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Simple structure for reactive power control of AC photovoltaic modules

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The objective of this paper is to propose a simple structure for reactive power control (RPC) of AC Photovoltaic (AC PV) modules. With the proposed structure, a cost-effective microcontroller can be adopted to achieve an effective reactive power control in order to support the grid voltage within acceptable bounds by absorbing or supplying reactive power. Moreover, the sliding mode control (SMC) is adopted to enhance the current control's dynamic response and reduce the current harmonic distortion. Comprehensive simulation of an AC PV module connected to grid using PSIM software with different operation modes are used to demonstrate the control strategy. The results from the simulation show that the proposal can provide good reactive power control for the AC PV modules.

Keywords

power, structure, simple, control, ac, photovoltaic, reactive, modules

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Simple Structure for Reactive Power Control of AC Photovoltaic Modules

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***Abstract* — The objective of this paper is to propose a simple structure for reactive power control (RPC) of AC Photovoltaic (AC PV) modules. With the proposed structure, a cost-effective microcontroller can be adopted to achieve an effective reactive power control in order to support the grid voltage within acceptable bounds by absorbing or supplying reactive power. Moreover, the sliding mode control (SMC) is adopted to enhance the current control's dynamic response and reduce the current harmonic distortion. Comprehensive simulation of an AC PV module connected to grid using PSIM software with different operation modes are used to demonstrate the control strategy. The results from the simulation show that the proposal can provide good reactive power control for the AC PV modules.**

***Index Terms*— PV system, Sliding mode control (SMC), Photovoltaic, AC PV module, reactive power control (RPC).**

I. Introduction

SOLAR (PV) resources play a vital role of distributed generation (DG) in low voltage (LV) distribution networks, and in particular, the rooftop photovoltaic (RPV) power generation system has become the most promising renewable energy source for residential applications. The use of AC PV modules without energy storage facilities is fast becoming the trend for low power grid-connected PV systems, especially for residential applications. New advances on power electronics, microprocessors, digital controls, and communications have finally allowed for a new generation of AC PV modules with low-cost, mass produced, PV panel mounted micro-inverter to reach commercial realization [1],[2]. In this configuration, a single 150-300W grid-tie micro-inverter is connected and attached to the back side of a single PV panel to convert the DC output of a single PV panel to AC as shown in Fig. 1. AC PV modules can offer modular solar power systems, greatly simplify system design and installation, and can eliminate safety hazards. Such AC PV module has been becoming the first to offer a Plug'N'Gen solar power system. Due to this, a high penetration of RPV systems into low-voltage (LV) distribution networks is increasing sharply. However, if the PV generation is greater than the local demand at the point of common coupling (PCC), the excess power from PV may produce reverse power flow in the feeder that would create voltage-rise problems [3] causing power quality issues.

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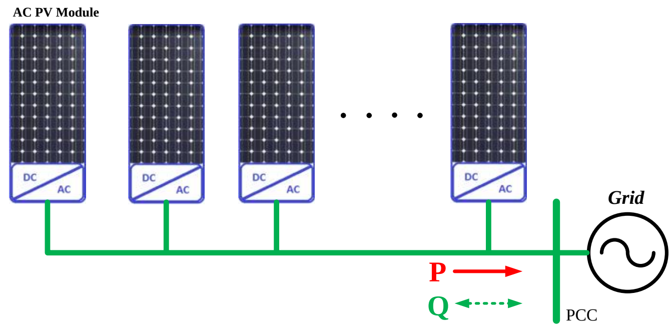

Fig. 1. AC PV Module system.

The idea of this paper is to control the AC PV modules to provide or absorb reactive power from the utility grid to improve its power quality. As a result, the AC modules with the reactive power management function will be addressed on this paper. In order to accurately control the reactive output power, the current reference generation (CRG), which can generate the required proper current reference to provide the demanded active and reactive power components, should be shaped in advance. In the literature, many reactive power control (RPC) strategies for the single-phase inverter have been proposed [4]–[9]. Among them, the direct-quadrature transformation [4] and the instantaneous reactive power theory [5]–[6] are the most commonly used control schemes to generate two orthogonal current references. Furthermore, some modified methods to improve the controlled performance were attracting much attention [7]-[9]. The authors in [7] used the feedback instantaneous power to compare with the instantaneous power command and the error between them is compensated by adopting a resonant controller. While the authors in [8] used a simplified calculation to estimate the output reactive power and compared it with the reactive power command. Although those methods are effective, a powerful computer platform is needed to deal with those complex functions. This will make an increase in cost of system designing. The diagram of the AC PV module is presented in Fig. 2. It comprises of a single PV panel compacts with a single sophisticated power stage module (PSM). Because of the low DC voltage in the output of single PV modules, the PSM includes a high gain step- up DC/DC converter and a DC/AC full bridge inverter with both active and reactive output power control. The DC/DC converter need to perform an efficient maximum power point tracking (MPPT) function and boosts the output voltage up to $400V_{DC}$ to supply sufficiently for input of the DC/AC inverter. A two loop control system is applied with an inner reactive control, and an outer grid voltage control. The SMC law is utilized for the output regulation of the DC/AC full bridge inverter due to its robustness, and simple algorithm that is easy to implement by a digital signal processor (DSP).

