Integration of Photovoltaic Sources and Power Active Filters

Gabriele Grandi, *Marco Landini*, *Domenico Casadei*, *Claudio Rossi*

Dept. of Electrical Engineering - University of Bologna
Viale Risorgimento, 2 - 40136, Bologna (Italy)
Tel. +39 051 20 93571, Fax. +39 051 20 93588
http://www.die.ing.unibo.it

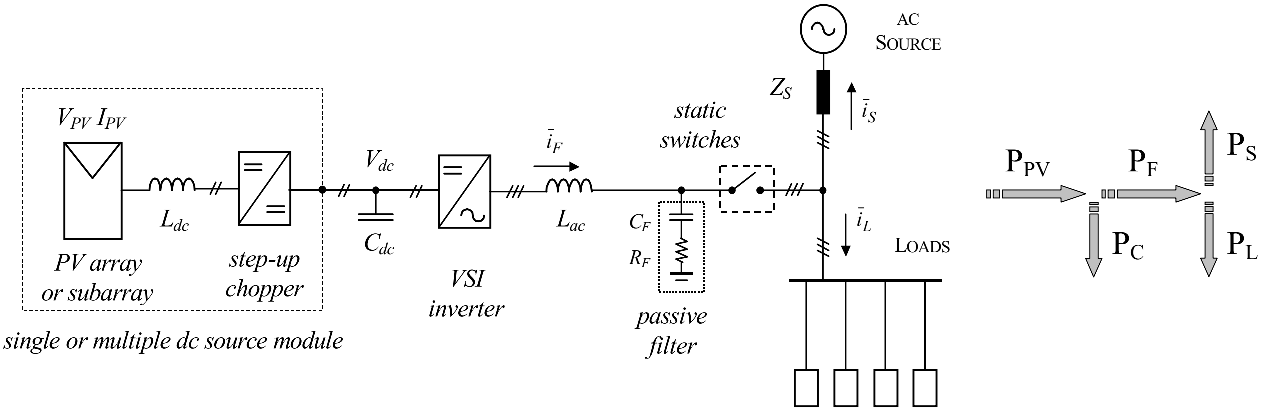
Abstract

The possibility to usefully combine photovoltaic sources with power active filters is analyzed and discussed in this paper. The PV source provides power to the active filter by an intermediate dc chopper, in order to exploit the solar energy for any incoming irradiance, maximizing the PV efficiency. The dc-link voltage is kept close to a reference value by the active filter that behaves as a power conditioner, regulating both the active and the reactive power injected into the mains. Furthermore, the system is able to compensate undesired load characteristics such as phase unbalances, power flickers, and low-order current harmonics, contributing to improve the power quality.

Introduction

Photovoltaic energy seems to become one of the most important renewable energy resources in the near future, since it is clean, pollution free, and inexhaustible. Nowadays, photovoltaic (PV) sources are used in many specific applications such as battery charging, water pumping, home power supply, swimming-pool heating systems, satellite power systems etc. Over these known advantages, the installation cost is still high and, in most applications, the generation system requires both a dc chopper and a three phase voltage source inverter (VSI) for the connection to the power grid, as represented in Fig. 1. On the other hand, due to the rapid growth in semiconductors and power electronic techniques, the solar energy is of increasing interest in electrical power applications, and a large research activity has been carried out in this field over the last years [1]-[6]. Since the solar cells still have relatively low conversion efficiency, the use of high efficiency power converters, designed to extract the maximum possible power from the PV module (maximum power point tracking, MPPT) is advisable [1]-[4].

The system proposed in this paper (see Fig. 1) is designed to inject into the mains all the available power extracted from the PV cells. In this way, the use of battery or other energy storage devices is avoided, reducing the operating costs and improving the overall system reliability. The considered configuration includes static switches able to disconnect the system in case of power mains failure (islanding prevention).



(a) - Block diagram of the overall system (b) - Power flow chart

Fig. 1 - Scheme of the PV generation system combined with a power active filter

The Power Conditioning System (PCS), connecting the dc bus to the mains, is controlled such as an active filter. In this way, the system is able to deliver besides the solar power, reactive power and current harmonics, in order to compensate non-linear and/or unbalanced loads [7]. Furthermore, the system is able to correctly operate under unbalanced supply voltages also. The proposed control strategy is based on keeping the source currents in phase with the corresponding positive sequence components of the supply voltages. This method leads to sinusoidal balanced source currents, regardless to supply voltages unbalance or distortion [8], [9]. Most of the analytical developments presented in this paper are based on stationary *d-q* transformations, representing the three-phase quantities by space vectors.

