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A Methodology for Power Quality improvement of Grid Connected Inverters and Standalone Distributed Generation System

D. Manohar* , M. Abdul Rahiman**
P RamaMohan Reddy***
1*,2**&3*** Assistant Professor,
Department of EEE,
GATES Institute of Technology,
Gooty, Andhra Pradesh

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Abstract

This paper discuss a methodology for inverters to concurrently improve the power quality of the inverter confined load voltage and the current exchanged with the grid. The proposed control strategy can be used to single-phase grid-connected inverters to inject balanced clean currents to the grid even when the confined loads (if any) are unbalanced and/or nonlinear. The methodology comprises of an inner voltage loop and an outer current loop, with both controllers designed using the H repetitive control scheme which leads to a very low total harmonic distortion in both the inverter local load voltage and the current exchanged with the grid at the same time. Simulations under different scenarios, with comparisons made to the current repetitive controller replaced with a current proportionalresonant controller, are presented to demonstrate the excellent performance of the proposed strategy.

1 Introduction

Decentralization of the power transmission distribution system is vital to the success and reliability of this system. Currently the system is reliant upon relatively few generation stations. This makes current systems susceptible to impact from failures not within said area. Micro grids would have local power generation, and allow smaller grid areas to be separated from the rest of the grid if a failure were to occur. Furthermore, micro grid systems could help power each other if needed. Generation within a micro grid could be a downsized industrial generator or several smaller systems such as photo-voltaic systems, or wind generation. When combined with Smart Grid technology, electricity could be better controlled and distributed, and more efficient. Traditionally, the inverters used in micro-grids behave as current sources when they are connected to the grid and as voltage sources when they work autonomously.

This involves the change of the controller when the operational mode is changed from stand-alone to grid-connected or vice versa. It is advantageous to operate inverters as voltage sources because there is no need to change the controller when the operation mode is changed. A parallel control structure consisting of an output voltage controller and a grid current controller was proposed in to achieve seamless transfer via changing the references to the controller without changing the controller. Another important aspect for grid connected inverters or micro-grids are the active and reactive power control.

Moreover, unbalanced utility grid voltages and utility voltage sags, which are two most common utility voltage quality problems, can affect micro-grid power quality. The inverter controller should be able to cope with unbalanced utility grid voltages and voltage sags, which are within the range given by the waveform quality requirements of the local loads and/or micro-grids.

In this paper, a cascaded control structure consisting of an inner-loop voltage controller and an outer-loop current controller is proposed to achieve this, after spotting that the inverter LCL filter can be split into two separate parts (which is, of course, obvious but nobody has taken advantage of it). The LC part can be used to design the voltage controller, and the grid interface inductor can be used to design the current controller. The voltage controller is responsible for the power quality of the inverter local load voltage and power distribution and synchronization with the grid, and the current controller is responsible for the power quality of the grid current, the power exchanged with the grid, and the over current protection. With the help of the H repetitive control, the proposed strategy is able to maintain low THD in both the inverter local load voltage and the grid current at the same time. When the inverter is connected to the grid, both controllers are active; when the inverter is not connected to the grid, the current controller is working under zero current reference. Hence, no extra effort is needed when changing the operation mode of the inverter, which considerably facilitates the seamless mode transfer for grid-connected inverters.

In other words, harmonic currents and unbalanced local load currents are all contained locally and do not affect the grid. It is worth stressing that the cascaded currentvoltage control structure improves the quality of both the inverter local load voltage and the grid current at the same time and achieves seamless transfer of the operation mode. The outer-loop current controller provides a reference for the inner loop voltage controller, which is the key to allow the simultaneous improvement of the THD in the grid current and the inverter local load voltage and to achieve the seamless transfer of operation mode.

The H repetitive control strategy is adopted in the paper to design the controllers, but this is not a must; other approaches can be used as well. Repetitive control, which is regarded as an internal model is infinite dimensional and can be obtained by connecting a delay line into a feedback loop.

Such a closed-loop system can deal with a very large number of harmonics simultaneously, as it has high gains at the fundamental and all harmonic frequencies of interest. It has been successfully applied to constant-voltage constant-frequency pulse-width modulated (PWM) inverters, grid-connected inverters, and active filters to obtain very low THD. This paper has demonstrated that excellent performance can be achieved with an inner-loop repetitive controller. The rest of this paper is organized as follows. The proposed control scheme is presented in Section II, followed by the voltage controller designed in Section III and the current controller designed in Section IV. An example design is described in Section V, and extensive experimental results are presented and discussed in Section VI. Finally, conclusions are made in Section VII.

