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Simplified Reactive Power Control for Grid-connected Photovoltaic Inverters

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Abstract

Reactive power plays an eminent role for the power system to operate efficiently as well as securely. In order to control the reactive power by the proposed Simplified Reactive Power Control (SRPC) strategy for single-phase grid-tied Photovoltaic (PV) inverters. In this proposed SRPC strategy, the reactive power control is achieve effectively by using the Current-Mode Asynchronous Sigma-Delta Modulation (CASDM). This CASDM is adopted to enhance the current control's dynamic response, reduce both the current harmonic distortion and electromagnetic interference. In this paper, the proposed PV inverter is to extract the maximum power from the PV panels and to inject the corresponding active power into the utility grid. In the meantime, the output reactive power Q_{out} calculated by the simplified power calculation. With both the SRPC and CASDM, the single-phase PV inverter can achieve the desired RPC with low current harmonic distortion.

Keywords: Current Mode Asynchronous Sigma-Delta Modulation (CASDM), Current Reference Generation (CRG), Photovoltaic (PV) Inverter, Reactive Power Control (RPC), Single-Phase

1. Introduction

Nowadays the energy demand is increased and the continuous reduction in existing sources of fossil fuels. The growing concern regarding environment pollution, have pushed mankind to explore new technologies for the production of electrical energy using clean, renewable sources. Because of its quietness and pollution free nature, the Photovoltaic (PV) power generation system has become the most promising renewable energy source for residential applications. Since the best way to utilize the PV power is to inject it into the ac mains without using energy storage facilities, the grid-connected PV inverter is always necessary for the PV power system. Moreover, the PV inverter is a potential candidate to provide reactive power for the utility grid to improve its power quality In order to accurately control the reactive output power, the Current Reference Generation (CRG), which can generate the proper current reference with demanded power components, should be established in advance. In different literature, many Reactive Power Control (RPC) strategies for the single-phase inverter have been proposed[1,3–10]. Among them, the direct-quadrature (d-q) transformation[3,4] and the instantaneous reactive power theory (the p-q theory)[5–7] are the most addressed control schemes to generate two orthogonal current references. Furthermore, some modified methods were presented to improve the controlled performance. The authors in [8] adopted a sinusoidal signal integrator along with the p-q theory to reduce the controlled sensitivity to the grid voltage distortion. While the authors in [9] used the discrete Fourier transform Phase Lock Loop (PLL) method to achieve more precise RPC. In order to reduce the computational burden and uses a simplified power calculation, where the active power and the reactive power can be easily calculated by two sampled current values within one ac mains cycle, is proposed in this paper.

The simplified power calculation along with a smooth power adjustment forms a Simplified RPC (SRPC) strategy. Moreover, in order to reduce the controlled sensitivity to the grid current distortion. And by using of Current-Mode Asynchronous Sigma-Delta Modulation (CASDM), which has the merit of low current harmonic distortion, fast dynamic response and

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low electromagnetic interference is adopted for the PV inverter's output current control strategy.

2. Simplified Power Calculation

The simplified power calculation, in which the active power and the reactive power can be easily calculated by two sampled current values within one ac mains cycle, is proposed in this paper. First, the grid voltage is assumed to be a purely sinusoidal waveform, so the output power of inverter's is determined directly by its injected sinusoidal current.

The typical phasor diagram of the inverter's output current i_{ac} is shown in Figure 1. The active power is produced by the current component i_p which is in phase with grid voltage v_{ac}, and the reactive power is controlled by the current i_q which is 90° out of phase with the voltage v_{ac}. The amplitudes of the currents i_p and i_q can be expressed

$$i_p = I_m \cos\theta_i \tag{1}$$

$$i_q = I_m \sin\theta_i \tag{2}$$

where I_m and θ_i are the amplitude and phase angle of the current $i_{ac,}$ respectively. By controlling the I_m and the θ_i of the current $i_{ac,}$ the active and reactive power control can be achieved.

The principle of the proposed simplified power calculation method can be explained by using the typical grid voltage and current waveforms shown in Figure 2.

The voltage and current waveforms equation can be expressed as

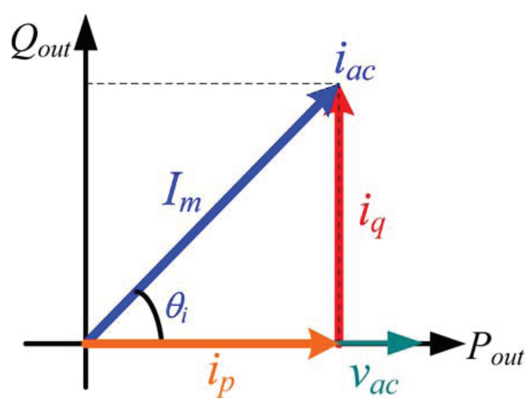


Figure 1. Phasor diagram of the ac output current.

