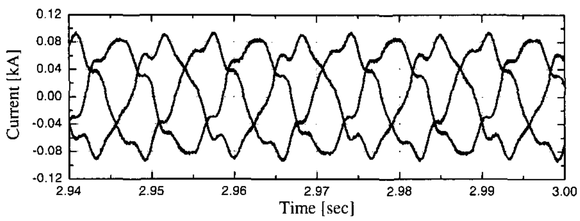


(c) Case 3

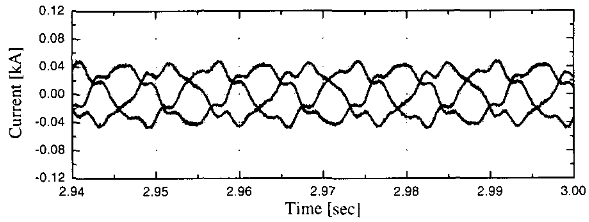
Fig. 8 Output current of inverter without AF function.



(a) Case 1

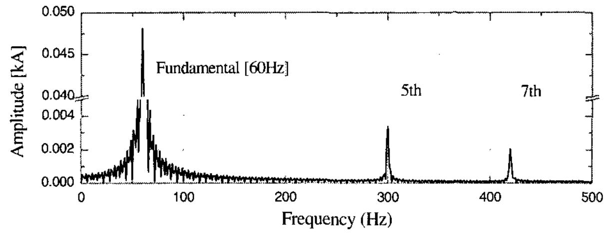


(b) Case 2

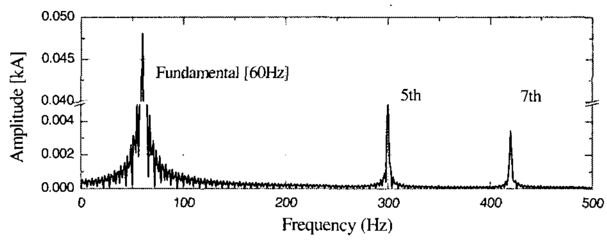


(c) Case 3

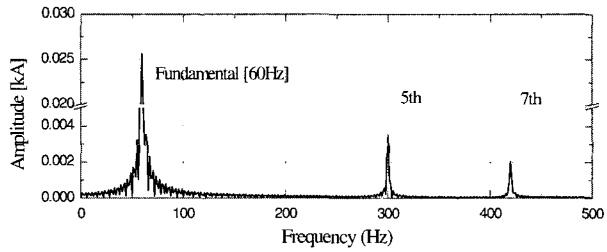
Fig. 9 Utility currents of each case without AF function.



(a) Case 1



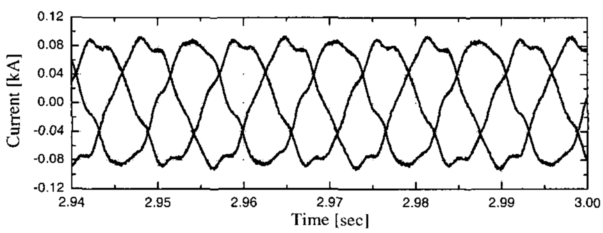
(b) Case 2



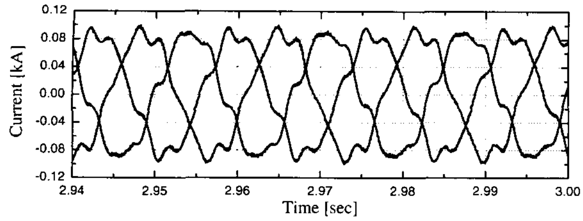
(c) Case 3

Fig. 10 The FFT results of utility current without AF function.

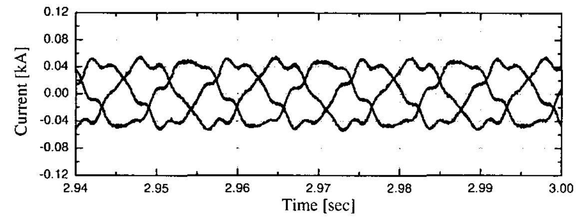
Figs. 11 and 12 show simulation results in which the function of the AF is included. As shown in Fig. 12, the sinusoidal source current is obtained by the PV-AF system implemented.



(a) Case 1

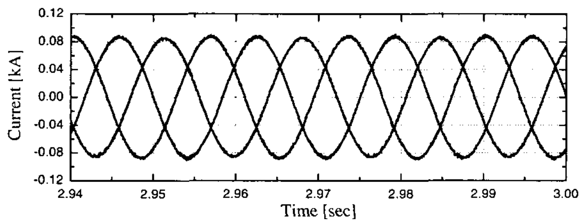


(b) Case 2

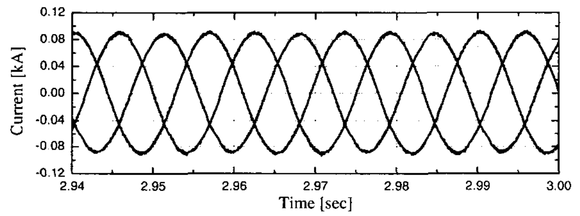


(c) Case 3

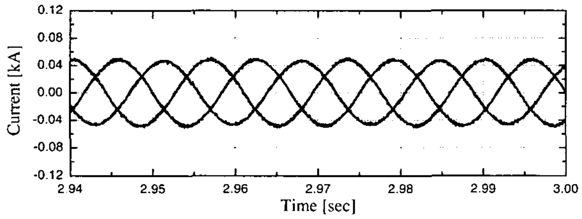
Fig. 11 Output current of inverter with AF function.



