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Low-Harmonics Three-Phase Power Conditioner for Photovoltaic Integration

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Abstract: This paper describes the design of a power conditioning unit (PCU) for photovoltaic power system to be interconnected with the utility grid (UG). The proposed PCU employs six-pulse three-phase inverter with modified-sinusoidal-pulse- width-modulation (MSPWM) switching technique, a parallel and series filters and an efficient control of dc to ac power conversion. The parallel and series filters are designed for both harmonics reduction and power factor correction. The efficient control of dc to ac power conversion makes the inverter output voltage immune to the variation in the dc voltage. The proposed PCU has been studied with both equation solving and extensive simulations. A 5 MW PCU has been designed and its performance has been investigated in detail.

Keywords: Photovoltaic energy, Power conditioning unit, Inverter, Pulse-width-modulation, Harmonic filters, Power factor correction

1. Introduction

Energy is a basic human need for both human development and economic growth. An international priority is to ensure secure, reliable, affordable, clean and sustained energy supply. Both Japan and Egypt are relatively modest in their resources of conventional energies (oil and gas). To ensure sustainability of energy supply in the long term, it is clear that we need to exploit additional sources other than oil and gas.

Japan plays a leadership role in global efforts to tackle greenhouse emissions, to elaborate the degree of social cognition and credibility over green power (wind power generation, photovoltaic power generation, and so on), and to improve the energy and the environmental problems in Japan[1). As the host of the Kyoto summit in 1997, Japan is keen to reposition itself at the forefront of the battle against climate change.

Egypt is now adopting a national energy strategy. It includes setting clear energy efficiency and conservation policies and plans, and upgrading contribution of renewable energies in the energy mix to levels compatible with the Egyptian natural potentials. The installed capacity needed by the year 2020 from renewable energy, in the light of forecasted growth, is estimated to be between 8000 to 10000 MW[2).

Renewable energy technologies hold a great promise to meet humanity's energy needs[3)−5). The photovoltaic (PV) system technologies have increasing roles in electric power technologies, providing more secure power sources and pollution free electric supplies. Great efforts have been done in developing the performance of the PV systems[16)−13).

A power conditioning unit (PCU) is required to convert dc voltage generated from PV systems into ac voltage required for many loads and interconnecting with the utility grid (UG)[14)−17).

In the following sections, the switching device shown is an ideal switch, but it could be any switch, the choice being determined by availability of required rating and ease of turn-on and turn-off.

This paper is organized as follows: The proposed power conditioning unit, which consists of three-phase inverter, transformer and filter, and inverter control technique, has been explained and analyzed in the following section. Then, simulation and results has been described. Finally, conclusions has been presented.

2. The Proposed Power Conditioning Unit

The block diagram of the over-all photovoltaic power system is illustrated in **Fig. 1**. It consists of a PV array, typical maximum power point tracker (MPPT), PCU, and a switching system for connecting with the UG. Our focus in this paper is on the PCU, which consists of three main units: Three-phase inverter, transformer and filter, inverter control and drive circuit. These three units are described as follows:

2.1 Three-phase inverter

The most frequently used three-phase inverter circuit consists of three legs, one for each phase, as shown in **Fig. 2**. Each inverter leg is similar to the one used in half-bridge inverter. In order to produce a sinusoidal output voltage waveform with magnitude and frequency