The structure of this paper is as follows. Section II presents the proposed method in full details for the estimation of the output reactive power using a 2nd order low pass filter. The SMC method is adapted to control single phase inverter and presented in section III. Simulation results and conclusions are presented in Section IV, and V, respectively.

II. Proposed RPC Method

In order to reduce the computational burden and the cost of design, a novel RPC with a simple CRG method is proposed in order to attain the proper demanded reactive power at the PCC point, as shown in Fig.3. It is required that AC PV modules should inject as much as possible active power into the grid while supporting to guarantee the normal voltage value at PCC point. Due to this, an efficient reactive power control strategy with different operational modes is adopted. Taking into consideration the voltage at PCC point, in case of it has a rise, the reactive power should be consumed by AC PV modules and by the contrast when the voltage is lower than the normal value, the AC PV module should inject the reactive power into the grid in order to support a rise of the voltage, and if the grid voltage is within the dead-band bound with the normal value, the reactive power is not injected or absorbed from the grid, the AC PV modules will be controlled to inject a maximum active power into the grid. Due to this, a reference current is shaped at first, based on the measured grid voltage at PCC point, the command reactive power Q_{ref} obtained from the Q(V) characteristic, as shown in Fig. 4, that calculates the reference reactive power for each AC PV module depending on the voltage magnitude at the corresponding PCC in order to support the grid voltage. The voltage at the PCC bus terminals is used as an input value to the outer control loop. This voltage may be computed as the averaged RMS value and expressed in per unit system. The operational modes are defined and explained as the Table 1.

TABLE I
SUMMARY OF OPERATION MODES

Modes	Description
I	Reactive power injection, the main objective is to increase the PCC voltage.
II	Dead-band, the AC PV module is not injecting or absorbing reactive power for a predefined voltage range.
III	Reactive power absorption, the objective is to decrease the mains voltage.

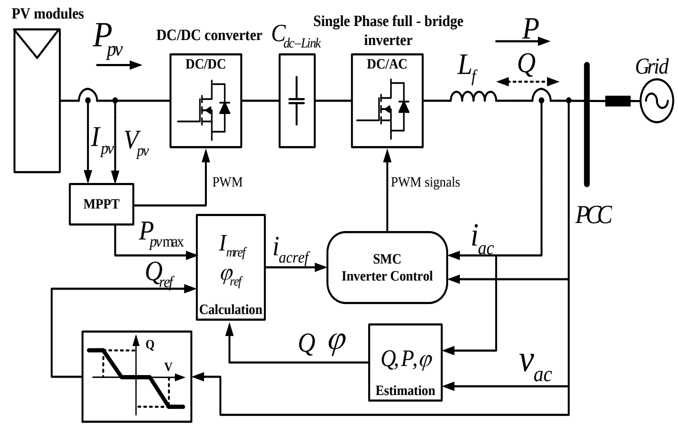

Fig. 2. Block diagram of the AC PV module.

