DECOUPLING CONTROL OF THE ACTIVE AND REACTIVE POWER FOR A THREE-PHASE INVERTER

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Abstract

We consider the control design of a grid-connected three-phase inverter which is meant to work with a small power generation unit. A two-level (nested) control system is presented. The inner control loop contains repetitive controllers which assure that the output voltage of each phase can track a sinusoidal reference voltage. These voltages are applied to the local loads, which are separated from the grid by small inductors. The outer control loop monitors the grid voltage and, based on given reference values for the active and reactive power injected into the grid, it generates three reference voltages for the inner control loop. The controller in the outer control loop consists of two parts: a power controller and a phase locked loop (PLL). This paper is about the design of the power controller, which involves decoupling the active and reactive power in order to control them independently and smoothly.

1 Introduction

For reasons of both exploiting renewable forms of energy and dealing with energy shortfalls in constrained systems, there has been a great deal of development recently of small, distributed power generation [1]. Some of the new technologies produce electrical energy in DC form, for instance fuel cells and photovoltaic arrays. Others generate at variable frequency AC, for instance wind turbines, or high frequency AC, for instance micro gas-turbines. Although some generators can be connected directly to the electric power grid, such as wind power driven asynchronous induction generators, there is a trend to adopt power electronics based interfaces which convert the power first to DC and then use an inverter to export power to the 50Hz (or 60Hz) AC grid. The inverter employs self-commutated devices, such as IGBTs, GTOs, or MCTs, which are characterised by large power and high switching frequency [2], and thus it offers more flexible control opportunities than a conventional synchronous machine. An inverter-based distributed generator can be used during power outages, like a UPS, and in normal circumstances (when the grid is up), it can improve power quality [3], such as mitigating voltage sag and swell, and waveform distortion, in addition to its main function as a generator.

The principle of repetitive control [4,5,6] is that if a system is subject to periodic reference or disturbance signals, it can use the error information from previous cycles, stored in a delay line, to achieve better performance. This can be applied for DC to AC power converters, but so far it has seen only limited uses [7,8,9]. In these papers, repetitive controllers are applied in constant-voltage, constant-frequency power sources supplying power to single-phase isolated loads. However, distributed generators should provide power not only to a local load, but should also transfer power to the grid. For power control, a direct inverter voltage control [10] is often used to adjust the angle and the magnitude of a voltage which determines the active power and reactive power transfer. However, each of the angle and the magnitude affects both the active power and the reactive power, thus it is difficult to control them independently. This paper presents a sophisticated controller design for inverters which leads to good power quality for grid-connected generation and also to an accurate and independent control of the active and reactive power. The control system consists of two loops. In the inner control loop, a repetitive controller is used on each phase offering very good waveform tracking; in the outer control loop, decoupling control is used to control active power P and reactive power Q independently. The controller in the outer loop generates three reference voltage signals for the three phase repetitive voltage controllers. The detailed design of the inner loop is presented in [11]; This paper only focus on the design of the outer loop.
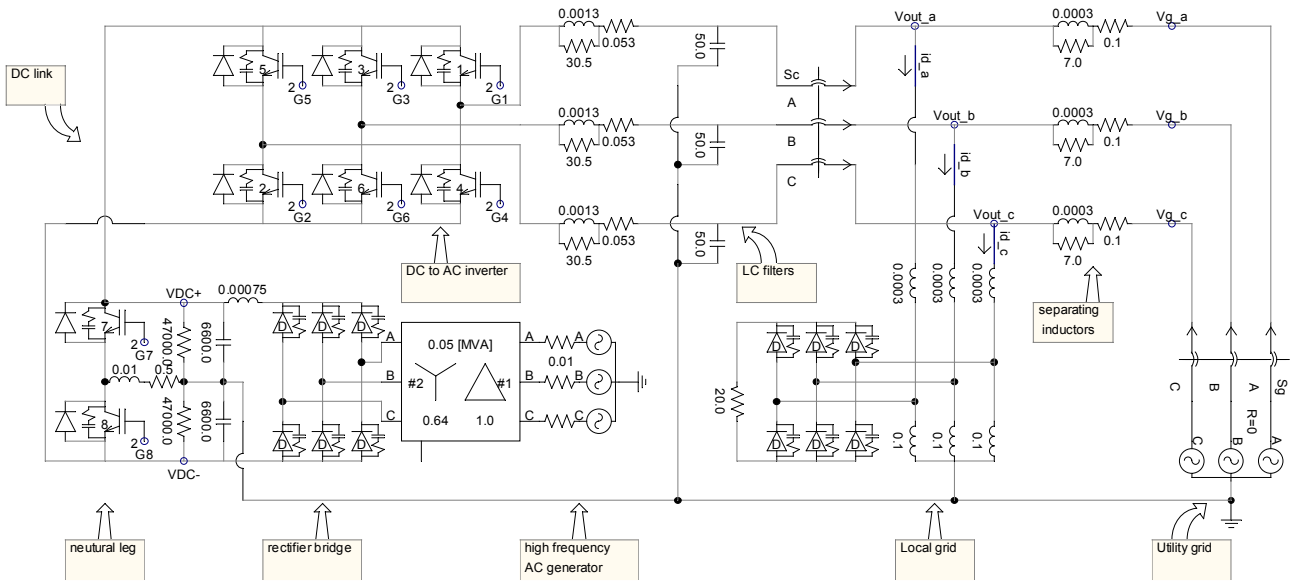
Fig. 1 Circuit diagram of the power conversion system, without sensors or controllers
(The units used here are Ω for resistance, H for inductance, and μF for capacitance.)