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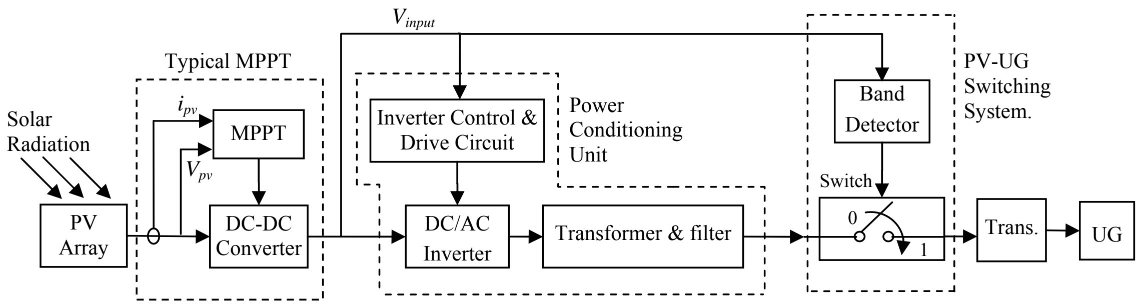

Fig. 1 Block diagram for overall photovoltaic power system.

controllable, a sinusoidal control signal at the desired frequency is compared to a triangular waveform, as shown in **Fig. 3**[18)−19)]. With the application of Fourier analysis[20)], the inverter output voltage and its harmonic parameters are analyzed as follows:

$$V_{an}(t)=a_o+\sum_{n=1}^{\infty}(a_n\cos(n\omega t)+b_n\sin(n\omega t)) \tag{1}$$

where; a_o, a_n and b_n are:

$$a_o=\sum_{m=1}^{m_f}\frac{V_d\,\delta_m}{2\pi} \tag{2}$$

where; m_f is the frequency modulation ratio:

$$a_n=\sum_{m=1}^{m_f}\frac{V_d}{n\pi}\sin(n(\alpha_m+\delta_m))-\sin(n\alpha_m) \tag{3}$$

$$b_n=\sum_{m=1}^{m_f}\frac{V_d}{n\pi}\cos(n\alpha_m)-\sin(n(\alpha_m+\delta_m)) \tag{4}$$

$$V_{bn}(t)=a_o+\sum_{n=1}^{\infty}(a_n\cos(n(\omega t-\frac{2\pi}{3}))+b_n\sin(n(\omega t-\frac{2\pi}{3}))) \tag{5}$$

$$V_{ab}(t)=V_{an}(t)-V_{bn}(t) \tag{6}$$

Then, the output of practical inverters contains harmonics and the quality of an inverter is normally evaluated in terms of the following performance parameters: Harmonic factor of nth harmonic, HF_n:

$$HF_n=\frac{V_n}{V_1} \tag{7}$$

Total harmonic distortion of voltage, THD_v:

$$THD_v=\frac{1}{V_1}(\sum_{n=2}^{\infty}V_n^2)^{1/2} \tag{8}$$

In the three-phase inverters, only the harmonics in the line-to-line voltages are of concern. The gating signals are generated by sinusoidal pulse width modulation (SPWM) technique. This technique generates the

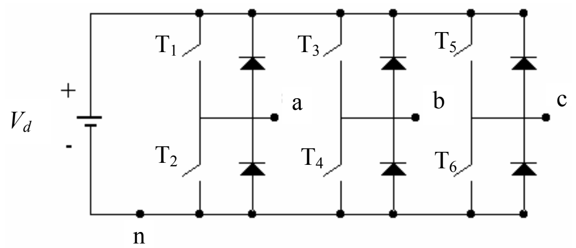

Fig. 2 Basic three-phase inverter.

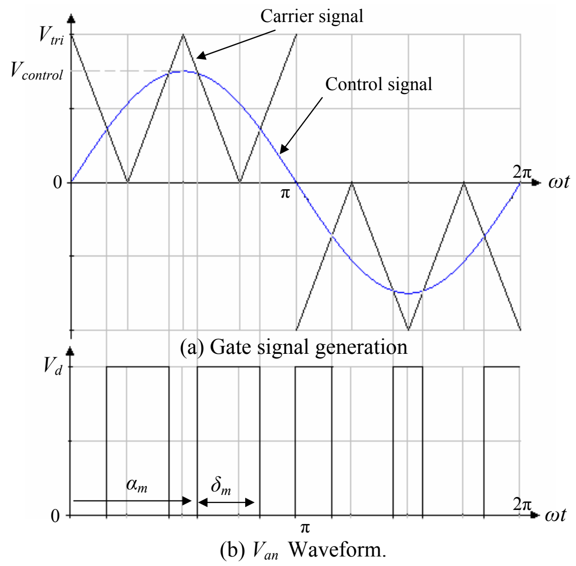

Fig. 3 Gate signals generation sinusoidal pulse-width modulation by basic SPWM technique.