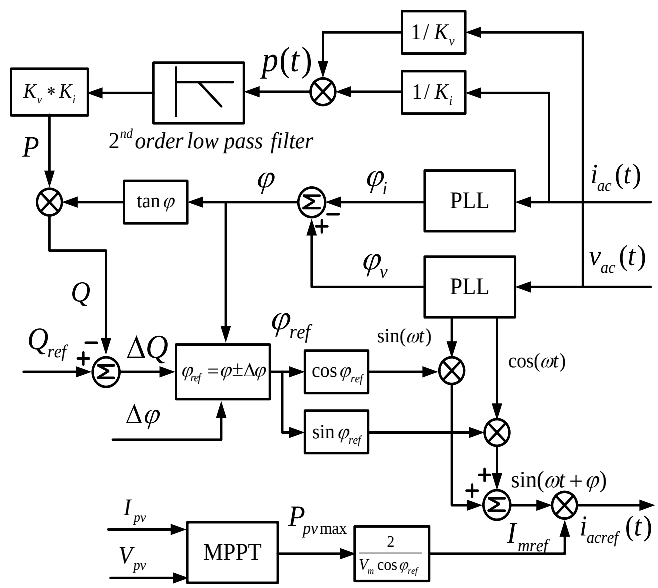

Fig. 3. Block diagram of the CRG.

The output of the outer control loop is the value of Q_{ref}, this value will be a input of the inner loop. The inner control loop will compare the value of Q_{ref} with the measured reactive power Q that is estimated using a 2nd order low pass filter along with phase-locked loop (PLL) blocks. The block diagram of a typical PLL is shown in Fig. 5, the phase angle of the inverter current and the grid voltage are estimated using PLLs, then the estimated reactive power Q is obtained through the estimation of the active power P by eliminating the double frequency AC component of the output inverter instantaneous power as shown in Fig. 3. This can easily be implemented by using single low cost digital processor with several analog inputs. The grid voltage is assumed to be a purely sinusoidal waveform and denoted by $v_{ac}(t) = V_m cos(\omega t)$ and, the inverter current that injected to the grid is $i_{ac}(t) = I_m \sin(\omega t + \varphi_i)$, I_m, φ_i are the amplitude and the phase angle of the inverter current, ω is the angular frequency, and V_m is the magnitude of the grid voltage. The grid current is controlled in such a way that the appropriate active P and reactive Q powers are injected to the grid. The instantaneous power is:

$$p(t) = v_{ac}(t) i_{ac}(t)$$

$$p(t) = \frac{1}{2} V_m I_m cos\varphi_i - \frac{1}{2} V_m I_m \cos(\omega t + \varphi_i) \quad (1)$$

The instantaneous power comprises a dc component and a double-frequency ac component. The DC component in (1) is the active power of the inverter output. Thus, it is possible to estimate the output reactive power through the active power P and the power factor angle $\varphi = \varphi_v - \varphi_i$, where φ_v is the phase angle of the grid voltage, and assumed to be 0 in (1) . A 2nd low pass filter with 10Hz cut- off frequency is designed to filter the double- frequency AC component.

$$G_F(s) = \frac{k * \omega_c^2}{s^2 + 2 * \varepsilon * \omega_c * s + \omega_c^2} \quad (2)$$

Where, ε is damping ratio, $f_c = \omega_c / 2\pi$ is the cut- off frequency.

The output of the filter is the active power P, the φ_i is estimated at the output of PLLs. Finally, the reactive power of the inverter output is calculated as:

$$Q = P * tan\varphi \quad (3)$$

When the PCC voltage V_{acRMS} is below a threshold voltage, V_{min} , the controller should inject the maximum reactive power at the AC PV module's terminals. When V_{acRMS} is in dead-band area, from V_{Dmin} to V_{Dmax} , the AC module does not inject any reactive power. The reference voltage V_{ref} is chosen according to the selected output voltage of the LV transformer at the secondary side (LV side) of the grid. When the PCC voltage V_{acRMS} reaches a threshold voltage V_{max}, the AC PV module should absorb the maximum reactive power at the AC