2 PROPOSED CONTROL SCHEME

Fig. 1 shows the structure of a single-phase inverter connected to the grid. It consists of an inverter bridge, an LC filter, and a grid interface inductor connected with a circuit breaker. It is worth noting that the local loads are connected in parallel with the filter capacitor. The currenti1 flowing through the filter inductor is called the filter inductor current in this paper, and the current flowing through the grid interface inductor is called the grid current in this paper. The control objective is to maintain low THD for the inverter local load voltage and, simultaneously, for the grid current i2. As a matter of fact, the system can be regarded as two parts, as shown in Figs. 2 and 3, cascaded together.

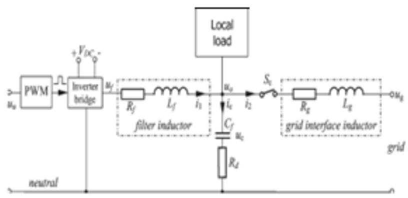

Fig. 1. Sketch of a grid-connected single-phase inverter with local loads.

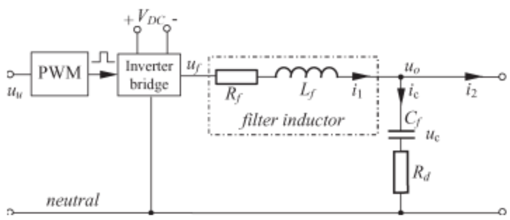

Fig. 2. Control plant Pu for the inner voltage controller

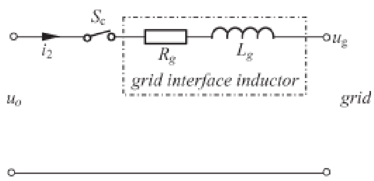

Fig. 3. Control plant Pi for the outer current controller.

Hence, a cascaded controller can be adopted and designed. The proposed controller, as shown in Fig. 4, consists of two loops: an inner voltage loop to regulate the inverter local load voltage and an outer current loop to regulate the grid current i2. According to the basic principles of control theory about cascaded control, if the dynamics of the outer loop is designed to be slower than that of the inner loop, then the two loops can be designed separately. As a result, the outer-loop controller can be designed under the assumption that the inner loop is already in the steady state, i.e., . It is also worth stressing that the current controller is in the outer loop and the voltage controller is in the inner loop. This is contrary to what is normally done. In this paper, both controllers are designed using the H repetitive control strategy because of its excellent performance in reducing THD.

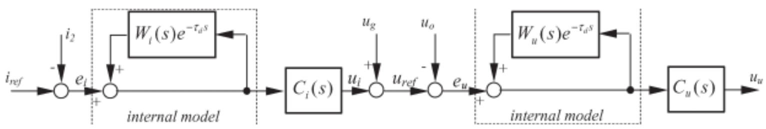

Fig. 4. Proposed cascaded currentvoltage controller for inverters, where both controllers adopt the H repetitive strategy.

The main function of the outer-loop current controller is to exchange a clean current with the grid even in the presence of grid voltage distortion and/or nonlinear (and/or unbalanced for three-phase applications) local loads connected to the inverter. The current controller can be used for over current protection, but normally, it is included in the drive circuits of the inverter bridge. A phase-locked loop (PLL) can be used to provide the phase information of the grid voltage, which is needed to generate the current reference i_{ref} (see Section V for an example). As the control structure described here uses just one inverter connected to the system and the inverter is assumed to be powered by a constant dc voltage source, no controller is needed to regulate the dc-link voltage (otherwise, a controller can be introduced to regulate the dc-link voltage). Another important feature is that the grid voltage ug is fed forward and added to the output of the current controller. This is used as a synchronization mechanism, and it does not affect the design of the controller, as will be seen later.

3 DESIGN OF THE VOLTAGE CONTROLLER

The design of the voltage controller will be outlined hereinafter, following the detailed procedures proposed in [16]. A prominent feature different from what is known is that the control plant of the voltage controller is no longer the whole LCL filter but just the LC filter, as shown in Fig. 2.

A. State-Space Model of the Plant

The corresponding control plant shown in Fig. 2 for the voltage controller consists of the inverter bridge and the LC filter (L_f and C_f). The filter inductor is modeled with a series winding resistance. The PWM block, together with the inverters is modeled by using an average voltage approach with the limits of the available dc-link voltage [15] so that the average value of u_f over a sampling period is equal tou_u . As a result, the PWM block and the inverter bridge can be ignored when designing the controller.