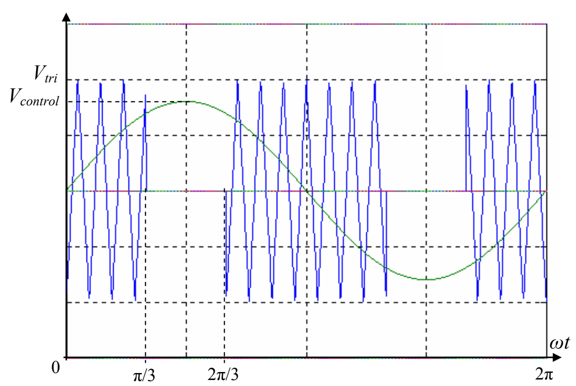

Fig. 4 Gate signals generation using MSPWM technique.

gating signals by comparing a sinusoidal reference signal with a triangular carrier wave. The SPWM technique can be modified to make the carrier wave has an effect only during the first and the last 60° intervals per half-cycle. This modified technique can be called MSPWM. The fundamental component is increased and its harmonic characteristics are improved, applied to a single phase inverter in 18). It reduces the number of the switching of the power devices and also reduces the switching losses. **Figure 4** shows the gate signal generation by MSPWM technique.

A MATLAB program is developed to achieve the analysis of the case study. It used the following data:

- Line frequency = 50 Hz,
- Dc input voltage = 2000 V (2 p.u.),
- Number of harmonics considered in calculations = 100,
- Number of pulses per cycle = 21, and
- Modulation index = 0.8.

Figure 5(a), **Fig. 6(a)**, **Fig. 7(a)**, and **Fig. 8(a)** show the line voltage waveform (V_{ab}), its harmonic spectrum, the line current waveform (I_L), and its harmonic spectrum, respectively. The following results have been obtained:

The fundamental voltage:

V_{ab1} = 1.165 p.u., and THD_v = 66.4223%

The fundamental current:

I_{L1} =1.2946 p.u., THD_i = 6.1708%

2.2 Transformer and filter

To attenuate the harmonic content of these waveforms, it is necessary to pass them through a filter. **Figure 9** shows the proposed filter circuit. It consists of two types of filters as described below:

2.2.1 Series filter

The harmonic currents can be reduced significantly by the simple addition of a series line reactance. The inductive reactance of the line reactor allows the 50 Hz current to pass easily but presents considerably higher impedance to all of the harmonic frequencies. Harmonic currents are thus well attenuated. An eight-percent inductive reactance including the isolating transformer reactance is best for reducing harmonic currents and voltages.

2.2.2 Shunt filters

The shunt-type single tuned (band stop) filter presents a low (resistive) impedance at the resonant frequency only. It behaves as high capacitive impedance at fundamental frequency, and produce valuable leading reactive volt-amps which is used for power-factor correction.

A suitable compromise, for the case study, is to use

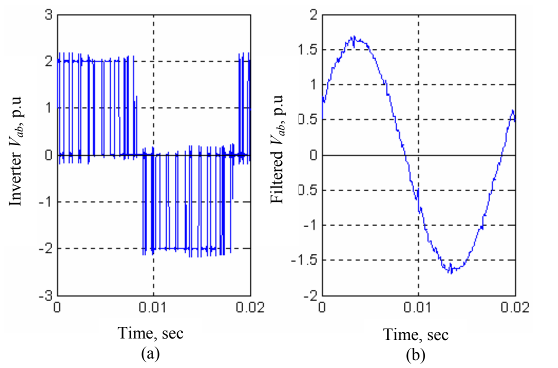

Fig. 5 Effect of the proposed filter on the line voltage: (a) unfiltered voltage, (b) filtered voltage.

