A New Approach with Modeling the Combination of Unified Power Quality Conditioner and Photovoltaic Arrays

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ABSTRACT

This paper presents a system that provides photovoltaic generation as well as the functions of a unified power quality conditioner (UPQC). The system can be controlled for current harmonics and reactive power compensation simultaneously by using a converter operating as active shunt filter. The other converter is used as active series filter and it compensates voltage harmonics or voltage sags and swells. Using only an inverter in photovoltaic energy conversion process, the system presents increased efficiency when compared to the conventional systems. Simulation results demonstrate the good performance of the proposed configuration. Experimental results corresponding to the operation of the series filter as voltage sag compensator are presented. The purpose of this paper is a design a photovoltaic generation system for connection in three-phase system using only a DC/AC inverter. The proposed system increases the conversion efficiency and also provides useful function any time, operating as power supply as well as harmonic and reactive power compensator when the sun is available. The proposed system modeling and simulation PSCAD/EMTDC is used.

1-INTRODUCTION

Photovoltaic (PV) energy has great potential to supply energy with minimum impact on the environment, since it is clean and pollution free [1]. A large number of solar cells connected in series and parallel set up to photovoltaic or solar arrays. One way of using photovoltaic energy is in a distributed energy system as a peaking power source [2].

The utilization of to DC/AC fully controlled converters makes the system have the most versatile structure of converters applied as energy conditioner. In this case, depending on the controller, the converters can have different functions of compensation. For instance, they can realize active series and shunt filters combined to compensate simultaneously load current and harmonics of the supplied voltage [3]. In this way, the equipment is called Unified Power Quality Conditioner (UPQC) [4].

An active shunt filter is a suitable device for current-based compensation [5]. This configuration includes current harmonics and reactive power compensations. The active shunt filter can also balance unbalancing currents.

The active series filter is normally used for voltage-based compensation [5]. In this case, voltage harmonics and voltage sags and dips are compensated.

Other applications can be found in literature for purposes of compensations of the fundamental frequency, such as reactive power compensation, flux control of active power and voltage regulation. In this case, it is called Unified Power Flow Controller (UPFC) [6]-[7].

Conventionally, grid connected photovoltaic energy conversion systems are composed of a dc-dc converter and an inverter [1]-[2]. The DC-DC converter is controlled to track the maximum power point of the photovoltaic array and the inverter is controlled to product current in such a way that the system current has low total harmonic distortion (THD) and it is in phase with the utility voltage. The efficiency of the conventional system is low because the DC-DC converter and the inverter are connected in series. The purpose of this paper is a design a photovoltaic generation system for connection in three-phase system using only a DC/AC inverter. Cost estimation shows that the use of additional components increases the cost in less than 12% to have another function to improve power quality. Also this converter does not change the efficiency of the PV energy conversion since the converters are connected in parallel. The control was implemented with the synchronous reference frame (SRF) method. Different pulse-width-modulation (PWM) techniques have been compared to suggest a configuration with optimal efficiency.

2- GRID CONNECTED PHOTOVOLTAIC SYSTEM

The proposed photovoltaic energy conversion system has high efficiency, low cost and high functionality. Figure 1 shows the block diagram of the proposed system. The converter 1 (PV converter) in figure 1 is responsible to convert the PV energy to the grid as well as to compensate current harmonics and reactive power. The converter 2 (Dynamic Voltage Restorer-DVR converter) in figure 1 is responsible to compensate voltage harmonics or voltage sags.