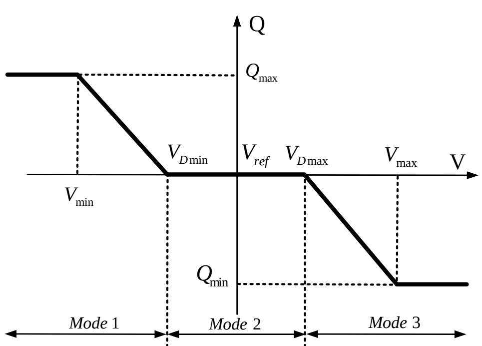

Fig. 4. Q(V) characteristic

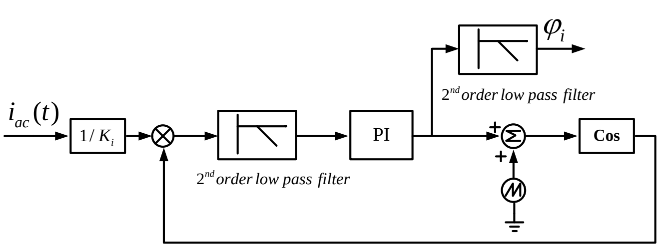

Fig. 5. Block diagram of the PLL blocks

module's terminals. The parameters V_{min} and V_{max} are chosen depending on the applicable lower and higher voltage limits of the inverters. According to EN 50160 [15] the mean RMS values of the supply voltage should not exceed ± 10% of the normal voltage. When the PV inverters are needed to comply also with the German directive VDE-AR-N 4105 [16], an additional limitation must be taken into account. The value of V_{max} should be selected in such a way that the voltage change at the PCC must not exceed 3% compared to the voltage when the AC PV modules are not connected. The parameters V_{Dmin} and V_{Dmax} are defined as the width of the voltage dead-band in which the AC module should not generate any reactive power. This region should restrict the AC PV module from injecting unnecessary reactive power when small variations are present around the nominal prescribed value, at the LV side of the distribution transformer. A too broad dead-band could also have negative effects, since AC PV modules closer to transformer station might not participate at all in regulating the voltage, while AC PV modules at the remote ends would provide maximum reactive power. Therefore, the AC PV modules situated at the end of the feeder will start absorbing reactive power earlier than the AC PV modules located near the transformer. The reactive output power Q is regulated by adjusting the power factor phase angle through the phase angle of the injected current. Due to this, a simple algorithm based on the difference between the estimated reactive power and reactive power command, $\Delta Q = Q_{ref} - Q$ is used to track the current reference phase angle φ_{ref} using:

$$if\ \Delta Q < 0\ then\ \varphi_{ref} = \varphi + \Delta\varphi$$

$$if\ \Delta Q > 0\ then\ \varphi_{ref} = \varphi - \Delta\varphi \quad (4)$$

As shown in Fig. 2, the inverter current reference:

$$i_{acref}(t) = I_{mref} \sin(\omega t + \varphi_{ref}) \quad (5)$$

$$i_{acref}(t) = I_{mref} [\sin \omega t cos\varphi_{ref} + cos\omega t sin\varphi_{ref}) \quad (6)$$

Equation (6) is used to calculate the component $\sin(\omega t + \varphi_{ref})$. The amplitude of the current reference I_{mref} is obtained based on the power balance between the PV side and the grid side. It is assumed that there is no power loss from the AC PV module to the grid, and the maximum power of the AC PV module is equal to the grid power average:

$$P_{pvmax} = P_{ac_{avg}} \quad (7)$$

$$P_{pvmax} = \frac{V_m I_{mref}}{2} cos\varphi_{ref} \quad (8)$$

$$I_{mref} = \frac{2 P_{pvmax}}{V_m cos\varphi_{ref}} \quad (9)$$

It is noted that the value of the amplitude of current reference depends on the power factor angle reference.

III. DC/AC Control Strategy

Due to the large availability of low cost of advanced digital signal processors, digital control strategies based on repetitive control, dead-beat control, and synchronous reference frame voltage control for controlling of grid-tie inverter have been proposed recently [10]-[12]. These techniques suffer from serious complexity in designing the controller, and require huge computations. As an alternative solution, the use of sliding mode control (SMC) method has been suggested, which is robust in the presence of parameter uncertainties and disturbances [13]-[14], [17]-[18]. It is able to constrain the system status to follow trajectories which lie on the sliding surface. For the sliding mode controller, the Lyapunov stability method is applied to keep the nonlinear system under control since the sliding mode approach transforms higher-order systems into first-order ones. In this way, the straightforward and robust control algorithms can be applied. Due to these advantages, SMC is widely utilized in controlling of DC/DC and DC/AC converters.

In order to obtain a high performance of the AC PV module, the SMC method is utilized in this paper for controlling the output voltage of the DC/AC inverter. The dynamic behavior of the inverter is described by the following state equation:

$$\dot{x} = f(x) + b(x)u \tag{10}$$

where $x=i_{ac}$ (t) is the state vector, and *u(t)* is control vector, further:

$$f(x) = -\frac{1}{L_f} v_{ac} \tag{11}$$

$$b(x) = \frac{K_{pwm}}{L_f};\ K_{pwm} = \frac{V_{dc_{Link}}}{v_{tri}} \tag{12}$$

where v_{tri} is the amplitude of a triangular carrier signal.