The filter inductor currenti1 and the capacitor voltage uc are chosen as state variables$x_u = \begin{bmatrix} i_1 & u_c \end{bmatrix}^T$. The external input $w_u = \begin{bmatrix} i_2 & u_{ref} \end{bmatrix}^T$ consists of the grid current i_2 and the reference Voltage u_{ref} . The control input is u_u. The output signal from the plant $p_u$is the tracking error $\theta_u = u_{ref} - u_0$ where $u_0 = u_c + R_d(i_1 - i_2)$is the inverter local load voltage. The plant Pu can be described by the state equation,

$$\dot{x}_u = A_u x_u + B_{u1} w_u + B_{u2} u_u \tag{1}$$

and the output equation

$$y_u = e_u = C_{u1} x_u + D_{u1} w_u + D_{u2} u_u \tag{2}$$

With

$$A_u = \begin{bmatrix} -\dfrac{R_f + R_d}{L_f} & -\dfrac{1}{L_f} \\ \dfrac{1}{C_f} & 0 \end{bmatrix}$$

$$B_{u1} = \begin{bmatrix} -\dfrac{R_d}{L_f} & 0 \\ -\dfrac{1}{C_f} & 0 \end{bmatrix}; B_{u2} = \begin{bmatrix} -\dfrac{1}{L_f} \\ 0 \end{bmatrix}$$

$$C_{u1} = \begin{bmatrix} -R_{d1} & -1 \end{bmatrix}$$

$$D_{u1} = \begin{bmatrix} R_d & 1 \end{bmatrix}; D_{u2} = 0$$

The corresponding plant transfer function is then

$$p_u = \begin{bmatrix} A_u & B_{u1} & B_{u2} \\ C_{u1} & D_{u1} & D_{u2} \end{bmatrix} \tag{3}$$

In order to guarantee the stability of the inner voltage loop, an H control problem, as shown in Fig. 5, is formulated to minimize the H∞ norm of the transfer function $\bar{T}_{z_u,w_u} = F_1(p_u, c_u)$from $\tilde{w}_u = \begin{bmatrix} v_u & w_u \end{bmatrix}^T$, after opening the local positive feedback loop of the internal model and introducing weighting parameters ξ and μ_u . The closed loop system can be represented as

$$\begin{bmatrix} Z_u \\ y_u \end{bmatrix} = p_u \begin{bmatrix} W_u \\ u_u \end{bmatrix}$$

$$u_u = C_u y_u \tag{4}$$

Where P_u is the generalized plant and C_u is the voltage controller to be designed. The generalized plant P_u consists of the original plant P_u, together with the low-pass filter.

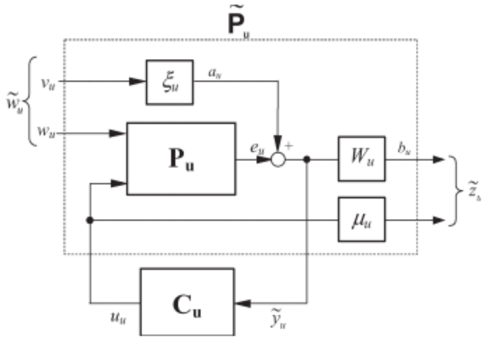

Fig. 5. Formulation of the H∞ control problem for the voltage controller.

$$W_u = p_u \left[\begin{array}{cc} A_{wu} & B_{wu} \\ C_{wu} & D_{wu} \end{array} \right]$$

,

which is the internal model for repetitive control. The details of how to select Wu can be found in [16] and [18]. A weighting parameter ξ_u is added to adjust the relative importance of vu with respect to w_u, and another weighting parameter μ_u is added to adjust the relative importance of uu with respect to b_u. The parameters u and u also play a role in guaranteeing the stability of the system; see more details in [16] and [18]. It can be found out that the generalized plant P_u is realized as

$$\tilde{P}_u = \left[\begin{array}{cc|cc|c} A_{wu} & 0 & 0 & B_{u1} & B_{u2} \\ B_{wu}C_{u1} & A_{wu} & B_{wu}\xi_u & B_{wu}D_{u1} & B_{wu}D_{u2} \\ \hline D_{wu}C_{u1} & C_{wu} & D_{wu}\xi_u & D_{wu}D_{u1} & D_{wu}D_{u2} \\ 0 & 0 & 0 & 0 & \mu_u \\ \hline C_{wu} & 0 & \xi_u & D_{u1} & D_{u2} \end{array} \right] \quad (5)$$

The controller Cu can then be found according to the generalized plan P_u using the H∞ control theory, e.g., by using the function hin f syn provided in MATLAB.