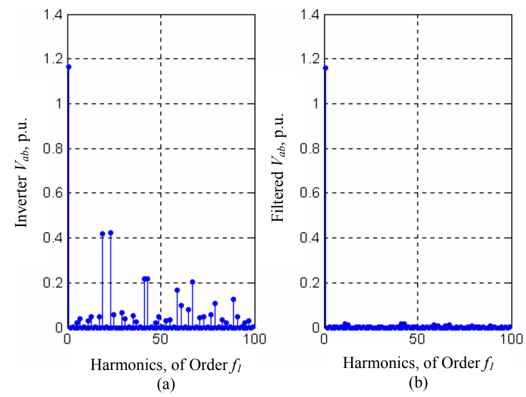

Fig. 6 Effect of the proposed filter on the line voltage harmonic spectrum: (a) unfiltered spectrum, (b) filtered spectrum.

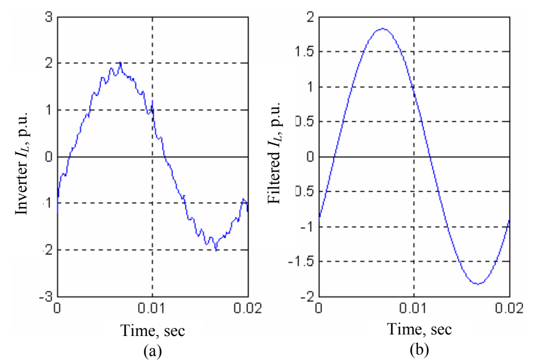

Fig. 7 Effect of the proposed filter on the line current: (a) unfiltered current, (b) filtered current.

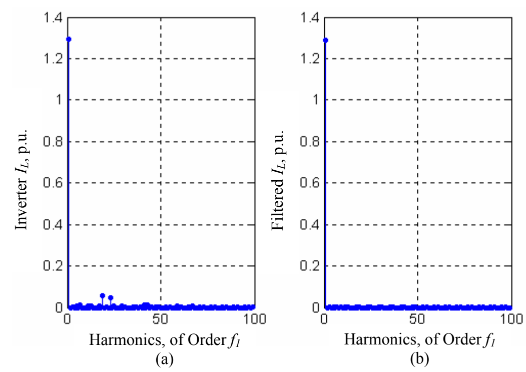

Fig. 8 Effect of the proposed filter on the line current harmonic spectrum: (a) unfiltered spectrum, (b) filtered spectrum.

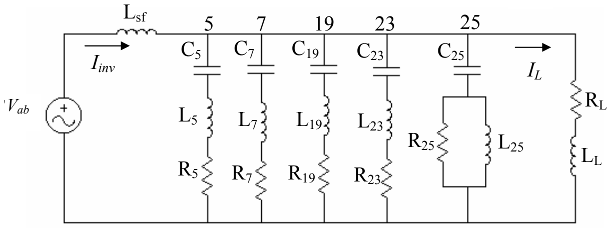

Fig. 9 The proposed filter circuit.

Table 1 Values of the designed shunt filter elements.

Element	Branch Order				
	5	7	19	23	25
F_o, Hz	250	350	950	1150	1250
R, Ω	12.077	8.6267	3.1783	2.6255	89.94
L, H	0.2863	0.1461	0.0198	0.0135	0.0115
C, μF	1.4157	1.4157	1.4157	1.4157	1.4157

resonant arms for harmonics orders 5, 7, 19, 23 plus a low-pass filter arm for harmonic orders 25 and upwards, all arms in parallel (see **Fig. 9**). This arrangement has been selected by trying to reach the one that gives the minimum possible harmonics. For the three-phase system, the suitable arrangement is the star connection of the filter groups with earthed neutral. The design of the single tuned filters and second order low-pass filter has been achieved using the equations in 21).