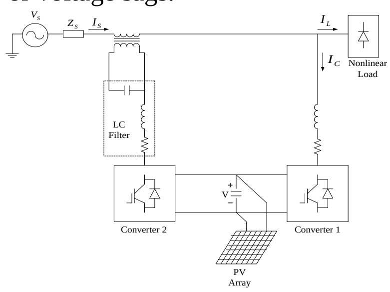


Fig.1. Proposed system: PV generation with UPQC function

3- MAXIMUM POWER POINT TRACKING

The controller of converter 1 in Figure 1 has to track the maximum power point of the photovoltaic array as well as to compensate harmonic and reactive power. When the system is operating as photovoltaic energy generator, the

maximum power point tracking (MPPT) controller is used to calculate the reference voltage. When the system is operating only as harmonic and reactive power compensator, the reference voltage is constant.
It is important to operate the photovoltaic system near the maximum power point to increase the efficiency of photovoltaic arrays. A MPPT method often used is the perturbation and observation method. However, in this paper, it is used the slope of power versus voltage, which decreases the oscillation problem and it is easy to implement [1]. Figure 2 shows characteristic $I-V$ and $P-V$ for maximum power point tracking is finding.

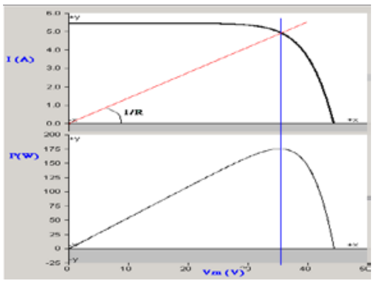


Fig.2. characteristic diagram of the solar energy

4-CURRENT BASED COMPENSATION

The converter is responsible to convert PV energy to the grid as well as to compensate current harmonics and reactive power. Under balanced operating conditions, it is possible to express the inverter phase output voltage in terms of the inverter output voltages with respect to the negative dc bus:

$$v_{kn} = v_{kN} - v_{nN} \qquad k = a, b, c \tag{1}$$

Each phase voltage can be written as:

$$v_{kn} = v_{sk} - L_c \, {}^{di_{ck}}/_{dt} \tag{2}$$

In a three-phase, three wire load:

$$v_{nN} = {}^1/_3 \, (v_{aN} + v_{bN} + v_{cN}) \tag{3}$$

Substituting v_{nN} from (3) into (1):

$$v_{1n} = {}^2/_3 \, v_{aN} - {}^1/_3 \, v_{bN} - {}^1/_3 \, v_{cN} \tag{4}$$

Similar equations can be written for phase b and c voltages. The phase voltage can be also written as:

$$\begin{bmatrix} v_{an} \\ v_{bn} \\ v_{cn} \end{bmatrix} = V \begin{bmatrix} {}^2/_3 & -{}^1/_3 & -{}^1/_3 \\ -{}^1/_3 & {}^2/_3 & -{}^1/_3 \\ -{}^1/_3 & -{}^1/_3 & {}^2/_3 \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \end{bmatrix} \tag{5}$$

Where the variable T_k represent the states of the inverter upper switches. T_k is 0 for opened switches and 1 for closed switches. Defining d_k as switching state function [8]:

$$\begin{bmatrix} d_a \\ d_b \\ d_c \end{bmatrix} = {}^1/_3 \begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \end{bmatrix} \tag{6}$$

On the dc side:

$$\frac{dV}{dt} = \frac{i_{dc}}{c} = \frac{1}{c}\left(T_a i_{ca} + T_b i_{cb} + T_c i_{cc}\right) \tag{7}$$

$$\frac{d}{dt}\begin{bmatrix} i_{ca} \\ i_{cb} \\ V \end{bmatrix} = \begin{bmatrix} 0 & 0 & -\frac{d_a}{L_c} \\ 0 & 0 & -\frac{d_b}{L_c} \\ \frac{2d_a+d_b}{c} & \frac{d_a+2d_b}{c} & 0 \end{bmatrix} \begin{bmatrix} i_{ca} \\ i_{cb} \\ V \end{bmatrix} + \frac{1}{L_c}\begin{bmatrix} V_{S1} \\ V_{S2} \\ 0 \end{bmatrix} \tag{8}$$