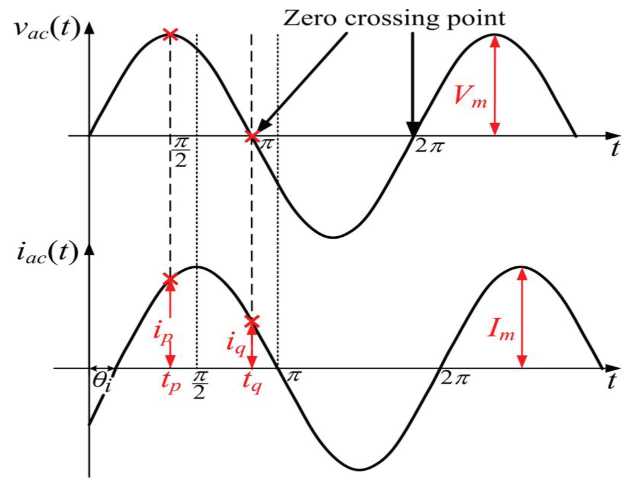


Figure 2. Typical voltage and current waveforms of the ac mains.

$$v_{ac}(t) = V_m \sin\omega t \tag{3}$$

$$i_{ac}(t) = I_m \sin(\omega t\text{-}\theta i) \tag{4}$$

where ω is the line frequency of the ac mains in radians per second.

At time $t_{p,}$ the amplitude of the injected ac current is expressed as

$$i_{ac}(t_p) = I_m \sin(\pi/2 - \theta i) = I_m \cos\theta i. \tag{5}$$

It should be mentioned that the current i_p can be measured by delaying a quarter of the ac line period when the zero crossing point of the ac mains voltage v_{ac} is detected. Equation (5) says that the sampled quantity at time t_p is equal to the amplitude of the active current component $i_{p.}$

Thus, the active output power of the inverter can be determined as

$$P_{out} = 1/2\, V_m I_m \cos\theta_i = 1/2\, V_m i_{ac}(t_p). \tag{5.a}$$

Similarly, the amplitude of the injected ac current at time t_q is

$$i_{ac}(t_q) = I_m \sin(\pi - \theta i) = I_m \sin\theta_i. \tag{6}$$

This current value can be measured when the zero crossing point of the ac mains voltage v_{ac} is detected. It is the amplitude of the reactive current component i_q and the reactive output power of the inverter becomes

$$Q_{out} = 1/2\, V_m\, I_m \sin\theta_i = 1/2\, V_m i_{ac}\left(t_q\right). \quad (6.a)$$

From the above equations, the active and the reactive power of the inverter can be easily calculated by two sampled current values within one ac line cycle. However, this method sensitive because of either current ripple or the current distortion, by adding a band pass filter in the current feedback loop the impact of the unavoidable current ripple to the power calculation can be easily eliminated. Thus, it is necessary to design a good current control strategy for reduce the current distortion.

3. Smooth Power Adjustment

After the active power and the reactive power are obtained, a proper controller is needed to compensate the power error. In general, the proportional-integral-derivative controller has advantage of fast transient response, but the sudden change of the ac output current it may cause large current distortion which will lead to inaccurate power calculation. Therefore, achieve smooth power adjustment is needed to control the active and the reactive power of the grid-connected inverter, the power phasor should move among these operation points. By adjusting the amplitude and phase angle of the reference current cycle by cycle, the desired active and reactive output powers can be achieved smoothly.

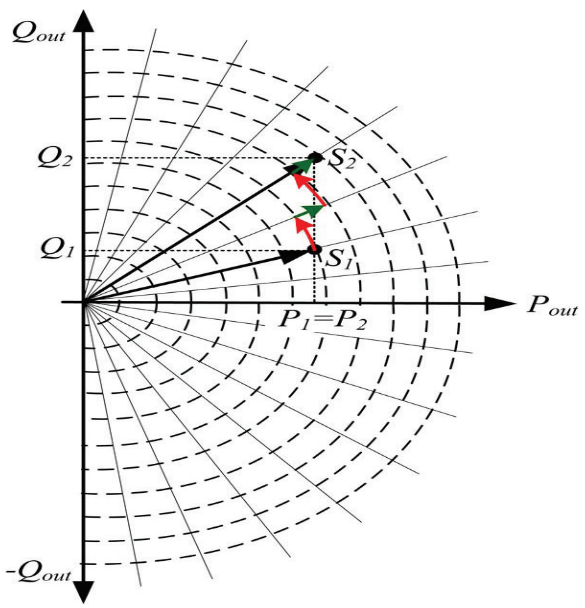


Figure 3. Conceptual diagram of the proposed smooth power adjustment.