PV Modules and DC Boost Converter

A photovoltaic cell combines the characteristics of a current source with those of a voltage source. The MPP is located within the operating range, close to the knee of the I/V curve, and it is the preferred working point. However, due to the changes in the environmental variables, i.e., temperature and irradiance, the MPP continuously moves and should be tracked by suitable algorithms to obtain optimal system performance [1]-[4].

The power output of a single module is too low to be useful for power applications, then, several modules are connected in a series/parallel arrangement to form a photovoltaic array, which can deliver the maximum power. In particular, identical PV modules are generally connected in series, in order to obtain a voltage level high enough to realize an efficient dc-dc conversion (the dc-link voltage is usually around 700 V). In these cases, the same current flows through each module, but the voltage across each module depends on the local environmental parameters. In fact, in addition to the moving shadows caused by the clouds, those created by neighboring buildings, trees, utility and/or telephone poles, partially cover some of the PV modules. Then, the MMP condition is not reached for each PV module, and the overall power generated is less than the sum of the maximum power that could be extracted by each module, for the specific environmental parameters of the module. To avoid this drawback, some Authors proposed to divide the complete area of PV array into smaller sub-arrays, each with its own independent dc-to-dc converter and maximum power controller. Such a scheme allows shaded sub-array to continue to operate close to the MPP, with a reduced power level [5], [6]. On the other hand, multiple dc-to-dc converters lead to lower dc conversion efficiency and reliability, and increasing installation costs. Owing to this, a solution with a single dc converter will be considered in this paper.

AC Power Conditioner

The aim of the power conditioner is to keep the dc-link capacitors voltage V_{dc} close to its reference value V_{dc}^*, by properly regulating the current injected into the mains (source current, $\bar{i}_S$), according to the block diagram shown in Fig. 2. In this way, all the power coming from the PV generator is

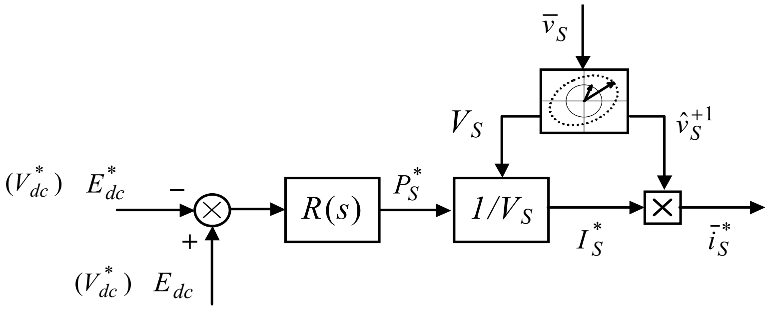


Fig. 2 - DC link energy regulation scheme

transferred to the electric network. The capacitor stored energy E_{dc} is considered instead of the capacitor voltage V_{dc} in order to obtain a linear system, allowing the representation of the power flows in terms of *Laplace* transfer functions.

The desired amplitude of the source currents, I_S^*, is generated by the regulator $R(s)$, considering the error of the stored energy in the dc-link capacitor as input variable. The reference value of the instantaneous source current vector, $\bar{i}_S^*$, is generated on the basis of the magnitude I_S^*, and the phase angle of the positive sequence component of the supply voltages [8], [9], which is represented by the unity space vector $\hat{v}_S^{+1}$ in Fig. 2.

The proposed power conditioning system is also able to compensate non-linear, reactive, pulsating, and/or unbalanced loads [10]. In this case, the ac current control system requires the measurement of both load and filter currents, $\bar{i}_L$ and $\bar{i}_F$ (see Fig. 3). The load current is used to calculate the reference value of the filter current $\bar{i}_F^*$, on the basis of the reference source current $\bar{i}_S^*$, given by the dc-link energy regulator, ($\bar{i}_F^* = \bar{i}_S^* - \bar{i}_L$).