In (8), the steady state fundamental components are sinusoidal. To reduce control complexity, the dq frame in (9) rotating at the supply frequency can be used. With this frame, the positive-sequence components at fundamental frequency became constant [8] in equation (9) :

$$\begin{bmatrix} i_{cd} \\ i_{cq} \\ i_{c0} \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} \cos\omega t & \cos(\omega t - 2\pi/3) & \cos(\omega t + 2\pi/3) \\ -\sin\omega t & -\sin(\omega t - 2\pi/3) & -\sin(\omega t + 2\pi/3) \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \begin{bmatrix} i_{ca} \\ i_{cb} \\ i_{cc} \end{bmatrix}$$

Taking into account the absence of the zero-sequence components in the currents in a three-wire system, the simplified transformation matrix can be used:

$$\begin{bmatrix} i_{cd} \\ i_{cq} \end{bmatrix} = \sqrt{2} \begin{bmatrix} \cos(\omega t - \pi/6) & \sin\omega t \\ -\sin(\omega t - \pi/6) & \cos\omega t \end{bmatrix} \begin{bmatrix} i_{ca} \\ i_{cb} \end{bmatrix} \tag{10}$$

The model in the dq frame is as in (11) [8]:

$$\frac{d}{dt}\begin{bmatrix} i_{cd} \\ i_{cq} \\ V \end{bmatrix} = \begin{bmatrix} 0 & \omega & -\frac{d_d}{L_c} \\ -\omega & 0 & -\frac{d_q}{L_c} \\ \frac{d_d}{c} & \frac{d_q}{c} & 0 \end{bmatrix} \begin{bmatrix} i_{cd} \\ i_{cq} \\ V \end{bmatrix} + \frac{1}{L_c}\begin{bmatrix} V_{Sd} \\ V_{Sq} \\ 0 \end{bmatrix} \tag{11}$$

$$L_c \frac{di_{cd}}{dt} = L_c . \omega \cdot i_{cq} - V \cdot d_d + V_{Sd} \tag{12}$$

$$L_c \frac{di_{cq}}{dt} = -L_c \cdot \omega \cdot i_{cd} - V \cdot d_q + V_{Sq} \tag{13}$$

Defining:

$$u_d = L_c . \omega \cdot i_{cq} - V \cdot d_d + V_{Sd} \tag{14}$$

$$u_q = -L_c \cdot \omega \cdot i_{cd} - V \cdot d_q + V_{Sq} \tag{15}$$

and considering that the current control is realized by using PI compensators, the equations (16) and (17) in figure 3 are:

$$d_d = \frac{V_{Sd} + L_c . \omega . i_{cq} - u_d}{V} \tag{16}$$

$$d_q = \frac{V_{Sq} - L_c \cdot \omega \cdot i_{cd} - u_q}{V} \tag{17}$$

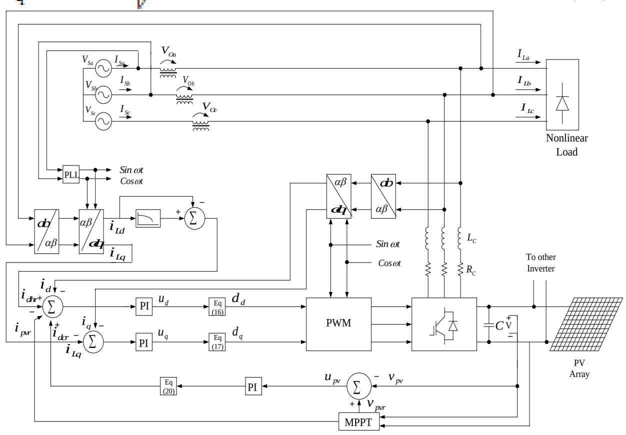


Fig 3. Control of the proposed system: PV generation/current harmonic and reactive power compensations