4 DESIGN OF THE CURRENT CONTROLLER

As seen before, when designing the outer-loop current controller, it can be assumed that the inner voltage loop tracks the reference voltage perfectly, i.e., $u_o = u_{ref}$. Hence, the control plant for the current loop is simply the grid inductor, as shown in Fig. 3. The formulation of the H∞ control problem to design the H∞ compensator C_i is similar to that in the case of the voltage control loop shown in Fig. 5 but with a different plant P_i and the subscript u replaced with i.

A. State-Space Model of the Plant Pi

Since it can be assumed that $u_o = u_{ref}$, there is $u_0 = u_g + u_i$ or $u_i = u_0 - u_g$ from Figs. 3 and 4, i.e., u_i is actually the voltage dropped on the grid inductor. The feed forwarded grid voltage u_g provides a base local load voltage for the inverter. The same voltage u_g appears on both sides of the grid interface inductorL_g , and it does not affect the controller design. Hence, the feed forwarded voltage path can be ignored during the design process. This is a very important feature. The only contribution that needs to be considered during the design process is the output u_i , of the repetitive current controller.

Table.1 PARAMETERS OF THE INVERTER

Parameter	Value	Parameter	Value
L_f	$150\mu H$	R_f	0.045Ω
L_g	$450\mu H$	R_g	0.135Ω
C_f	$22\mu F$	R_d	1Ω

The grid current i_2 flowing through the grid interface inductor L_g is chosen as the state variable $x_i = i_2$. The external input is $w_i = i_{ref}$, and the control input is u_i . The output signal from the plant Pi is the tracking error ,$e_i = i_{ref} - i_2$ i.e., the difference between the current reference and the grid current. The plant Pi can then be described by the state equation

$\dot{x}_i = A_i x_i + B_{i1} w_i + B_{i2} u_i$

and the output equation

$y_i = e_i = C_{i1} x_i + D_{i1} w_i + D_{i2} u_i$

Where

$A_i = -\frac{R_g}{L_g}; B_{i1} = 0; B_{i2} = \frac{1}{L_g}$

$C_{i1} = -1; D_{i1} = 1; D_{i2} = 0$

The corresponding transfer function of Pi is

$$P_i = \left[\begin{array}{c|cc} A_i & B_{i1} & B_{i2} \\ \hline C_{i1} & D_{i1} & D_{i2} \end{array}\right] \tag{6}$$

B. Formulation of the Standard H Problem

Similarly, a standard H∞ problem can be formulated as in the case of the voltage controller shown in Fig. 5, replacing the subscript u with i. The resulting generalized plant can be obtained with weighting parameters ξ_i and $\mu_i$and low-pass filter ,$\begin{bmatrix} A_{wi} & B_{wi} \\ C_{wi} & D_{wi} \end{bmatrix}$ which can be selected similarly as the corresponding ones for the voltage controller. The controller Ci can then be found according to the generalized plant Pi using the H control theory, e.g., by using the function hin f syn provided in MATLAB.

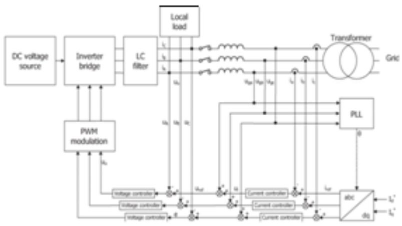

Fig. 6. Sketch of a grid-connected three-phase inverter using the proposed strategy.

5 SIMULATION RESULTS

The above-designed controller was implemented to evaluate its performance in both stand-alone and grid-connected modes with different loads. The seamless transfer of the operation modes was also carried out. The H repetitive current controller was replaced with a proportionalresonant (PR) current controller for comparison in the grid-connected mode. In the stand-alone mode, since the grid current reference was set to zero and the circuit breaker was turned off (which means that the current controller was not functioning).