A MATLAB program is developed to design the desired filter and then it calculates the load voltage and current waveforms after filtering. **Table (1)** shows the designed shunt filter elements components values. The following results have been obtained:
The fundamental voltage:
$V_{ab1} = 1.162$ p.u., and $THD_v = 3.2663\%$
The fundamental current:
I_{L1} =1.2911 p.u., $THD_i = 0.3955\%$

Figure 5(b), **Fig. 6(b)**, **Fig. 7(b)**, and **Fig. 8(b)** show V_{ab}, its harmonic spectrum, I_L, and its harmonic spectrum, respectively.

2.3 Inverter control technique

To be utility interactive, alternate energy source system have to produce an ac voltages at the inverter output of fixed magnitude and frequency even though the dc input is an unregulated source. An inverter control technique is needed a make the inverter's output voltage immune to the variation in the input dc voltage. This has been achieved by controlling the inverter switching strategy in accordance to the input voltage variation.

The applied method[14] is a feed-forward approach to suitably alter the modulating function for inverter switching control to counter the fluctuation in the input dc voltage. Let sw_1, sw_2, and sw_3 be the inverter switching functions. The Fourier series expansions of the switching functions can be written as,

$$SW = \begin{bmatrix} SW_1 \\ SW_2 \\ SW_3 \end{bmatrix} = \begin{bmatrix} \sum_{n=1}^{\infty} a_n \sin(n\omega t) + b_n \cos(n\omega t) \\ \sum_{n=1}^{\infty} a_n \sin(n(\omega t - \frac{2\pi}{3})) + b_n \cos(n(\omega t - \frac{2\pi}{3})) \\ \sum_{n=1}^{\infty} a_n \sin(n(\omega t + \frac{2\pi}{3})) + b_n \cos(n(\omega t + \frac{2\pi}{3})) \end{bmatrix} \tag{9}$$

For a constant dc input voltage $(V_i) = V_{dc}$, the inverter line to neutral output voltages are given by,

$$V_n = \begin{bmatrix} V_{an} \\ V_{bn} \\ V_{cn} \end{bmatrix} = V_{dc} \times SW \tag{10}$$

The line to the line voltage at the inverter output is given by,

$$V_L = \begin{bmatrix} V_{an} - V_{bn} \\ V_{bn} - Vcn \\ Vcn - V_{an} \end{bmatrix} = \sqrt{3}\, V_{dc} \times \begin{bmatrix} \sum_{n=1}^{\infty} a_n \sin(n(\omega t + \frac{\pi}{6})) + b_n \cos(n(\omega t + \frac{\pi}{6})) \\ \sum_{n=1}^{\infty} a_n \sin(n(\omega t - \frac{\pi}{2})) + b_n \cos(n(\omega t - \frac{\pi}{2})) \\ \sum_{n=1}^{\infty} a_n \sin(n(\omega t + \frac{5\pi}{3})) + b_n \cos(n(\omega t + \frac{5\pi}{3})) \end{bmatrix} \tag{11}$$

It is assumed that the dc voltage varies, and then the inverter input voltage can be represented as,

$$V_i = V_{dc}(1 + D(t)) \tag{12}$$

where; $D(t)$ is the change of the input voltage round the rated dc voltage, V_{dc}.