The voltage equation in the model (11) can be written as:

$$C\frac{dV}{dt} = d_d \cdot i_{cd} + d_q \cdot i_{cq} \tag{18}$$

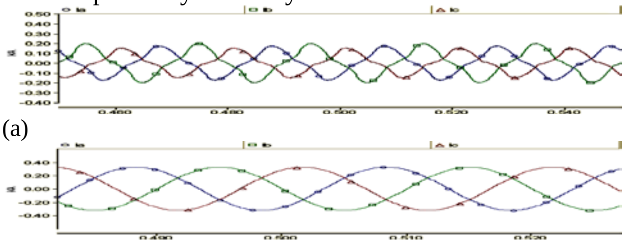
Defining:

$$u_{pv} = d_d \cdot i_{cd} + d_q \cdot i_{cq} \tag{19}$$

and considering that the voltage control is realized by using a PI compensator, the equation (20) in Figure 3 is:

$$i_{dcr} = \sqrt{\frac{2}{3}}\,\frac{V}{V_{sup}}\,V_{pv} \tag{20}$$

The phase-locked-loop (PLL) circuit detects the amplitude and the position of supply voltage vector. When the system is operating as photovoltaic energy generator, the maximum power point tracking controller is used to calculate the reference voltage. When the system is operating only as current harmonic and reactive power compensator, the reference voltage is constant [1].
Fig. 4 shows the three-phase loads currents. In Fig. 4 (a), the loads currents are non-sinusoidal. As it is shown in Fig. 4 (b), loads currents have been compensated by converter 1 to make the source current sinusoidal.
Fig. 5 shows the phase voltage and line current of the nonlinear load for the phase a. similar wave-forms can be plotted for phase's b and c. As it can be seen in this figure, there is no phase leading-lagging between line current and voltage. They are in phase and sinusoidal. As a result, the proposed control system is capable of controlling the current injected into the grid at unity power factor by changing the converter 1 injected reactive power dynamically.



(a)

(b)

Fig. 4. There phase nonlinear load currents : (a) without converter 1 and (b) with converter 1.

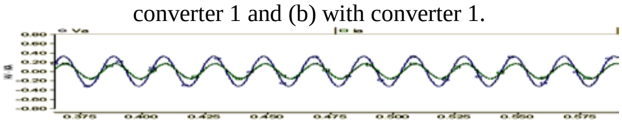


Fig. 5. Phase voltage and line current of the nonlinear load for the phase a.

5-VOLTAGE BASED COMPENSATION

The voltage compensator is a system based on power electronics that detects the feeder voltage and in case the voltage is different of the desired voltage, it supplies the necessary voltage to compensate the voltage error. It can be used to compensate voltage harmonics at the point of common coupling (PCC) or voltage sags, keeping the load voltage around its rated value.
In this paper, it is presented the voltage sag compensation control. Its use more justified when many sensitive loads are connected to the same feeder.
Under balanced operating conditions, it is possible to express the inverter phase output voltages in terms of the inverter output voltages with respect to the negative dc bus:

$$v_{kO} = v_{kN2} - v_{ON2} \qquad k = a, b, c \tag{21}$$

Each phase voltage can be written as:

$$v_{k0} = v_{KO} - L_f\,\frac{di_{fk}}{dt} \tag{22}$$

In a three-phase, three wire load:

$$v_{ON2} = \frac{1}{3}\left(v_{aN2} + v_{bN2} + v_{cN2}\right) \tag{23}$$

The variables T_{k2} represent the states of the converter 2 upper switches. T_{k2} is 0 for opened switches and 1 for closed switches. Defining d_{K2} as switching state function:

$$\begin{bmatrix} d_{a2} \\ d_{b2} \\ d_{c2} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}\begin{bmatrix} T_{a2} \\ T_{b2} \\ T_{c2} \end{bmatrix} \tag{24}$$

