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Decoupled control of grid connected inverter with dynamic online grid impedance measurements for micro grid applications

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ABSTRACT

This paper presents a decoupled control of grid connected inverter using dynamic online grid impedance measurements for a micro grid application. The proposed controller is implemented in synchronous reference frame (SRF) and controlled using linear PI controllers. The mutual coupling introduced between the *d* and *q* control loops due to the transformation into SRF is accurately decoupled using the dynamically measured grid impedance using a feed-forward control. The decoupling allows independent control of active and reactive powers against step changes in the active/reactive power references. The online measurement of the actual impedance and its use further for decoupling is proposed in this paper for making the decoupling accurate inspite of the network configuration being altered like in micro grids. Here the grid resistance and inductance are measured during the operation using a non-characteristic frequency current continuously injected into the grid, and subsequently calculating the impedance using discrete Fourier transforms. The continuous injection of non-characteristic current at 75 Hz avoids the injection of sub-harmonics into the grid during measurements. The control loop is updated periodically with the estimated grid impedance, thus enabling the independent control of active and reactive powers delivered by the inverter. The proposed decoupled controller with grid impedance measurement is tested through simulation studies and hardware experiments. The experiments are conducted with the proposed controller on a scaled down laboratory model of micro-grid with a 1 kVA solar inverter, and the performances are presented for step changes in the power references and the results are presented.

Introduction

The exponential growth of energy demand with deteriorating environment has lead to the research on renewable energy generation systems like wind power, solar photo voltaic power, etc. Renewable energy sources are connected to the grid through inverters [1,2] with one or more of the following control requirements viz. (i) Independent control of active and reactive powers (ii) synchronization to grid, (iii) meeting the harmonics standards, (iv) control under healthy and fault grid conditions and (v) islanding detection and isolation.

The power delivered by the inverter is controlled either by PWM voltage control [1] or by current control [3,4]. PI control is commonly used and recently the PR control is advocated [5,6]. The selection of controller is based on the steady state and transient state performance requirements to meet the power quality standards.

PR controllers operate, both with the stationary reference frame quantities or directly with time varying *abc* quantities. PR controller, proposed in [5,6] for grid connected applications tracks the ac reference quantities with zero steady state error without introducing any phase delay. Also it does not require synchronous *d–q* transformation of the three phase quantities. However, PR controller is very sensitive to the grid frequency fluctuations, as it introduces infinite gain at grid frequency. If the frequency is outside the band, the system may go to unstable conditions [7] unless the band is wide enough, which in turn causes increased steady state error.

With linear PI regulators, the ac quantities are transformed into dc quantities using synchronously rotating reference frame transformations [1,2,8–12]. This makes it possible to derive a dc control loop to track the ac quantities with zero steady state error. The information about the phase, the form and magnitude of the grid voltage is necessary for the *abc* → *dq* transformation. This transformation

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introduces mutual coupling terms linking the d and q axis control loops due to the presence of the impedance between inverter and grid [1,2,7]. Consequently, a step change in the active power reference causes change in the reactive power delivered, in spite of the reactive power reference being kept constant. Similar change is felt with step change in reactive power reference as well. Thus independent control of active and reactive powers is not possible. Both feed forward and feedback based controllers have been suggested in literature to cancel the mutual coupling effect [13,15–18,20–23]. They use a constant value of impedance in the decoupling terms. However, in practice, the impedance will vary from system to system. It also varies depending on the operating conditions of the system. For e.g. in a micro grid, several renewable energy sources and conventional energy sources operate together. The switching in and switching out of any distributed generator will cause variation in the impedance seen by the grid connected inverters [19]. So, it becomes necessary to measure the grid impedance in an actual application to make the decoupling independent of the system and the operating conditions. Measurement of grid impedance magnitude has been done in [24–28], by burst of non characteristic frequency current injection and discrete Fourier transform (DFT) based calculations.

This paper proposes continuous injection of a non characteristic frequency component for online measurement of grid impedance and periodic update of these impedance values into the control loop for the removal of cross coupling. The briefing of the modeling and design of a generic PI based current controller for grid connected VSI is done in Section 'Modeling of synchronous reference frame current controllers for grid connected VSI'. The concept of removal of cross coupling between the d and q axis control loops with grid impedance for a typical micro-grid is explained in Section 'Existence of cross-coupling and its effect of on active–reactive power control', and the effect of variation of source inductance on decoupling is presented in Section 'Decoupling the dependency of active and reactive powers on each other'. Section 'Configuration changes in micro grids and its effect on decoupling' explains the measurement of grid impedance. Section 'Grid impedance measurement' describes the proposed decoupled control of grid connected VSI with online grid impedance measurement and its performance evaluation. Finally Section 'The proposed decoupled control of grid connected VSI with on-line grid impedance measurement' presents the conclusions and the future scope for the proposed system.