In order to control the output current of the inverter a suitable sliding surface has to be found from the switching law. Considering that $e= i_{ac} - i_{acref}$, the sliding surface *s=(e,t)* can be chosen as:

$$s = e\left(\frac{d}{dt} + \beta\right)^{n-1}, \beta > 0, n = 1 \tag{13}$$

In the phase plane (e, $\dot{e}$), *s=0* represents a line, called sliding line. In general, the sliding mode control exhibits two modes: the reaching mode and the sliding mode. In the reaching mode, a reaching control law is applied to drive the state variables into the sliding surface rapidly. When the system states are on the sliding surface, the system is supposed to be in the sliding mode, where in which an equivalent control law is applied to drive the system states on the sliding surface into the origin. When the system is in the sliding mode, the robustness of the inverter will be guaranteed and the dynamic responses of the inverter will depend on the slope of the sliding line. It is well known that the reaching mode of the sliding mode control exists if:

$$s(e,t)\dot{s}(e,t) < 0 \tag{14}$$

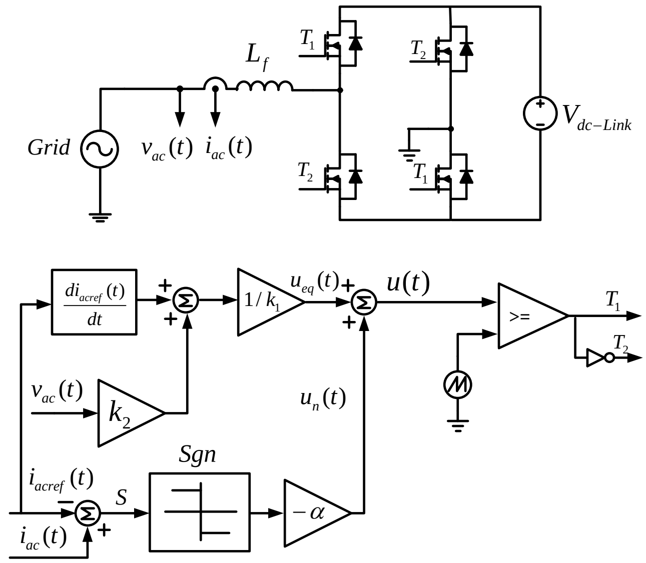

Fig. 6. Block diagram of the Sliding Mode Control (SMC) for controlling DC/AC inverter.

Equation (14) guarantees that the system trajectories reach the sliding surface in a finite time. Now, consider the following Lyapunov function.

$$V = \frac{1}{2}s^2(e,t) \tag{15}$$

From the Lyapunov's stability theorem, we know that if $\dot{V}$ is negative definite, the system state trajectory will be driven toward the sliding surface and remains moving on until the origin is reached. The control law satisfying the aforementioned conditions is presented in the following form:

$$u(t) = u_{eq}(t) + u_s(t) \tag{16}$$

where, *u(t)* is control signal,

$$u_{eq}(t) = \frac{1}{b(x)}\left[-f(x) + \dot{i}_{acref}\right] \tag{17}$$

$u_{eq}(t)$ is an equivalent control-input that determines the system's behavior on the sliding surface, which is non-linear switching input, which drives the state to the sliding surface and maintains the state on the sliding surface in the presence of the parameter variations and disturbances. Further:

$$u_s(t) = -\frac{1}{b(x)}Ksgn(s) \tag{18}$$

where K is the controller gain. The control signal is compared with the pulse-width modulation ramp and generates the appropriate switching pattern of the inverter. Figure 4 shows the block diagram of the SMC implemented using PSIM software.

IV. Simulation Results

To verify the performance of the AC PV module with the proposed RPC, a simple test circuit of the AC PV module was built and simulated under various transient conditions for each operation mode using PSIM 9.1 software. The 20-kHz PWM-modulated driving signals are adopted for controlling the full-bridge inverter. Based on the switching frequency and the output fundamental frequency, an output filter with the values of L_f = 6.5 mH is selected as shown in Fig.6. The DC link voltage is 400V_{DC}, and the normal grid voltage is 220V$_{RMS}$ at 50 Hz. The parameters of the SMC method for the DC/AC inverter are chosen to achieve the best transient control performance by considering the requirement of the stability.