In the filter output voltage:

$$\frac{dv_{k0}}{dt} = -\frac{1}{C_f}\left(i_{fk} - i_{Lk}\right) \tag{25}$$

The complete model of the system in the abc referential is shown in (26):

$$\frac{d}{dt}\begin{bmatrix} i_{fa} \\ i_{fb} \\ v_{0a} \\ v_{0b} \end{bmatrix} = \begin{bmatrix} 0 & 0 & \frac{1}{L_f} & 0 \\ 0 & 0 & 0 & \frac{1}{L_f} \\ -\frac{1}{C_f} & 0 & 0 & 0 \\ 0 & -\frac{1}{C_f} & 0 & 0 \end{bmatrix}\begin{bmatrix} i_{fa} \\ i_{fb} \\ v_{0a} \\ v_{0b} \end{bmatrix} + \begin{bmatrix} -\frac{d_{a2}}{L_f}V \\ -\frac{d_{b2}}{L_f}V \\ \frac{1}{C_f}i_{La} \\ \frac{1}{C_f}i_{Lb} \end{bmatrix}$$

In (26), the steady state fundamental components are sinusoidal. To reduce control complexity, the dq frame rotating at the supply frequency can be used. Taking into account the absence of the zero-sequence components in a three-wire system, the model in the dq frame is an in (27):

$$\frac{d}{dt}\begin{bmatrix} i_{fd} \\ i_{fq} \\ v_{0d} \\ v_{0q} \end{bmatrix} = \begin{bmatrix} 0 & \omega & \frac{1}{L_f} & 0 \\ -\omega & 0 & 0 & \frac{1}{L_f} \\ -\frac{1}{C_f} & 0 & 0 & \omega \\ 0 & -\frac{1}{C_f} & -\omega & 0 \end{bmatrix}\begin{bmatrix} i_{fd} \\ i_{fq} \\ v_{0d} \\ v_{0q} \end{bmatrix} + \begin{bmatrix} -\frac{d_{d2}}{L_f}V \\ -\frac{d_{q2}}{L_f}V \\ \frac{1}{C_f}i_{Ld} \\ \frac{1}{C_f}i_{Lq} \end{bmatrix}$$

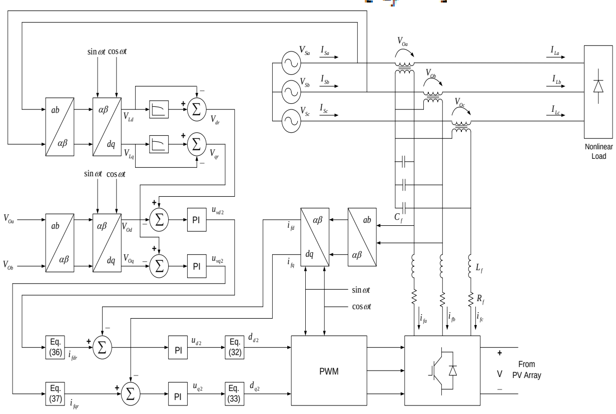


Fig.6. Control of the proposed system: PV generation / current harmonics and reactive power compensation

The current equation in the model (27) can be written as:

$$L_f\,\frac{di_{fd}}{dt} = L_f \cdot \omega \cdot i_{fq} + v_{0d} - V \cdot d_{d2} \tag{28}$$

$$L_f\,\frac{di_{fq}}{dt} = -L_f \cdot \omega \cdot i_{fd} + v_{0q} - V \cdot d_{q2} \tag{29}$$

Defining:

$$u_{d2} = L_f \cdot \omega \cdot i_{fq} + v_{0d} - V \cdot d_{d2} \tag{30}$$

$$u_{q2} = -L_f \cdot \omega \cdot i_{fd} + v_{0q} - V \cdot d_{q2} \tag{31}$$

And considering that the current control is realized by using PI compensators, the equations (32) and (33):

$$d_{d2} = \frac{v_{0d} + L_f \cdot \omega \cdot i_{fq} - u_{d2}}{V} \quad (32)$$

$$d_{q2} = \frac{v_{0q} - L_f \cdot \omega \cdot i_{fd} - u_{q2}}{V} \quad (33)$$

The voltage equations in the model (27) can be written as:

$$C_f \frac{dv_{0d}}{dt} = -i_{fd} + C_f \cdot \omega \cdot v_{0q} + i_{Ld} \quad (34)$$