Modeling of synchronous reference frame current controllers for grid connected VSI

There have been several methods proposed [4,6–13] for current control of grid tied inverters. Control of grid connected inverters is done with variables in synchronous reference frame (SRF), in which they appear as dc quantities. The control action is performed with simple PI controllers. Fig. 1 shows the circuit diagram of a three phase grid connected VSI. u_a, u_b and u_c are the inverter pole voltages, e_a, e_b and e_c are the grid phase voltages, L_i is the filter inductance and L_g is the grid inductance. The currents injected into the grid in each phase are i_a, i_b and i_c.

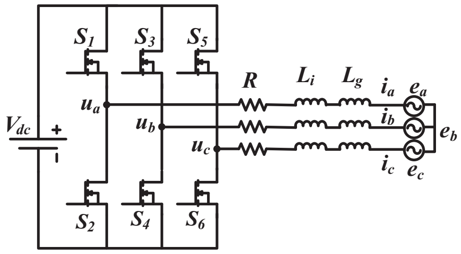

Fig. 1. Three phase grid connected VSI.

The differential equation for the system shown in Fig. 1 is

$$L\left[\frac{di}{dt}\right]_{abc} = [u]_{abc} - [e]_{abc} - R[i]_{abc} \tag{1}$$

where L is the total inductance from the inverter to the mains, i.e. $L = L_i + L_g$. If $\omega = 2\pi f$, where f is the grid frequency, then Eq. (1) is written in synchronously rotating reference frame [13,14] as

$$u_{dq} = L\frac{di_{dq}}{dt} + (R + j\omega L)i_{dq} + e_{dq} \tag{2}$$

Resolving (2) to its real and imaginary parts results

$$u_d = L\frac{di_d}{dt} + Ri_d - \omega L i_q + e_d \tag{3}$$

$$u_q = L\frac{di_q}{dt} + Ri_q + \omega L i_d + e_q \tag{4}$$

Based on Eqs. (3) and (4) the general block diagram for current control of grid connected VSI in synchronous reference frame is obtained as shown in Fig. 2, where i_d^*, i_q^* are d and q axes reference currents respectively. A PLL gives the necessary phase information of the grid voltage to the abc–dq transformation blocks.

The voltage drop due to the line impedance is compensated using a PI controller in each loop. The control equations for u_d and u_q are given as

$$u_d = e_d - \omega L i_q + \left(k_p + \frac{k_i}{s}\right)(I_d^* - I_d) \tag{5}$$

$$u_q = e_q + \omega L i_d + \left(k_p + \frac{k_i}{s}\right)_p (I_q^* - I_q) \tag{6}$$

Also the active power P and reactive power Q in the SRF using dq quantities are given as

$$P = \frac{3}{2}(u_d i_d + u_q i_q) \tag{7}$$

$$Q = \frac{3}{2}(u_d i_q - u_q i_d) \tag{8}$$

But, Eqs. (7) and (8) exhibits a mutual coupling between the d and q axis quantities thus, makes it impractical to control P and Q independently. It is obvious that when the d axis voltage and currents are varied to vary the active power delivered, there is no grip to maintain the reactive power delivered unvarying. This dependency can be eliminated by setting $u_q = 0$. It can be achieved by aligning the space-vector on the d-axis making the projection of it on the q-axis zero. Now the active and reactive powers expressions are modified as

$$P = 3/2 u_d i_d \tag{9}$$

$$Q = 3/2 u_d i_q \tag{10}$$

Eqs. (9) and (10) revels that the active power is carried by d-axis current alone and the reactive power is carried by the q-axis current alone. This makes the active and reactive powers being controlled by controlling the respective currents independently.

Existence of cross-coupling and its effect of on active–reactive power control

Even though independent active–reactive power control is successful, still there exists an interaction between the two axis variables when looking back Eqs. (3) and (4) thus the dependency persist between the control loops. With reference to Eqs. (3) and