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Improved droop control strategy for grid-connected inverters

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ABSTRACT

An improved control strategy for grid-connected inverters within microgrids is presented in this paper. The strategy is based on the classical $P-\omega$ and $Q-V$ droop method. The improvement in the proposed control strategy is twofold: Firstly, the transient response of the droop controller is improved by replacing the traditional method of measuring average power, which is based on using a first order low pass filter, by a real time integration filter. This is shown to reduce the imported transient energy when connecting to the grid. Secondly, the steady state output current quality is improved by utilising a virtual inductance, which is shown to reject grid voltage harmonics disturbance and thus improve the output current THD. A small signal model of the inverter based on the transfer function approach is developed to analyse its stability and determine droop gains. Simulation and experimental results are presented to validate the model and demonstrate the controller capabilities.

1. Introduction

The use of frequency and voltage droop method to control power sharing of parallel and grid-connected PWM inverters is well established in the literature [1–16]. This method requires active and reactive power to be measured in order to droop the frequency and voltage accordingly such that the inverter mimics the behaviour of a synchronous generator. In reported systems [2–12], a low pass first order filter is used to obtain the average power from single phase instantaneous power measurement. In a balanced three phase system, the instantaneous power equals the average power and such a filter might not be necessary. However, in an unbalanced three-phase system, the instantaneous power has a ripple component and a filter becomes essential to prevent the ripple component from propagating to the frequency and amplitude through the droop control feedback. However, this filter has a significant effect on the dynamics of the droop controller due to associated phase lag [12]. In [13,17,18] the average power was measured by integrating the instantaneous power. However, no discussion regarding the advantage of this method over the low pass filter was provided. In this paper it is shown that the real time integration method for calculating average power gives superior controller dynamic performance compared to the low pass filter method.

When droop control is used for grid-connected inverters, the current injected into the grid is basically controlled by adjusting the power angle, and hence, there is no direct control over the quality of the output current in contrast to traditional current mode grid-connected inverters [19–21] where the control is performed using a feedback signal of the output current. In the presence of grid voltage harmonics, harmonic currents will flow from/to the inverter due to its low output impedance of the inverter and its output filter. In grid-connected inverters, an *LCL* filter is normally used (rather than *LC*) as shown in Fig. 1. The grid side inductor L_2 is used to block the high switching frequency component of the output current from being injected into the grid. The presence of L_2 increases the output impedance of the inverter and to a certain extent it improves the output current Total Harmonic Distortion (THD). However, the design criterion for choosing the inductance of L_2 is to block the high switching frequency current [20,21] and hence L_2 is normally chosen to be relatively small (increasing L_2 will increase size and cost). The other disadvantage of increasing L_2 is that it worsens the voltage THD when the inverter operates in island mode and supplies a non-linear load. In this paper, a virtual inductance is proposed to further increase the output impedance of the inverter but without compromising size and cost. This virtual inductance can be deactivated or reduced in standalone island mode so it does

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not affect the voltage THD when supplying a non-linear load. The use of virtual impedance has in fact been proposed in the literature [2,3,5–7] but it has been proposed for inverters operating in standalone parallel mode to guarantee a predominant inductive output impedance of parallelled inverter so that the active power is predominantly determined by the power angle and the reactive power is predominantly determined by the voltage amplitude. The main motivation, however, for using the virtual inductance in this paper is to improve the quality of the output current in grid-connected mode. Although some previous publications discussed the effect of grid side inductance on the controller stability of grid-connected inverters [21–23], they only considered the effect of physical inductance. Also, in such grid-connected systems, the inverter is typically controlled as a current source injecting certain amount of current into the grid. In this paper, however, the effect of a virtual inductance on the stability of grid connected inverters, based on droop-control, is discussed taking into account the effect of the low pass filter required for practical implementation. The model (current–voltage transfer function) of a virtual inductor is different from a physical inductor.

Several publications have proposed small signal models for droop controlled inverters operating in grid-connected mode [24–26]. These models used state-space equations to describe the inverter dynamics. In this paper, an intuitive model based on the transfer function approach is presented. The model is used to analyse stability and choose the droop coefficients.

Applications such as photovoltaic single-phase micro-inverters have used droop control in order to achieve a flexible operation of both grid-connected and island modes [13,27–29]. Although small-signal analysis has been done for droop-controlled grid-connected inverters powered by ideal DC sources, to the best knowledge of the authors, still there are no studies on how the droop controller affects the DC-link voltage especially when the inverter first connects to the grid.