2 The power conversion system

The power conversion system studied here consists of a high frequency three-phase AC generator (possibly driven by a small gas turbine), an AC/DC/AC converter, local grid and a utility grid. The electric circuit of this system, without sensors and controllers, is shown in Fig. 1. A three-phase diode rectifier bridge is used to convert high frequency AC to DC. On the DC side, split DC link capacitors with neutral point are used for smoothing and short-term energy storage. The DC-AC inverter system consists of a three-phase IGBT bridge and LC filters. The switching frequency of the IGBT bridge is 10kHz. The LC low-pass filter has been designed to provide a good attenuation of the switching frequency component of the output voltage. Three inductors are used to separate the local grid from the external utility grid, to enable the control of the voltage of the local grid with high precision, even with nonlinear loads connected to the local grid. Each filter inductor and each separating inductor is modelled, taking into account its high frequency behaviour, as an ideal inductor in parallel with a resistor and then in series with another resistor. In our studies, the local load consists of a inductive load in parallel with a three-phase rectifier bridge supplying another resistive load. The rectifier bridge draws harmonically distorted current and thus it causes a disturbance to the local grid voltage. The two switches S_c and S_g in the Fig.1 are needed in the start-up and shut-down procedures of the inverter. The conversion system is regarded as three independent single-phase systems from the control viewpoint. The power to the grid is controlled by manipulating the fundamental frequency component of the three voltages on the local load. Assuming that these voltages track the reference voltages rather accurately, the control of the power flow is achieved by adjusting the reference voltages.

3 Control system design and implementation

3.1 The structure of the two-level control system

In order to achieve control objectives, a two-level control system is presented, as depicted in Fig.2. The inner loop contains the internal model, the stabilizing compensator C (computed by H^∞ design), and the plant to be controlled (the PWM inverter, LC filters, local loads and separating inductors). The disturbances acting on the plant (load disturbance i_d, DC link average voltage $v_{ave} = (V_{dc}^+ + V_{dc}^-)/2$, and the grid voltage v_g) are assumed to be periodic. The repetitive voltage controller, based on the internal model principle, assures that the output voltage of each phase is tracking a periodic reference. The outer loop controller consists of two parts: the phase-locked loop (PLL) and the power controller. It monitors the grid voltage and, based on given reference values for active and reactive power injected into the grid, generates the three reference voltages for the inner loop. The PLL is used to extract the fundamental frequency component of the grid voltages and generate also the corresponding quadrature signals which are needed to calculate the active power and reactive power to the grid.