The inverter current and grid voltage waveforms along with the active and reactive power are shown respectively in Fig. 7. At time from 0 to t_1, the grid voltage v_{ac} at PCC is 226V_{RMS} , higher than the normal voltage. The AC module should be working in mode 3, where the reactive power from the grid is absorbed by AC module in order to reduce the voltage rise at PCC. As can be observed from Fig. 7, both the measured active power, P, and reactive power, Q, during the entire time period (0 - t_1) are presented, where the active output power is around 1400 [W], and the reactive power absorbed by the AC PV module is approximately 900[VAr]. The partially expanded waveforms of the current and the voltage before time t_1 are shown in Fig. 8. Fig. 8 clearly shows that the current is lagging the grid voltage by 30^0. From t_1 to t_2, the grid voltage v_{ac} at PCC is 220V_{RMS} , the normal voltage, and the AC PV module should be working in mode 2 in order to inject the maximum active power into the grid as shown in Fig. 7 . It can be seen that during the entire time period (t_1- t_2), the active output power reaches a maximum value of 1500 [W], and no reactive power is absorbed or injected by the AC PV module. The partially expanded waveforms of the current and voltage from t_1 to t_2 are shown in Fig. 9. Obviously, the gird voltage and the current are in phase. Thus, the active power injected to grid is maximum and the reactive power injected to grid is zero. After t_2, the grid voltage, v_{ac} , at PCC is 214V_{RMS} , lower than the normal voltage, and the AC module should be working in mode 1, where the reactive power is injected into grid by AC PV module in order to support the grid voltage at PCC.Fig. 7 shows that during the time period after time (t_2 -), the active output power is around 1400 [W], and the reactive power that injected into the grid is approximate -900[VAr]. The partially expanded waveforms of the current and grid voltage after time t_2 are shown in Fig. 10. Fig.10 shows that the current is leading the grid voltage by 30^0.

Fig. 11 shows the transient behavior of the inverter current during the transition between the different modes. It can be observed that very little transient is observed during the transition. This implies that the current distortion is very low.

Fig. 12 shows the current and grid waveforms during the islanding mode. As can be observed, the AC module will stop injecting the active and reactive power into grid when an interruption of the grid voltage is detected. The simulation results prove that the proposed RPC and the SMC method can smoothly control the AC PV module's reactive output power in order to ensure that the grid voltage is always within the required voltage limits and effectively inject the full active power into the grid when needed.

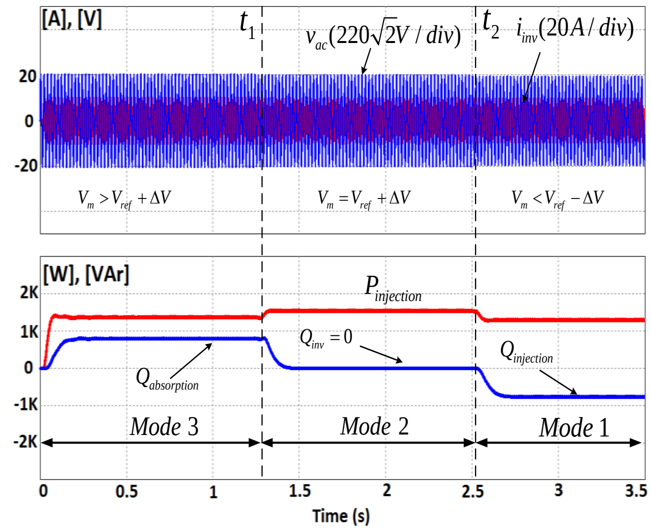

Fig. 7. Output current of the AC module with the different grid voltage

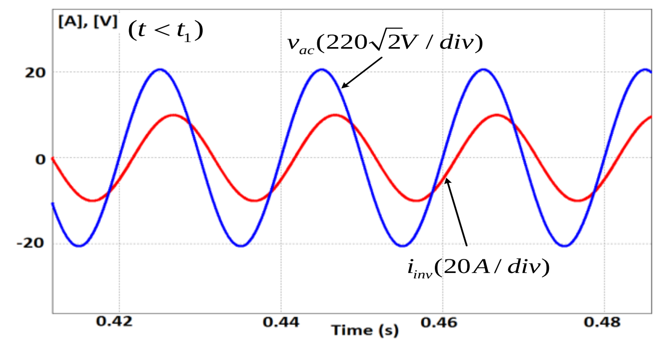

Fig. 8. The partially expanded waveforms of the current and voltage before time t_1.