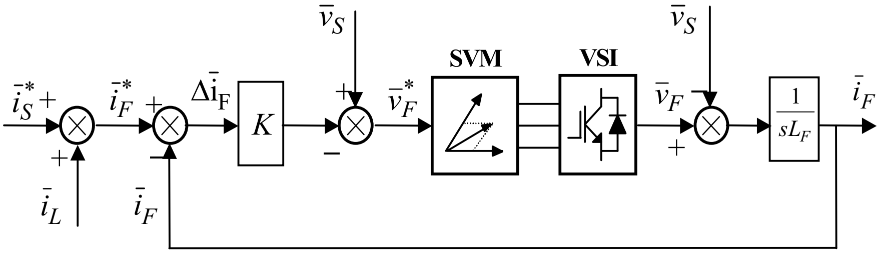


Fig. 3 - Block diagram of the ac current control loop

The measurement of the filter current is used to implement the ac current control loop. A hysteresis current regulator acting on the instantaneous current error $\Delta\bar{i}_F = \bar{i}_F^* - \bar{i}_F$ can be employed to determine the inverter switch states. Alternatively, a PWM (or SVM) current regulator can be used avoiding the drawbacks of hysteresis current controllers. In this case, the reference voltage for the inverter can be calculated by the voltage equation written across the ac-link inductance L, according with the block diagram represented in Fig. 3. Neglecting the resistive effects and introducing a variational model, this equation yields

$$\bar{v}_F^* = \bar{v}_S - \frac{L}{\Delta t}\Delta\bar{i}_F . \tag{1}$$

The parameter $L/\Delta t$ in (1) can be adjusted to obtain the desired regulator performance.

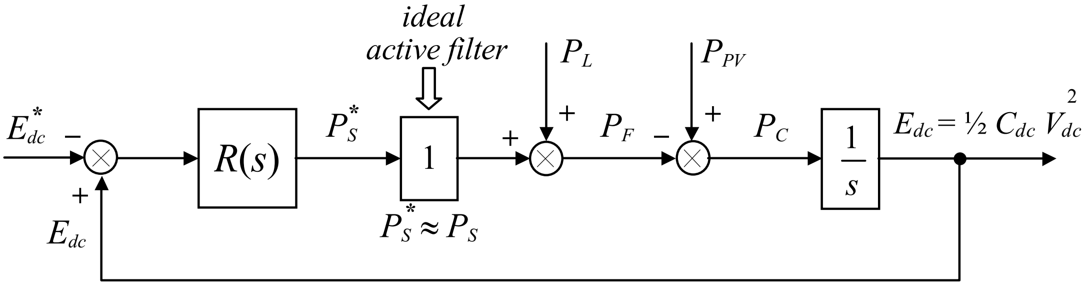


Fig. 4 - Block diagram of the dc-link energy control loop

Dynamic Behavior of the PCS

According to the block diagram shown in Fig. 4, the source power can be expressed as function of P_{PV}, P_L and E^{*}_{dc}, leading to

(2) $$P_S = \frac{R(s)}{R(s)+s} P_{PV} - \frac{R(s)}{R(s)+s} P_L - \frac{s\,R(s)}{R(s)+s} E^{*}_{dc} .$$

This equation shows the influence of photovoltaic or load power variations on the source power. It is interesting to note that the relationship between P_{PV} and P_S is the same of that between P_L and P_S. Basically, the regulator $R(s)$ should be designed for satisfying the source requirements in terms of power quality. Once the regulator $R(s)$ is defined, and the regulator parameters have been tuned to satisfy the desired source power dynamics, the dc-link capacitor should be designed to ensure that the voltage fluctuations during transients would not exceed a prefixed voltage range. The variation of the energy stored in the capacitor can be evaluated on the basis of the block diagram shown in Fig. 4 as follows

(3) $$E_{dc} = \frac{1}{R(s)+s} P_{PV} - \frac{1}{R(s)+s} P_L + \frac{R(s)}{R(s)+s} E^{*}_{dc} .$$

Then, the capacitance C_{dc} can be calculated with reference to the maximum allowed dc-link voltage variation as

(4) $$C_{dc} \geq \frac{2\,\Delta E_{dc}}{\left(V_{dc}^{max}\right)^2 - \left(V_{dc}^{*}\right)^2}, \text{ where } \Delta E_{dc} = E_{dc} - E^{*}_{dc} .$$

In this paper a simple proportional gain K_p is considered for the dc-link regulator

(5) $$R(s) = K_{\mathrm{p}} .$$

By introducing (5) in (2) and (3) yields

(6) $$P_S = \frac{1}{1+\tau s} P_{PV} - \frac{1}{1+\tau s} P_L - \frac{s}{1+\tau s} E^{*}_{dc} ,$$

(7) $$E_{dc} = \frac{1}{K_p}\frac{1}{1+\tau s} P_{PV} - \frac{1}{K_p}\frac{1}{1+\tau s} P_L + \frac{1}{1+\tau s} E^{*}_{dc} .$$

Considering photovoltaic or load power variations, the source power is smoothed by the PCS with a first-order low-pass filtering action having a time constant $\tau = 1/K_p$, as shown in (6), resulting in an improved power quality from the point of view of the electric distributing network.