3.2 Calculation of active power and reactive power

The definition of active power for a periodic voltage $v(t)$ and a periodic current $i(t)$ is $P = \dfrac{1}{T}\int_0^T v(t) \cdot i(t) dt$, where T is the period. If the voltage v is sinusoidal, the fundamental component of the active power P_1 and the reactive power Q_1 can be calculated as:

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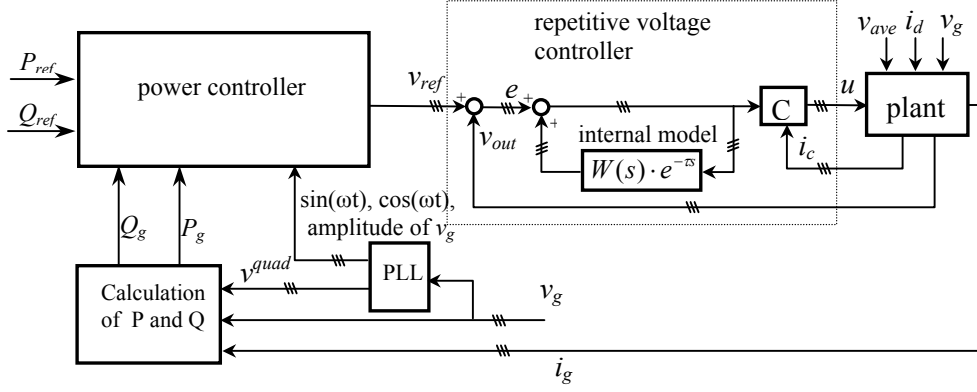
Fig. 2 Block diagram of the two-level control system

$$P_1 = \frac{1}{T} \int_0^T v(t) \cdot i_1(t)dt = VI\cos\psi$$

and

$$Q_1 = \frac{1}{T} \int_0^T v(t) \cdot i_1^{quad}(t)dt = VI\sin\psi ,$$

where i_1 is the fundamental component of the current i, V the RMS value of v, I the RMS value i_1, ψ the phase angle between v and i_1, and i_1^{quad} the quadrature current, $i_1^{quad}(t) = i_1(t - \frac{T}{4})$. In this paper, we propose a method for calculating the active and reactive power injected into the grid as:

$$P_g(t) = \frac{1}{T} \int_{t-T}^t \left[v_{ga}(\tau) \cdot i_{ga}(\tau) + v_{gb}(\tau) \cdot i_{gb}(\tau) + v_{gc}(\tau) \cdot i_{gc}(\tau) \right]d\tau$$

$$Q_g(t) = \frac{1}{T} \int_{t-T}^t \left[v_a^{quad}(\tau) \cdot i_{ga}(\tau) + v_b^{quad}(\tau) \cdot i_{gb}(\tau) + v_c^{quad}(\tau) \cdot i_{gc}(\tau) \right]d\tau$$

where v_a^{quad}, v_b^{quad} and v_c^{quad} are the quadrature of fundamental components of the grid voltages v_{ga}, v_{gb}, and v_{gc} respectively. The reactive power is measured by averaging the products of quadrature grid voltage signals and the corresponding line currents over a period. Assume that phase signals of grid voltages are acquired through the PLL and $\sin(\omega t)$ accurately follows the phase of the fundamental component of the phase-A grid voltage, therefore the quadrature signals can be calculated as

$$v_a^{quad} = V_g \cdot \cos(\omega t) ,$$

$$v_b^{quad} = V_g \cdot \cos(\omega t - \frac{2}{3}\pi)$$

and

$$v_c^{quad} = V_g \cdot \cos(\omega t + \frac{2}{3}\pi) ,$$

where V_g represents the amplitude of the fundamental component of the grid voltage v_g.