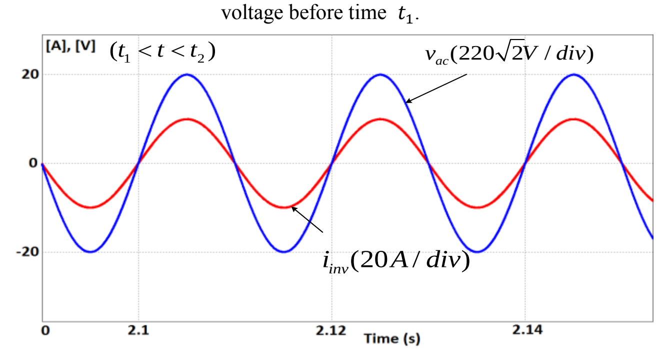

Fig. 9. The partially expanded waveforms of the current and voltage from t_1 to t_2 .

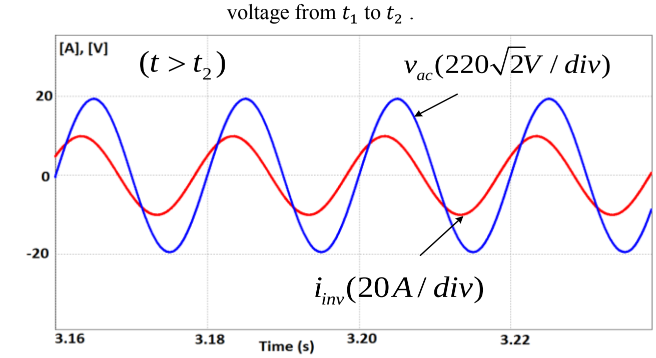

Fig. 10. The partially expanded waveforms of the current and grid voltage after time t_2.

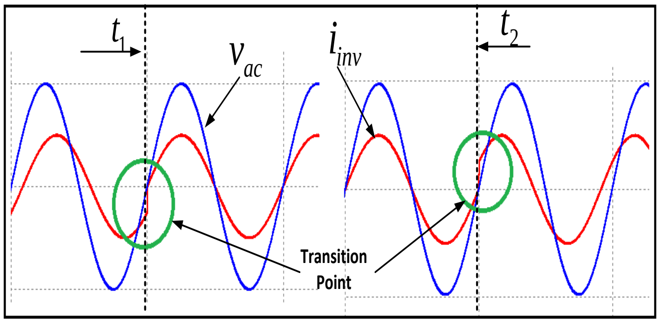

Fig. 11. Transient waveforms of different operational modes.

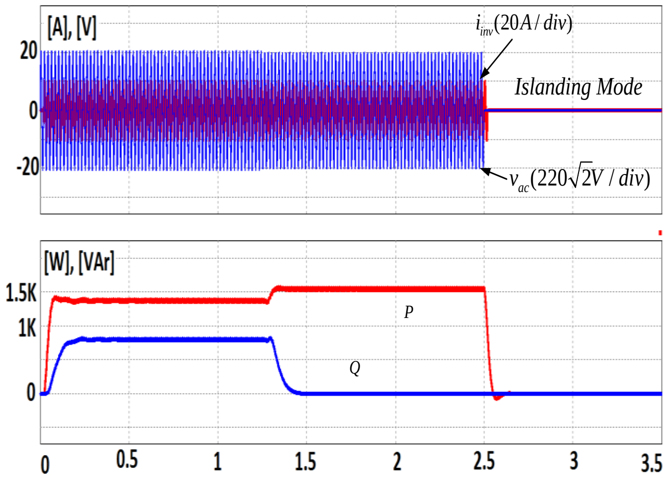

Fig. 12. Output current of the AC module during the Islanding Mode

V. Conclusions

In this paper, a low cost AC module with effectively simple structure for reactive power control is presented. The proposed RPC method can reduce the computational burden of the processor significantly, so a low-cost microprocessor can be adopted to implement the proposed AC PV modules. The analysis for the SMC strategy is also presented to prove the control stability. Using both the RPC and the SMC strategy, low-cost reliable AC PV modules with smart functions can become practical in the near future. This can have the capability to reduce the detrimental impact of rooftop solar PVs on the distribution grid, and hence can allow a high penetration of solar PVs to meet the renewable energy target of individual country.

References

[1] P. Mazumdar, P. N. Enjeti, and R. S. Balog, "Analysis and Design of Smart PV Modules," IEEE JOURNAL OF EMERGING AND SELECTED TOPICS IN POWER ELECTRONICS, vol. 2, pp. 451-459, September 2014.