The line to neutral inverter output voltage can be obtained from (10) and is given by,

$$V_n = V_{dc}(1 + D(t)) \times SW \tag{13}$$

In order to achieve total immunity to input dc voltage fluctuation, the proposed strategy is to suitably alter MSPWM switching function which introduces a counter modulation in the inverter control. The modified switching function for the above described situation would be,

$$SW_{new} = \frac{1}{(1 + D(t))} \times SW \tag{14}$$

Using (10), the inverter line-to-neutral voltage becomes,

$$V_n = V_{dc}(1 + D(t)) \times SW_{new} \tag{15}$$

Substituting (14) in (15),

$$V_n = V_{dc} \times SW \tag{16}$$

However, (16) is identical to (10) in which the input dc voltage was assumed constant. Therefore, employing the proposed technique; i.e., suitably altering the inverter switching function (SW_{new}), achieved a significant immunity to input variation. The block diagram implementation of the proposed scheme is illustrated in **Fig. 10**. For practical implementation of the above technique, the input dc is sensed and processed in the control phase in order to generate a counter modulating function for inverter control. If the dc voltage increases the inverter needs to be operated at a lower modulation and vice versa. This would effectively eliminate the influence of the input voltage variation on the inverter output voltage. If the inverter modulation index is sited at 0.8 for normal operation, and a 1.1/33 kV transformer is used, the dc voltage variation from 1600 V to 2200 V can be tolerated with the proposed scheme to produce 33 ± 10% kV ac voltage output. According to the proposed scheme the changes in the input voltage are accommodated by changing the inverter modulation which consequently changes the switching instants of the inverter switches.

Therefore if the input voltage increases then the width of the MSPWM pulses decreases and if the input voltage decreases then the width of the MSPWM increase.

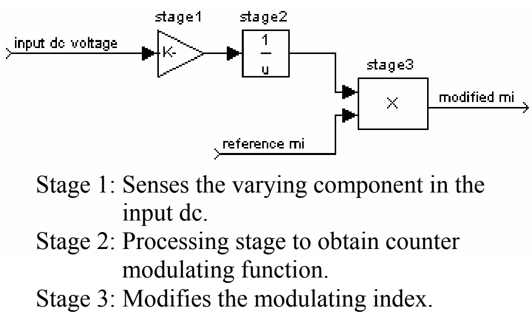

Fig. 10 Block diagram of the control technique.

Table 2 Effect of using the designed filter on voltage and current parameters.

Item	without using filters	with using the designed filters
Fundamental voltage, kV	41.72	38.08
THDv, %	66.15	3.407
Fundamental current, A	123	112.2
THDi, %	7.252	0.4041

3. Simulation and Results

The proposed system was simulated in MATLAB simulink. The simulation was performed for the six-pulse three-phase inverter with MSPWM switching technique at 1050 HZ switching frequency and 0.8 modulation index. A three-phase 50 Hz transformer is required for the purpose of isolation and voltage matching, so the inverter output is connected to three-phase 1/33 kV step-up transformer that feeds the 5 MW load with 0.9 p.f. lag at 33 kV line voltage via the designed filter. The simulation results waveforms were then compared with the results of equation solving by the presented previous programs in this paper, and the results are in agreement with each other. **Table (2)** shows the effect of using the designed series and parallel filters on voltage and current parameters.

4. Conclusions

From this paper, it can be concluded that:

(1) The MSPWM is the best technique for six-pulse three-phase inverter, because it pushes the undesirable harmonics in high frequency range, in the same time it increases the fundamental harmonic voltage value, rather than it decreases the switching losses of the power electronic switches.

(2) The designed parallel and series filters eliminates most of the undesirable harmonics, which is appeared clearly from the THD_v and THD_i which are equals to 3.2663% and 0.3955% respectively. This filter output release the standard specifications limits required to interactive with the UG which are specified by IEEE929[22].

(3) The variation of the PVPS output voltage is limited to be between ±10% of the rated ac output voltage by using the feed forward control technique.

(4) The PCU designed here based on MSPWM provides the following specifications:
   - Dc input voltage to the inverter, $Vdc = 1600$ V to 2200 V,
   - Ac output voltage, using the 1.1/33 kV transformer, $V_L = 33$ kV ±10% at THD_v and THD_i within the allowable standard specifications limits.

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