Since the active output power P_{out} is regulated by changing the amplitude of the injected ac current, the measured power P_{out} is compared with the hysteresis comparator with high bound $P_{ref,H}$ and low bound $P_{ref,L}$. The positive or negative amplitude adjustment ΔI is determined by the following algorithm:

(a) The current amplitude generator

if $P_{out} > P_{ref,H}$ then k=-1;
else if $P_{out} < P_{ref,L}$ then k=+1;
else k=0;

$$I_m(n+1) = I_m(n) + k \times \Delta I \quad (7)$$

where $I_m(n)$ and $I_m(n+1)$ are the amplitudes of the injected current reference for the nth and $(n+1)^{th}$ ac mains cycles.

On the other hand, the reactive output power Q_{out} is regulated by adjusting the phase angle of the injected current. Similarly, the measured reactive power is compared with the hysteresis comparator with high bound $Q_{ref,H}$ and low bound $Q_{ref,L}$.

The positive or negative phase shift adjustment $\Delta\theta$ is determined by the following algorithm:

(b) The current phase angle generator

if $Q_{out} > Q_{ref,H}$ then m=-1;
else if $Q_{out} < Q_{ref,L}$ then m=+1;
else m=0;

$$\theta_i(n+1) = \theta_i(n) + m \times \Delta\theta \quad (8)$$

where $\theta i(n)$ and $\theta i(n+1)$ are the phase angles of the injected current reference for the n^{th} and $(n+1)^{th}$ of ac mains cycles. It should be mentioned that the active power P_{out} and the reactive power Q_{out} vary cosine and sine functions, respectively. Therefore, for θ_i close to 90° and P_{out} - Q_{out}, a change in current magnitude will cause a significant change in $Q_{out,}$ and a change in phase angle will cause a relatively larger change in $P_{out.}$

The power transition will take a long time if the ΔI and $\Delta\theta$ are too small. Thus, an adaptive adjustment, which has larger ΔI and $\Delta\theta$ values during large power change transient and smaller ones during steady state, is adopted to improve the overall performance.

The block diagram of the single-phase PV inverter with the proposed control strategy is shown in Figure 5. The power stage of the PV inverter consists of a boost

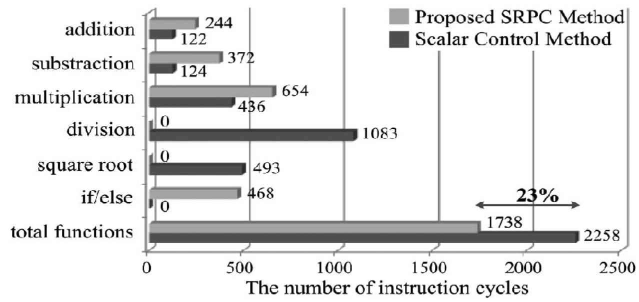


Figure 4. Graphic comparison of computational burden.

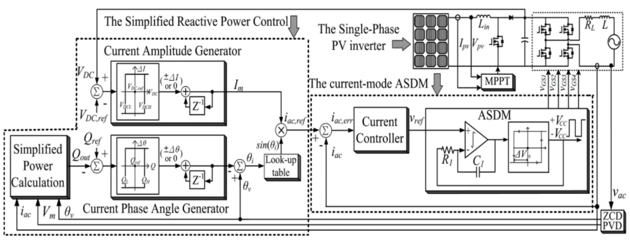


Figure 5. Block diagram of the single-phase grid-connected PV inverter.

converter with the Maximum Power Point Tracking (MPPT) function and a full bridge inverter with both active and reactive power output.

The control algorithm consists of the SRPC method and the CASDM control strategy. The objective of the proposed PV inverter is to extract the maximum power from the PV panels and to inject the corresponding active power into the utility grid. In the meantime, the output reactive power Q_{out} calculated by the simplified power calculation and the reactive power command Q_{ref} are compared to determine the phase shift of the current reference, $\theta_{i.}$ The amplitude and the phase angle of the grid voltage are captured by using the Peak Value Detector (PVD) and the Zero-Crossing Detector (ZCD), respectively. It should be mentioned that the ZCD along with the PVD is an easy-to-implement approach. On the other hand, the performance of the proposed SRPC method can be further improved by using a PLL circuit.