A variation in P_{PV} or in P_L leads to a steady-state error in the capacitor energy, proportional to the time constant $\tau = 1/K_p$, as shown in (7). In particular, higher PV powers correspond to higher dc-link steady-state voltages. This feature suggests to consider the possibility to directly couple the PV arrays to the dc bus, avoiding the intermediate dc choppers.

A more detailed system analysis is presented in [11], with reference to both steady-state and dynamic characteristics obtained by means of different types of standard regulators.

Simulation Results

A realistic model implemented in the Simulink environment of Matlab has been employed to simulate the PV generation system represented in Fig. 1. The rated power of the photovoltaic system is 10 kW. The dc/dc chopper is considered as an ideal converter, injecting all the PV generated power to the dc-link bus, regardless to the dc-link voltage value.

The dc-link capacitor has a capacitance value C_{dc} = 20 mF. The reference value of the dc-link voltage is V_{dc}^{*} = 700 V. In this way, the energy stored in the dc-link capacitors is high enough to obtain smoothed source power variations, when the PV power and/or the load power suddenly change. The control of the dc-link capacitor energy and the generation of the reference source current have been implemented according to the scheme of Fig. 2. Then, the instantaneous value of the reference filter current $\bar{i}_F^*$ is determined as represented in the scheme of Fig. 3. The voltage source inverter is controlled by a Space Vector Modulation (SVM) technique, using a carrier frequency of 10 KHz. The three-phase ac line inductor parameters are L_{ac} = 2 mH, R_{ac} = 0.1 Ω. Ideal sinusoidal source voltages (380 V, 50 Hz) have been assumed during the system operation.
The numerical results of all the simulations have been obtained by a simple proportional regulator $R(s) = K_p = 8$, to control the dc-link energy E_{dc}.
The performance of the power conditioning system connected to the photovoltaic array has been evaluated in both steady-state and transient operating conditions.

Fig. 5 depicts the behaviour of the PCS for idealized step variations of the PV power, with a three-phase R-L load (P = 2 kW, cos φ = 0.8) permanently connected to the mains. At the beginning of the simulation, the PV array is disconnected and the PCS operates as active power filter, compensating the reactive power of the load. The dc-link voltage reaches a steady-state value of 680 V. At time t = 1 s the PV array is connected, generating the rated power of 10 kW. The power flows into the dc-link determining a transient in the capacitor energy and in the source power. The source does not receive instantaneously the full-generated PV power, but only an increasing percentage, being the remaining amount stored in the dc-link capacitors. The steady-state value of the source power is reached 0.5 s after the connection of the PV array, and it is equal to the difference between the generated PV power and the power supplied to the load. In these operating conditions the steady-state value of the dc-link voltage is 770 V. At time t = 1.5 s the PV generated power is reduced to the 50% of the rated value (i.e., 5 kW). The corresponding source power variation is smoothed by the PCS by exploiting a fraction of the energy stored in the dc-link capacitor.

Fig. 6 depicts the behaviour of the PCS for step variations of the load power (a switch-on and -off cycle). In this case the three-phase R-L load is characterized by the following parameters: P = 7 kW, cos φ = 0.6. The power generated by the PV array is assumed constant and equals to the rated value (10 kW). At the beginning of the simulation, the load is switched off, and the PCS transfers the whole power generated by the PV array into the mains. In this condition, the dc-link voltage reaches a steady-state value of 780 V. At time t = 0.5 s the load is switched on determining a transient in the dc-link voltage and in the source power. At time t = 1 s the load is switched off. As shown in Fig. 6, the source power variations are smoothed as in the case of PV power variations.

It should be noted that the smoothing effects on the source power introduced by the PCS is a very important feature aimed to avoid perturbations on the electric network caused by step variations of injected or absorbed power.