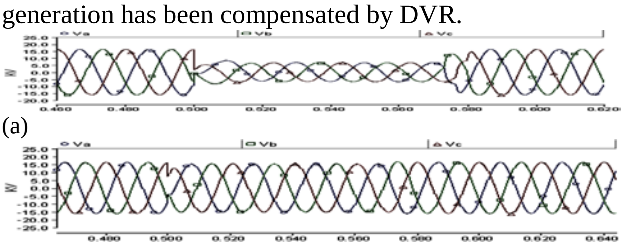
$$C_f \frac{dv_{0q}}{dt} = -i_{fq} - C_f \cdot \omega \cdot v_{0d} + i_{Lq} \quad (35)$$

Therefore:

$$i_{fdr} = i_{Ld} + C_f \cdot \omega \cdot v_{0q} - u_{vd2} \quad (36)$$

$$i_{fqr} = i_{Lq} - C_f \cdot \omega \cdot v_{0d} - u_{vq2} \quad (37)$$

The controller can compensate voltage sags effectively as shown in Figure 8. Fig. 8 shows the phase voltages at the terminal of the load with and without DVR, respectively. Corresponding to this figure, the voltage sag without PV generation has been compensated by DVR.

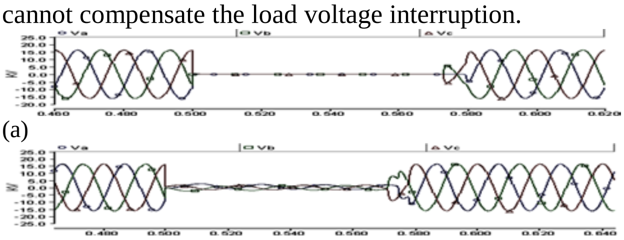


(a)

(b)

Fig. 8. Three-phase load voltages: (a) without DVR and (b) with DVR.

Fig. 9 shows voltage sag higher than 50% are considered as an interruption. Corresponding to Fig. 9 (b), DVR cannot compensate the load voltage interruption.

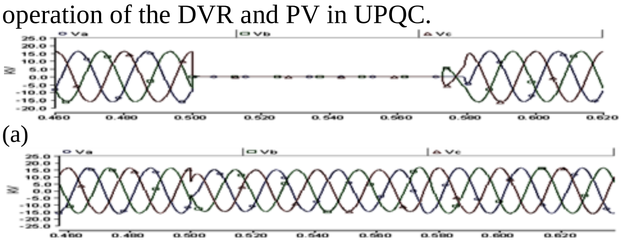


(a)

(b)

Fig. 9. Three phase load voltages: (a) without DVR and (b) with DVR.

Fig. 10 shows the compensation state of interruption using PV connected to DC bus of DVR. Corresponding to this figure, the source voltage has a voltage interruption. The load voltage maintains constant value by combined operation of the DVR and PV in UPQC.



(a)

(b)

Fig. 10. Three phase load voltages: (a) without DVR and (b) with PV connected to DC bus of the DVR.

The prototype of the DVR is composed of a capacitor set (dc-link), an inverter, an output filter and a series transformer. It is also included a three-phase resistive load. The experimental testes have been realized with 380 V (line-to-line voltage). The control system consists of a microcomputer with interfaces dedicated to measure the electrical variables and to command the converters switches.

6-CONCLUSION

The proposed design introduced in this paper improves functionality in grid connected photovoltaic generation systems. The design was used to do a comparative study of PWM techniques for this specific situation. The system can be connected to three-phase system of any electric utility if a matching transformer is used. The excellent performance of the system is verified from simulated results using PSCAD/EMTDC.

The voltage waveform in the photovoltaic array follows the reference voltage for all irradiation conditions. Besides that, the controller also compensates harmonic and reactive power. Using the design based on simulation results, it is possible to make a comparative study of different possibilities of control.

The good performance of the DVR system is verified from simulated and experimental results. The voltage waveform in the load follows the reference voltage keeping the load voltage in the rated value.

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