[2] N Bzura. J. J, "The AC module: An overview and update on self-contained modular PV systems, " Power and Energy Society General Meeting, 2010 IEEE, pp 1-3, Jul. 2010.

[3] M. J. E. Alam, K. M. Muttaqi, D. Sutanto, " A Novel Approach for Ramp-Rate Control of Solar PV Using Energy Storage to Mitigate Output Fluctuations Caused by Cloud Passing," *IEEE Trans. Energy. Convers*., vol. 29, no. 2, pp. 507–518, Jun. 2014.

[4] M. Saitou, N. Matsui, and T. Shimizu, "A control strategy of single-phase active filter using a novel d-q transformation," in *Conf. Rec. IEEE* 38th IAS Annu. Meeting, 2003, pp. 1222–1227.

[5] M. Saitou and T. Shimizu, "Generalized theory of instantaneous active and reactive powers in single-phase circuits based on Hilbert transform," in *Proc. IEEE PESC*, 2002, pp. 1419–1424.

[6] Q. Zhang, X.-D. Sun, Y.-R. Zhong, M. Matsui, and B.-Y. Ren, "Analysis and design of a digital phase-locked loop for single-phase grid-connected power conversion systems," *IEEE Trans. Ind. Electron*., vol. 58, no. 8, pp. 3581–3592, Aug. 2011.

[7] S. A. Khajehoddin, M. Karimi-Ghartmani, A. Bakhshai, and P. Jain, "A power Control Method With Simple Structure and Fast Dynamic Response for Single-Phase Grid-Connected DG Systems," *IEEE Trans. Power Electron*, vol. 28, pp. 221-233, Jan. 2013.

[8] C.-H. Chang, Y.-H. Lin, Y.-M. Chen, and Y.-R. Chang, "Simplified Reactive Power Control for single phase Grid connected photovoltaic inverter," *IEEE Trans. Ind. Electron*., vol. 61, pp. 2286-2296, May 2014.

[9] Y. Yang, H. Wang, and F. Blaabjerg, "Reactive Power Injection Strategies for Single- Phase Photovoltaic Systems Considering Grid Requirements," *IEEE Trans. Ind. Appl*., vol. 50, pp. 4605-4076, Dec. 2014.

[10] K. Zhang, Y. Kang, J. Xiong, and J. Chen, "Direct repetitive control of SPWM inverter for UPS purpose," *IEEE Trans. Power Electron*., vol. 18, no. 3, pp. 784–792, May. 2003.

[11] R. Ortega, G. Garcera, E. Figueres, O. Carranza, and C. L. Trujillo, "Design and application of a two degrees of freedom control with a repetitive controller in a single phase inverter," in *Proc. IEEE ISIE*, Jun. 2011, pp. 1441–1446.

[12] M. Monfared, S. Golestan, J. M. Guerrero, "Analysis, design, and experimental verification of a synchronous reference frame voltage conrol for single-phase inverters," *IEEE Trans. Ind. Electron*., vol. 61, no. 1, pp. 258–269, Jan. 2014.

[13] K. D. Young, V. I. Utkin, U. Ozguner, "A control engineer's guide to sliding mode control," *IEEE Trans. Contr. Sys. Technology*, vol. 7, no. 3, pp. 328–342, May. 1999.

[14] S. C. Tan, Y. M. Lai, C. K. Tse, Sliding Mode Control of Switching Power Converters, first ed. CRC Press, Taylor & Francis Group, Jul. 2011.

[15] Application guide to the European Standard EN 50160 on "voltage characteristics of electricity supplied by public distribution systems", Ref: 23002Ren9530, Jun. 1995.

[16] VDE-AR-N 4105: 2011-08. Power generation systems connected to the low-voltage distribution network, technical minimum requirements for the connection to and parallel operation with low-voltage distribution.

[17] L. Shang, D. Sun,J. Hu, "Sliding-mode-based direct power control of grid-connected voltage-sourced inverters under unbalanced network conditions," *IET Power Electronics*, vol. 4, no. 5, pp. 570–579, May. 2011.

[18] J. Hu, L. Shang, Y. He and Z. Q. Zhu, "Direct Active and Reactive Power Regulation of Grid-Connected DC/AC Converters Using Sliding Mode Control Approach," *IEEE Trans. Power Electron*., vol. 26, no. 1, pp. 210–222, Jan. 2011.