Figs. 7 and 8 have been obtained expanding the time scale of Fig. 6 around the time instant t = 0.5 s and t = 1 s, respectively. In this way it is possible to better emphasize the behaviour of the PCS operating as active filter. In particular, it can be noted that the source current is exactly in phase with the source voltage before, during and after the switching-on and -off transients. This means that the proposed PCS is able to compensate the load reactive power for any operating conditions.

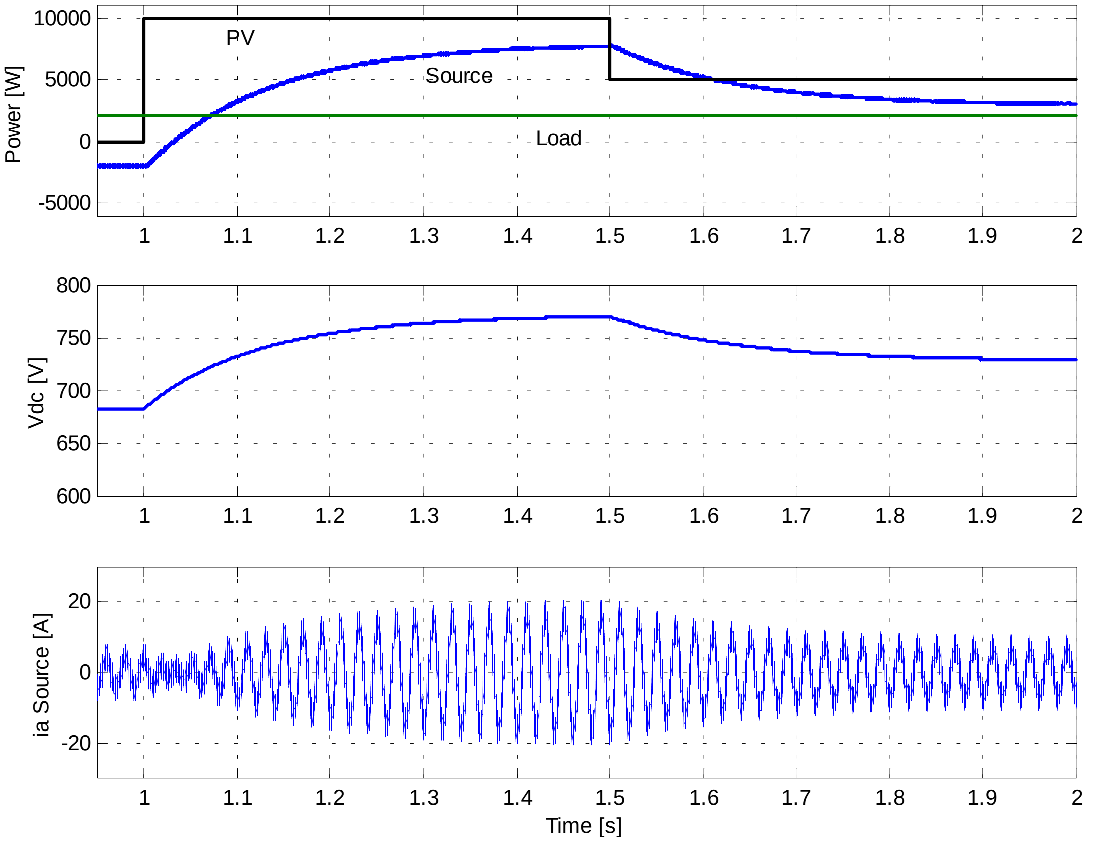


Fig. 5 - Response of the PCS to step variations of the PV generated power

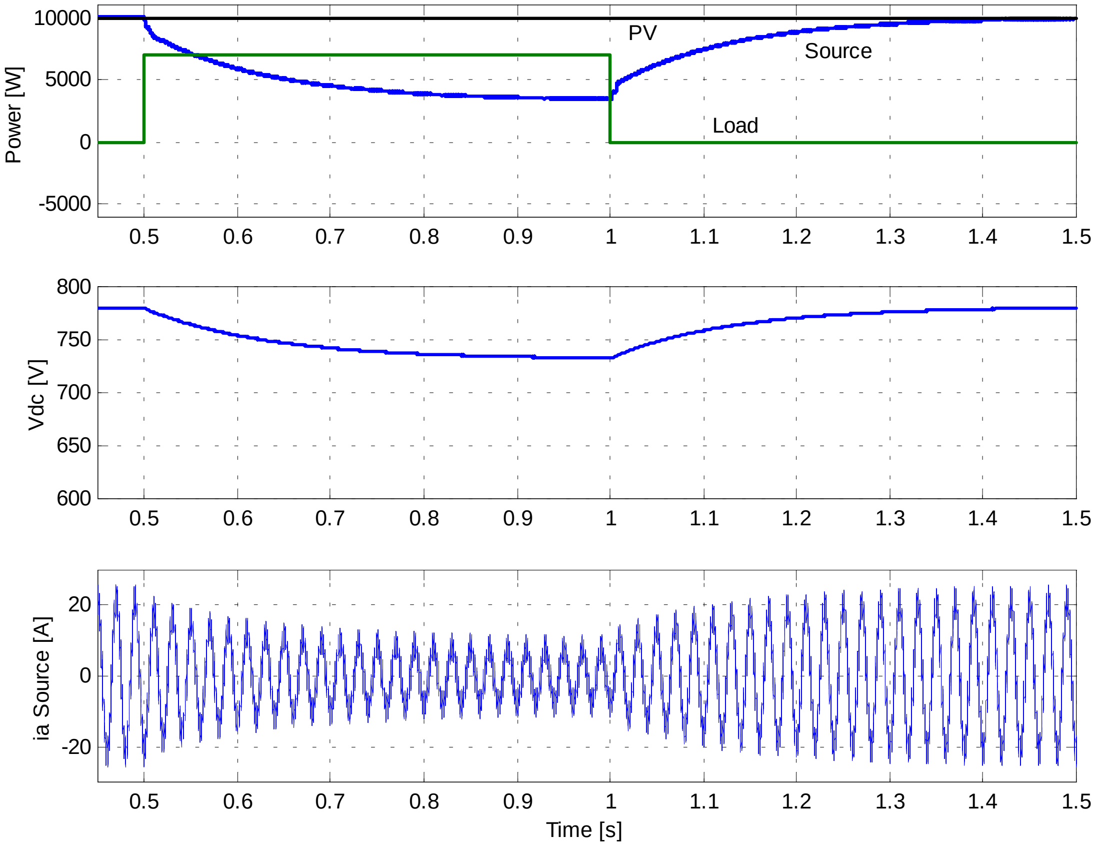


Fig. 6 - Response of the PCS to step variations of the load power

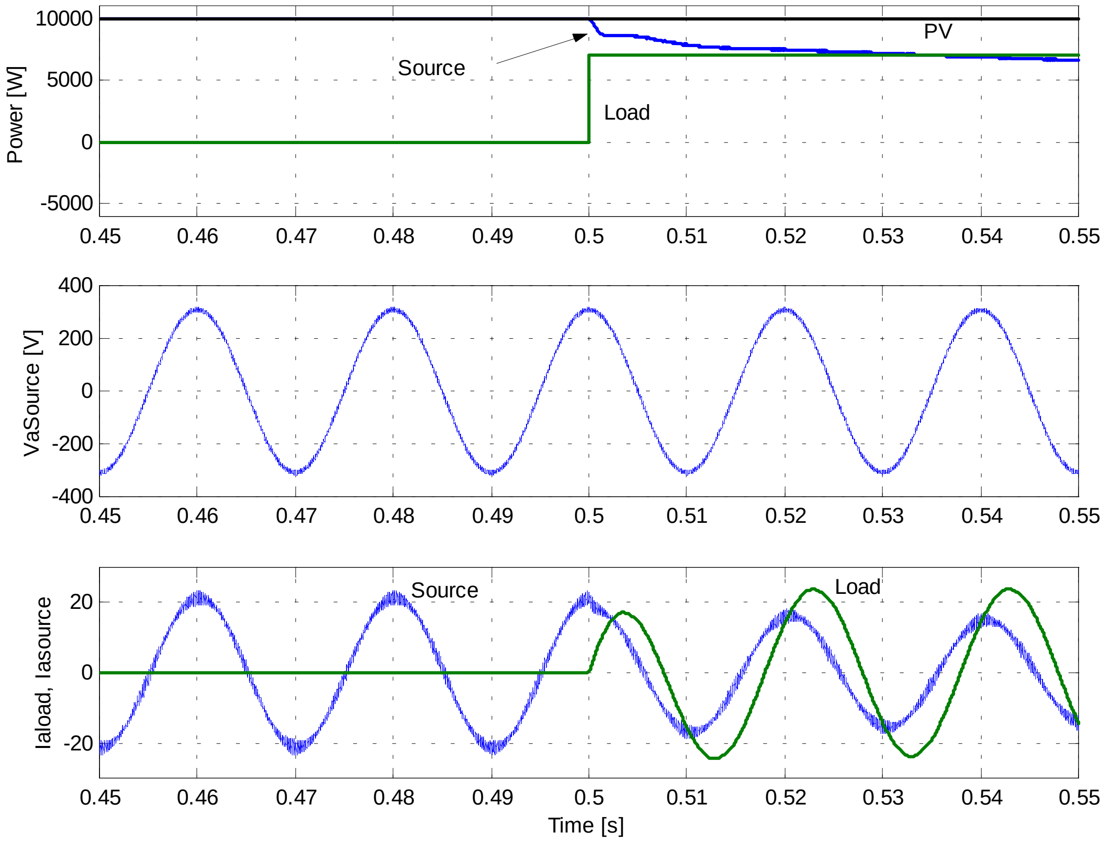


Fig. 7 - Compensation of the load reactive power during the load switching-on