A. In the Stand-Alone Mode

The voltage reference was set to the grid voltage (the inverter is synchronized and ready to be connected to the utility grid).The evaluation of the proposed controller was made for a resistive load (RA=RB=RC=12), a nonlinear load (a three-phase uncontrolled rectifier loaded with an LC filter with L= 150μH and C= 1000μF and a resistor R=20), and an unbalanced load (RA=RC=12Ω and RB=∞). The local load voltage uA, voltage reference uref, and filter inductor current Ia are shown in Fig. 7(a). Fig. 7(b) shows the spectra of the inverter local load voltage and the local load current. The recorded local voltage THD was 1.27%, while the grid voltage THD was 1.8%. Since the utility grid voltage was used as the reference, it is worth mentioning that the quality of the inverter local load voltage was better than that of the grid voltage, even without using an active filter.

B. In the Grid-Connected Mode

The current reference of the grid currenti_d^* was set at 2 A (corresponding to 1.41 A rms), after connecting the inverter to the grid. The reactive power was set at 0 var (i_q^* =0).The resistive, nonlinear, and unbalanced loads used in the previous section were used again. Moreover, the case without a local load was carried out as well. Finally, the transient responses of the system were evaluated.

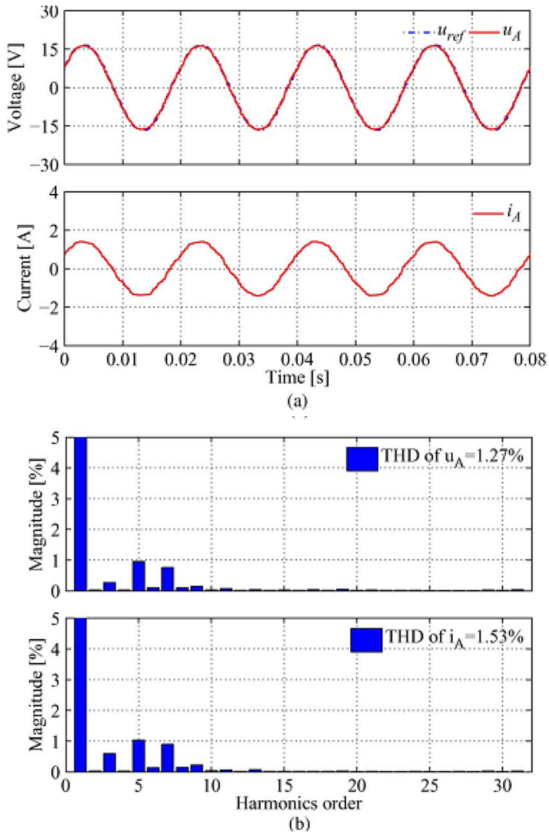

Fig. 7. Stand-alone mode with a resistive load. (a) (Upper)uA and its reference uref and (lower) current iA. (b) (Upper) Voltage THD and (lower) current THD

6 CONCLUSION

In this paper the controllers are designed using the H repetitive control but can be designed using other approaches as well. The proposed methodology also achieves seamless transfer between the stand-alone and the grid-connected modes. It can be used for single-phase grid connected inverter systems. The cascaded currentvoltage control strategy has been proposed for inverters in micro-grids it consists of an inner voltage loop and an outer current loop and offers excellent performance the proposed strategy significantly improves the THD of the inverter local load voltage and the grid current at the same time. As a result, the nonlinear harmonic currents and unbalanced local load currents are all contained locally and do not affect the grid.

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1. D MANOHAR He had received B.Tech. degree in Electrical & Electronics Engineering from JNTU Hyderabad in 2008, M.Tech in ENERGY SYSTEMS FROM NITT TRICHY In 2011. At present he is working as Assistant Professor In Department of Electrical and Electronics Engineering, GATES Institute of Technology, Gooty. He has 7 years teaching experience manohar@intell.com, +919493268963.

2. M Abdul Rahiman He had received B.Tech. degree in Electrical & Electronics Engineering from JNTU-K in 2012, M.Tech in POWER SYSTEM FROM JNTU-K In 2016. At

present he is working as Assistant Professor IN Department of Electrical and Electronics Engineering GATES Institute of Technology, Gooty. He has 3 years teaching experience. abdul0259@gmail.com , +919666941472.

3. P RamaMohan Reddy He had received B.Tech. degree in Electrical & Electronics Engineering from JNTU Hyderabad in 2008, M.Tech in ELECTRICAL POWER SYSTEM FROM JNTA In 2013. At present he is working as Assistant Professor IN Department of Electrical and Electronics Engineering GATES Institute of Technology, Gooty. He has 5 years teaching experience. ramamohan703@gmail.com ,