3.3 Formation of the reference voltage signals

In Fig. 3, an equivalent single-phase system circuit is given. The active power P and the reactive power Q to the grid will be controlled by manipulating the output voltage v_{out}. $v_{out} = V_{out}\cos(\omega t + \theta_{out})$ is the inverter output voltage. For power control, a direct control is often used to adjust angle θ_{out} and magnitude V_{out}, which determine the active power and reactive power respectively. However, each of the angle and the magnitude affects both the active power and the reactive power. It can not control them independently. A decoupling design is presented and phasor analysis for forming of a reference signal of the output voltage will be carried out as shown in Fig. 4.

The grid voltage is regarded as the reference phasor, with angle zero:

$$\overline{V}_g = V_g$$

The current to the grid can be expressed as

$$\overline{I}_g = I_{gx} + j \cdot I_{gy}$$

and hence the power to the grid on each phase is:

$$P = I_{gx} \cdot V_g$$

and

$$Q = -I_{gy} \cdot V_g .$$

Assuming that the output voltages track the reference voltages $\overline{V}_{ref}$ rather accurately with the repetitive voltage controllers, the power control is achieved by manipulating $\overline{V}_{ref}$:

$$\overline{V}_{ref} = \overline{V}_g + \overline{V}_{zg} = V_g + (I_{gx} + j \cdot I_{gy}) \cdot Z_g$$

where Z_g is the equivalent impedance of the separating inductor and short distance of transmission line for grid connection, thus:

$$\overline{V}_{ref} = V_g + \frac{P}{V_g} \cdot Z_g - j\frac{Q}{V_g} \cdot Z_g .$$
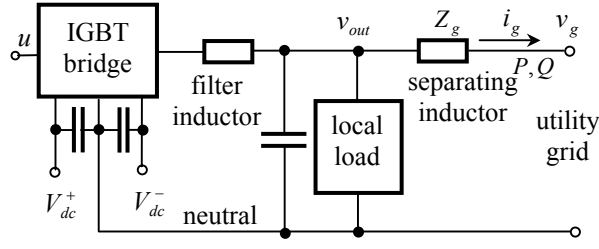
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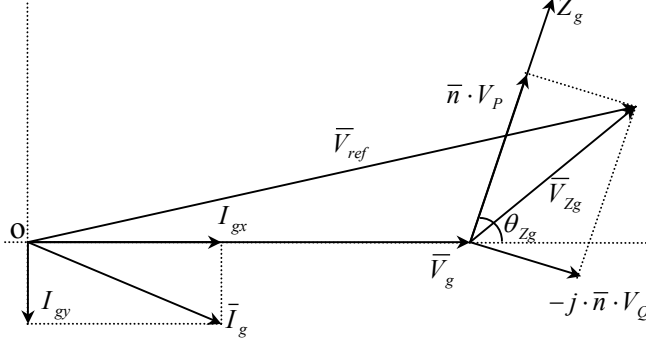Fig. 3 An equivalent single-phase system circuit

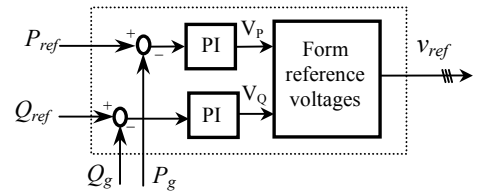Fig. 4 Phasor diagram for generating the reference voltage

Fig.5 Decoupling power controller

Since in practice, precise value of Z_g is hard to acquire, it is difficult to calculate $\overline{V}_{ref}$ directly according to the above equation. However, it is much easier to find the impedance angle θ_{zg} of Z_g with reasonable accuracy, therefore, we introduce a unit vector:

$$\overline{n} = Z_g / |Z_g| = \cos(\theta_{zg}) + j\sin(\theta_{zg})$$

and let

$$V_P = \frac{P}{V_g} \cdot |Z_g| \ , \ \ V_Q = \frac{Q}{V_g} \cdot |Z_g|$$

then

$$\overline{V}_{ref} = V_g + V_P \cdot \overline{n} - jV_Q \cdot \overline{n}$$

Using phase signals $\sin \omega t$ and $\cos \omega t$ obtained from the PLL, and grid voltage amplitude, three phase instantaneous reference voltages are given by:

$$v_{refa} = (V_P \cos\theta_{Zg} + V_Q \sin\theta_{Zg} + V_g) \cdot \sin\omega t$$
$$+ (V_P \sin\theta_{Zg} - V_Q \cos\theta_{Zg}) \cdot \cos\omega t$$

$$v_{refb} = (V_P \cos\theta_{Zg} + V_Q \sin\theta_{Zg} + V_g) \cdot \sin(\omega t - \frac{2}{3}\pi)$$
$$+ (V_P \sin\theta_{Zg} - V_Q \cos\theta_{Zg}) \cdot \cos(\omega t - \frac{2}{3}\pi)$$

$$v_{refc} = (V_P \cos\theta_{Zg} + V_Q \sin\theta_{Zg} + V_g) \cdot \sin(\omega t + \frac{2}{3}\pi)$$
$$+ (V_P \sin\theta_{Zg} - V_Q \cos\theta_{Zg}) \cdot \cos(\omega t + \frac{2}{3}\pi)$$

which are fed to the inner control loop as the voltage reference signals.

3.4 Active power and reactive power controller

If V_g is known, active power P is only related to V_P and reactive power Q to V_Q respectively. Hence decoupling between P and Q can be achieved through adjusting V_P and V_Q respectively. Two separate controllers can be used to generate V_P and V_Q. As shown in Fig.5, two PI controllers as follow are adopted:

$$V_P = (P_{ref} - P_g)(K_{PP} + K_{IP}/S)$$

and

$$V_Q = (Q_{ref} - Q_g)(K_{PQ} + K_{IQ}/S)$$

Through tuning control parameters, good transient and steady state performance of power controller have been achieved using: $K_{PP} = 0.5$, $K_{IP} = 6.67$, $K_{PQ} = 0.5$ and $K_{IQ} = 6.67$. In the design of the decoupling control, only one system parameter, impedance angle θ_{zg}, is needed. Even in practice, inevitable parameter uncertainties is encountered, it is expected to have small influence on the power controller. The instantaneous reference voltages, v_{refa}, v_{refb} and v_{refc} will be fed to the repetitive controller, and IGBT control signals u_a, u_b, and u_c are thus formed.
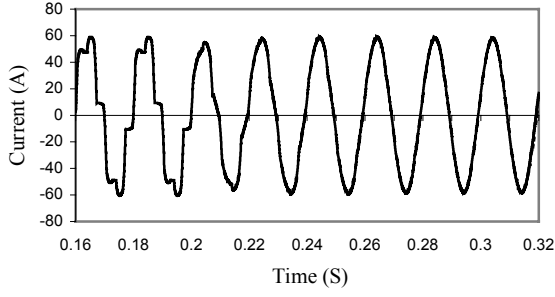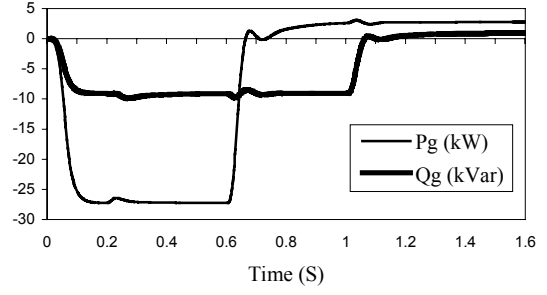
Fig.6 Waveform of current to the grid

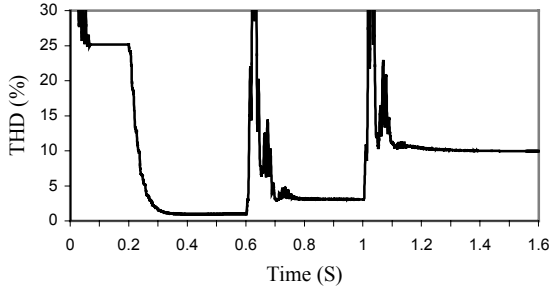Fig.7 Power curves with decoupling control
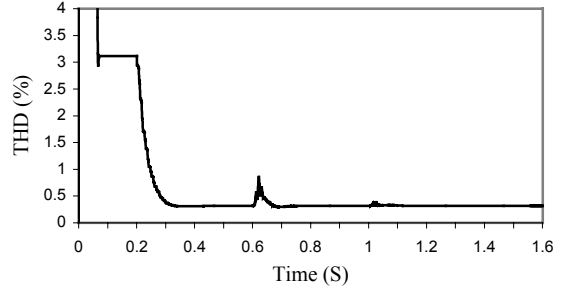