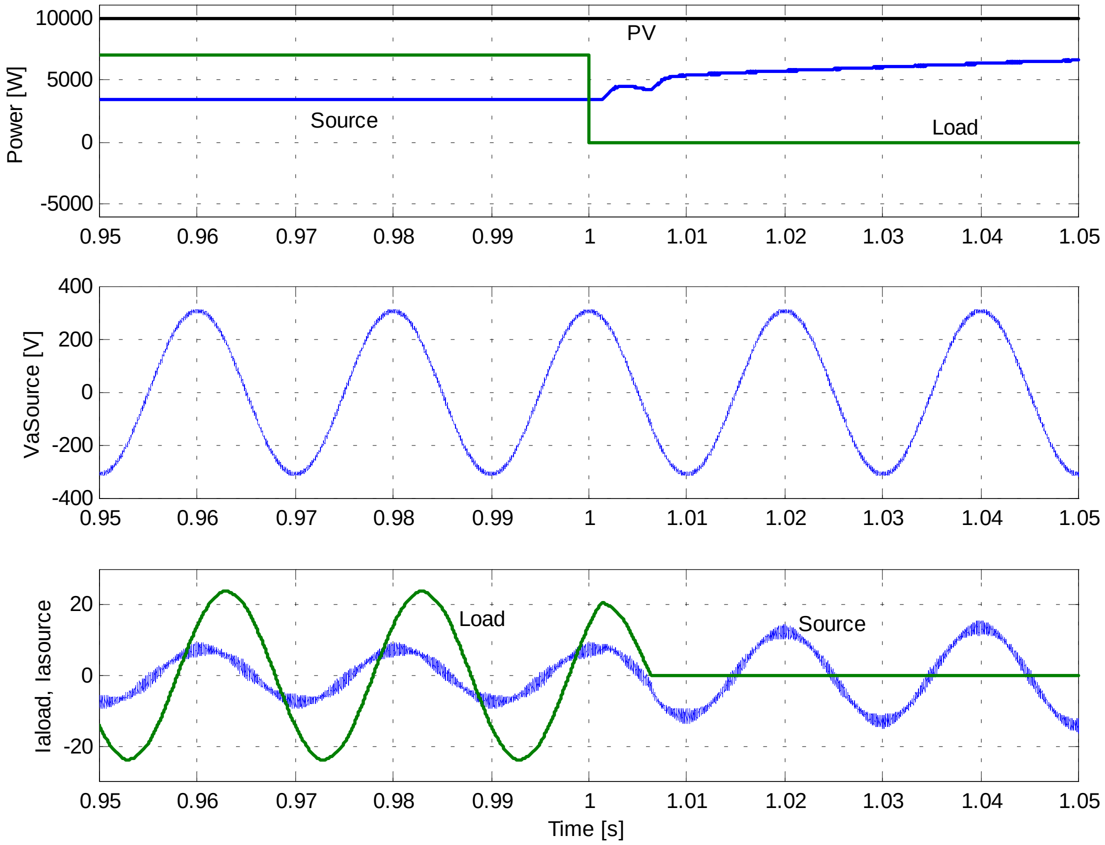


Fig. 8 - Compensation of the load reactive power during the load switching-off

Conclusion

An energy generation system consisting of a combination of PV panels and an active power filter is considered in this paper. The proposed system is designed to inject into the mains all the power extracted from the PV cells and to perform all the additional tasks typical of active power filters.