(a) Case 1

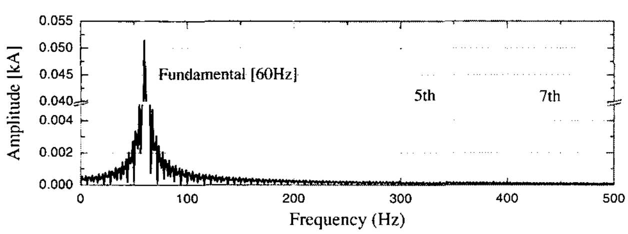


(b) Case 2

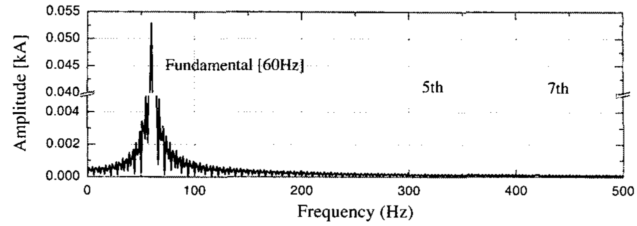


(c) Case 3

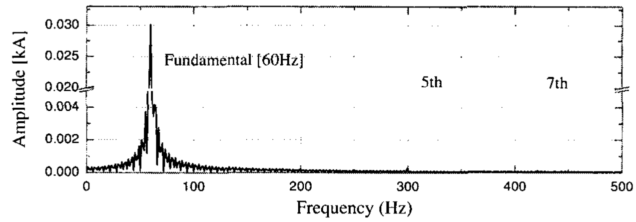
Fig. 12 Utility currents of each case with AF function.



(a) Case 1

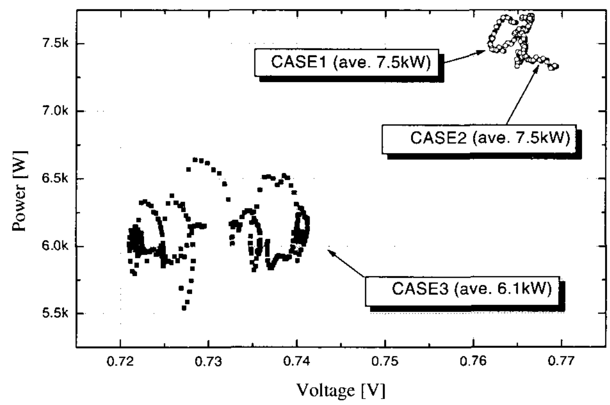


(b) Case 2

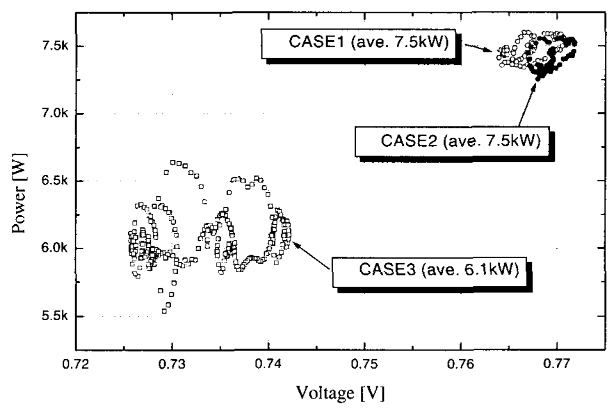


(c) Case 3

Fig. 13 The FFT results of utility current with AF function.



(a) Without AF



(b) With AF

Fig. 14 Utility currents of each case with AF function.

The output power of the PV array flows into the 5th and 7th harmonics load. The lack current is supplied from the source current. The AF compensation current also flows from VSI(Voltage Source Inverter) and makes the source current sinusoidal. As shown in Fig. 13, there are no longer any harmonics.

Fig. 14 shows the output power and voltage of the PV array. The simulation result without AF is shown in (a) and with AF in (b). At each case, comparing (a) and (b), the average power is nearly the same, which means that the function of the AF neither wastes power nor affects the power flow of the utility system.

6. Conclusions

In this paper, a novel PV power generation system including the function of a shunt active filter is proposed and confirms the possibility of combining the AF theory and the three-phase PV system connected to a utility system. Analysis of the simulation results further supports the theoretical possibility of realizing the PV-AF system. To stabilize VSI output current, the reference voltage MPPT control is applied in this work. Moreover, total compensation for harmonics via the active filter function included in the PV power generation systems is confirmed. As a result, utility power quality can be improved by the application of the AF function of the PV power generation system.

Acknowledgements

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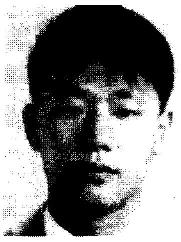

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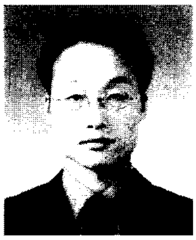

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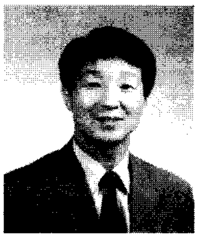

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