4. Current Control Strategy

The hysteresis controller can be made with either a current- or a voltage-loop. In this hysteresis controllers the saw tooth-shaped carrier with ideally having straight slopes, the linear modulation is caused and also infinite power supply rejection ratio.

For the PV inverter's active power control, the voltage V_{DC} should be regulated by the current amplitude generator with a hysteresis comparator to generate the current reference's amplitude I_m. The algorithm of the current amplitude generator to regulate the voltage V_{DC} can be expressed as

$$\text{if } V_{DC} > V_{DC}H \text{ then } k=+1;$$
$$\text{else if } V_{DC} < V_{DC}L \text{ then } k=-1;$$
$$\text{else } k=0;$$
$$I_m(n+1) = I_m(n) + k \times \Delta I. \tag{9}$$

Eventually, the current reference $i_{ac,ref}$ is obtained and the current amplitude is multiplying I_m with the signal sin(θi). For the output current control, the measured output current i_{ac} is compared with the current reference $i_{ac,}$ ref to generate the current error signal $i_{ac,}$ err which is sent into a current controller to generate the voltage reference v_{ref}.

5. Asynchronous Sigma-Delta Modulation

Delta modulation is based on quantizing the change in the signal from sample to sample rather than the absolute value of the signal at each sample. The most striking feature of a sigma delta modulator, which is the main

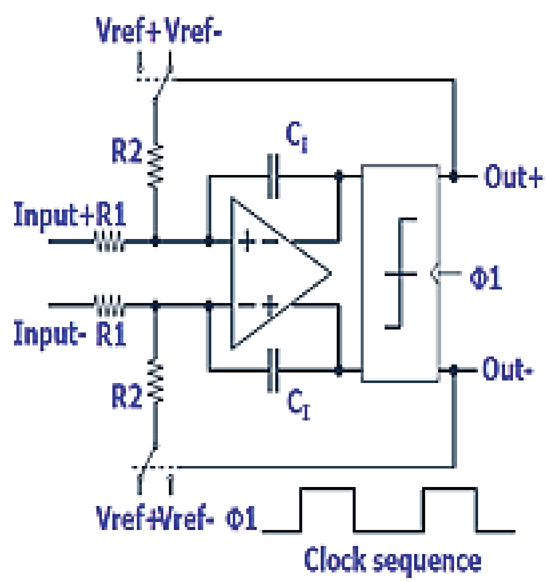
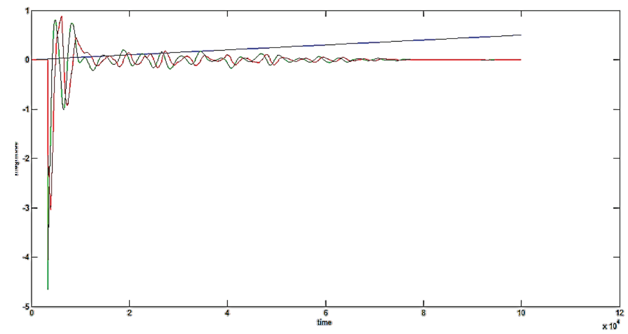


Figure 6. Functional diagram of single-bit sigma delta modulator.



component of sigma delta ADCs, is that these modulators use a very high sampling rate. The sampling rate used is in the range of MHz, which is much higher than the Nyquist rate, generally in the range of kHz. Hence, the over sampling ratio is very high, because of which these are sometimes referred to as over sampling ADCs. Then, the ASDM, which is an analog-to-digital signal converter with various frequency features, is adopted because to generate the gate signals, as vGS1–vGS4.

6. Simulation and Results

A Simplified Reactive Power Control (SRPC) strategy for single-phase grid-tied photovoltaic (PV) inverter, where the active and reactive power control is achieved by the following simulation results is obtained from the MATLAB/SIMULINK.

With both the SRPC and CASDM, the single-phase PV inverter can achieve the desired RPC with low current harmonic distortion.

7. Conclusion

This paper proposed a SRPC method along with the CASDM for the single-phase grid-connected PV inverter with RPC. The proposed SRPC method can reduce the computational burden of the processor Along with the small signal analysis for the CASDM is presented to prove the control stability. With both the SRPC and CASDM, So this the PV inverter can achieve the desired RPC.

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