Fig.8 Current total harmonic distortion

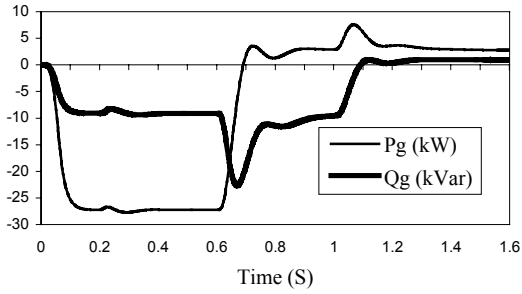Fig.9 Voltage total harmonic distortion

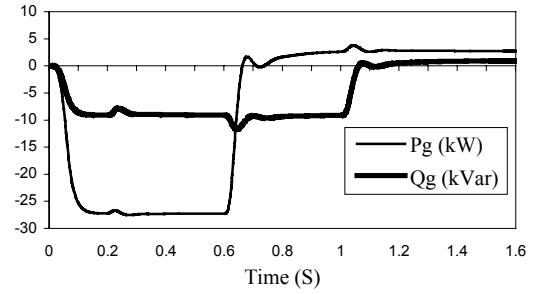

Fig.10 Power curves with magnitude-phase control

Fig.11 Power curves with 20% error of θ_{zg}

4 Simulations

Simulations are carried out using PSCAD/EMTDC software. Fig. 6 shows that waveform of current injected into the grid improves when repetitive control starts to operate at 0.2s. The THD (total harmonic distortion) of load voltage decreases from 3.12% to 0.3% and the current THD decreases from 25.2% to 0.98%. Fig.7 gives results of active power and reactive power to the grid in response of change of reference values with the proposed decoupling power controller. Before the inverter is connected to the load, power flows from the grid to load, therefore, about –27.2kW of active power and –9.1kVar of reactive power flow to the grid. After the inverter is connected to the load from 0.2s, the power controller tries to maintain the power to grid unchanged. From 0.6s, P_{ref} is increased by 30kW, meanwhile Q has only a small fluctuation in magnitude, about 1kVar. From 1.0s, Q_{ref} is increased by 10kVar, meanwhile P has also only a small fluctuation about 0.6kW in magnitude. Fig.8 and Fig.9 give total harmonic distortions of the current to the grid

and the load voltage in response of the power changes. Since the output power from the inverter increases, power from the grid to the load decreases accordingly. Particularly, after 1.0s, the active and reactive power to the grid becomes small. Therefore, although the harmonic currents are small, they account for the large proportion (about 10%) of the total current injected into the grid, while the voltage THD is still about 0.3%.

For comparison, a simulation result with a magnitude-phase angle power controller is given in Fig.8, in which responses of P and Q have certain interaction, changes in magnitude of Q and P are 13kVar and 9kW respectively corresponding to changes of P_{ref} and Q_{ref}. If there is an error for the impedance angle of Z_g, actual value of θ_{zg} is 43 degree while 51 degree is used for controller design, with 20% error. Fig.9 gives simulation results, from which it can be seen that this error has only minor influence on the power performance. The results manifest that system performance has been significantly improved with the proposed decoupling power control.

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5. Conclusions

A decoupling control for active power and reactive power is presented and applied for a grid-connected three-phase inverter. The power controller is designed to generate reference voltage signals for the repetitive voltage controllers. The PQ-decoupling function ensures an independent control of active power and reactive power and reduces their interaction in dynamic process. Simulations have proved the effectiveness of the controller.

Acknowledgements

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