The whole PV generating system have analyzed to emphasize the impact on the electric distribution network in terms of power quality, with particular reference to sudden variation in the solar irradiance. The system is able to correctly operate under unbalanced supply voltages also. In fact, the proposed control algorithm is based on keeping the currents injected into the mains in phase with the corresponding positive sequence voltage components. This method leads to sinusoidal balanced source currents, regardless to source voltages unbalance or distortion.

A dynamic analysis of the dc-link energy regulator has been carried out analytically by introducing suitable transfer functions.

Numerical simulations of the whole PV generating system in both steady state and transient operating conditions have been presented. The numerical results confirm the theoretical developments and emphasize the capability of the system to smooth the source power variations caused by sudden changes of either the power generated by the PV array or the power absorbed by the load. The system capability to operate as active filter has been verified also.

The proposed PCS configuration can be considered as a viable solution for the better exploitation of the solar energy, complying with the power quality requirements. These combined features allow to decrease the operating costs and to improve the overall system efficiency.

References

[1] Y.C. Kuo, T.J. Liang, J.F. Chen, "Novel maximum-power-point-tracking controller for photovoltaic energy conversion system," *IEEE Trans. on Industrial Electronics*, Vol. 48 No. 3, June 2001, pp. 594-601

[2] J.A.M. Bleijs, J.A. Gow, "Fast maximum power point control of current-fed DC-DC converter for photovoltaic arrays," *Electronics Letters*, Vol. 37, N. 1, 4 Jan. 2001, pp. 5-6

[3] T.Y. Kim, H.G. Ahn, S.K. Park, Y.K. Lee, "A novel maximum power point tracking control for photovoltaic power system under rapidly changing solar radiation," *Proc. of IEEE International Symposium on Industrial Electronics*, ISIE 2001, Pusan, Korea, Vol. 2, pp. 1011-1014

[4] J.A. Gow, C.D. Manning, "Controller arrangement for boost converter systems sourced from solar photovoltaic arrays or other maximum power sources," *IEE Proceedings of Electric Power Applications*, Vol. 147, No. 1, Jan. 2000, pp. 15-20

[5] T. Shimizu, M. Hirakata, T. Kamezawa, H. Watanabe, "Generation control circuit for photovoltaic modules," *IEEE Trans. on Power Electronics*, Vol. 16, No. 3, May 2001, pp. 293-300

[6] J.A. Gow, J.A.M. Bleijs, R. Jones, "Optimization of a utility interface for large-scale photovoltaic power systems," *Proc. of European Power Electronic Conference*, EPE'01, Gratz (Austria), Sept. 2001

[7] D. Casadei, G. Grandi, U. Reggiani, G. Serra, "Analysis of a Power Conditioning System for Superconducting Magnetic Energy Storage," *Proc. of IEEE International Symposium on Industrial Electronics*, ISIE, Pretoria (SA), July 7-10, 1998

[8] D. Casadei, G. Grandi, U. Reggiani, G. Serra, A. Tani, "Behavior of a Power Conditioner for μ-SMES Systems under Unbalanced Supply Voltages and Unbalanced Loads," *Proc. of IEEE International Symposium on Industrial Electronics*, ISIE, Bled (SI), July 12-16, 1999

[9] D. Casadei, G. Grandi, C. Rossi, "Effects of Supply Voltage non-Idealities on the Behavior of an Active Power Conditioner for Cogeneration Systems," *Proc. of IEEE Power Electronic Specialist Conference*, PESC, Galway (Ireland), 18-23 June, 2000

[10] D. Casadei, G. Grandi, C. Rossi, "A Parallel Power Conditioning System with Energy Storage Capability for Power Quality Improvement in Industrial Plants", European Conference on Power Electronics and Applications, EPE, Graz, Austria, 27-29 August, 2001

[11] D. Casadei, G. Grandi, C. Rossi, "Dynamic Performance of a Power Conditioner Applied to Photovoltaic Sources," *Proc. of the 10^{th} International Power Electronics and Motion Control* Conference, EPE-PEMC 2002, Cavtat & Dubrovnik, Croatia, 9-11 September 2002.