The main novel contributions of the paper are: (1) A detailed investigation, not reported before in the literature, of the effect of average power measurement techniques (low pass filtering and integration of instantaneous power methods) on the performance of the power flow controller; the integration method is shown to be superior, (2) Using virtual inductance as an effective method to reduce current THD and investigate its practical realisation using a high-pass filter and its effect on stability and current THD; previous work in the literature, including our own, only considered the effect of physical inductance on stability and THD (3) A new intuitive small signal model of a droop controlled grid connected inverter based on transfer function approach, (4) a study of the impact of the droop controller on DC-link voltage, which has not been considered before in the literature.

The paper is organised as follow. Section 2 gives an overview of the system. Section 3 discusses the inner loop controller of the inverter. In Section 4 the development of a small signal model of the inverter and the design of the droop control are presented. Simulation and experimental results are presented in Sections 5 and 6, respectively.

2. System overview

The grid-connected inverter considered in this paper is shown in Fig. 1. It consists of a three-phase half bridge inverter with *LCL* filter. The inverter parameters are given in Table 1. The inverter controller is illustrated in Fig. 2. It consists of an outer power flow controller that sets the voltage amplitude and frequency demand for an inner voltage inner loop controller. The power flow controller regulates the amount of active and reactive power injected into the grid. The voltage inner loop controller regulates the capacitor voltage V_c by utilising two feedback loops of the capacitor voltage and current. The detailed design of the inner loop controller is discussed in Section 3 and the design of the power flow controller is discussed in Section 4.

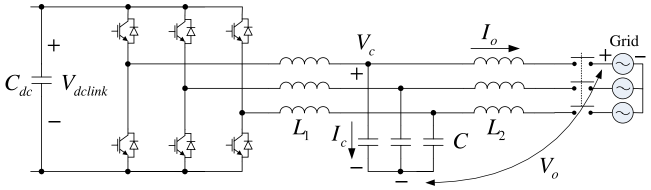

Fig. 1. Circuit diagram of the grid-connected inverter.

Table 1
Inverter parameter values.

Symbol	Value	Description
L_1	350 μH	Inverter-side filter inductor
C	160 μF	Filter capacitor
L_2	250 μH	Grid-side filter inductor
C_{dc}	2 mF	DC-link capacitor
P_{max}	60 kW	Maximum active power rating
Q_{max}	45 kVAR	Maximum reactive power rating

3. Inner loop controller

Fig. 3 shows the block diagram of one inverter phase and its inner loop controller. The controller is implemented in the *abc* frame. The controller could also be implemented in the *dq* rotating frame where a Proportional–Integral (PI) controller is equivalent to a Proportional Resonant (PR) controller in the stationary frame. It has been reported that implementing a PI controller in the *dq* frame is better than a PR controller in the stationary frame as the latter can lead to analytical errors especially at the low frequencies [30]. In this design, only proportional term will be used in the inner voltage controller. Therefore, the *abc* stationary frame is used for its simplicity. The inner loop voltage controller consists of an outer feedback loop of the capacitor voltage and an inner feedback loop of the capacitor current; the latter provides damping of filter resonance. A feedforward loop of the reference voltage is also implemented to improve the speed of response and minimise the steady state error.

Without the virtual inductance loop, the output voltage can be shown to be given by

$$V_o = G(s)V_c^* - Z(s)I_o \tag{1}$$

where $G(s)$ is the closed loop transfer function and $Z(s)$ is the system output impedance,

$$G(s) = \frac{k_v + 1}{L_1Cs^2 + k_cCs + k_v + 1} \tag{2}$$

$$Z(s) = \frac{L_1s}{L_1Cs^2 + k_cCs + k_v + 1} + L_2s. \tag{3}$$

The voltage and current proportional gains k_v and k_c were chosen to be 2.0 and 2.2, respectively to provide good transient and steady state response. In terms of transient response, the aforementioned gains give a damping ratio $\zeta = k_c\sqrt{L_1C/(k_v+1)}/2L_1 = 0.43$ and a step response settling time of about 1 ms. The steady state response can be analysed using the bode diagram of $G(s)$ which is shown in Fig. 4. At the fundamental frequency $f = 50$ Hz, the gain is 0.01 dB and the phase lag is 2.12°. This is a characteristic of the closed loop system, which also depends on system parameters uncertainty. The phase lag will cause the inverter to import some transient power when connecting to the grid as will be shown later.

Virtual inductance and grid harmonics rejection

The ideal transfer function of a virtual inductance L_v is given by

$$Z_{vi}(s) = sL_v. \tag{4}$$

However, implementing the derivative as in (4) experimentally introduces the well-known problem of noise amplification.