POWER QUALITY IMPROVEMENT IN GRID CONNECTED INVERTER WITH LOCAL LOAD BY USING FUZZY LOGIC CONTROLLER

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ABSTRACT—In this paper, fuzzy logic control strategy is proposed for inverters to simultaneously improve the power quality of the inverter local load voltage and the current exchanged with the grid. It also enables seamless transfer of the operation mode from stand-alone to grid-connected or vice versa. This 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 while comparing with the current–voltage controller. The proposed control strategy can be used to single-phase inverters and three-phase four-wire inverters. It enables grid-connected inverters to inject balanced clean currents to the grid even when the local loads (if any) are unbalanced and/or nonlinear. Simulation results of fuzzy logic controller in all cases are presented.

I. INTRODUCTION

MICROGRIDS are emerging as a consequence of rapidly growing distributed power generation systems. Improving the control capabilities and operational features of micro grids brings environmental and economic benefits. The introduction of micro grids leads to improved power quality, reduces transmission congestion, decreases emission and energy losses, and effectively facilitates the utilization of renewable energy. Microgrids are normally operated in the grid-connected mode; however, it is also expected to provide sufficient generation capacity, controls, and operational strategies to supply at least a part of the load after being disconnected from the distribution system and to remain operational as a standalone (islanded) system [1]–[6]. 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 [7].

This involves the change of the controller when the operational mode is changed from stand-alone to grid-connected or vice versa [8]. 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 [8] to achieve seamless transfer via changing the references to the controller without changing the controller. Another important aspect for grid-connected inverters or microgrids is the active and reactive power control; see, e.g., [9] and [10] for more details. As nonlinear and/or unbalanced loads can represent a high proportion of the total load in small-scale systems, the problem with power quality is a particular concern in micro grids [11]. Moreover, unbalanced utility grid voltages and utility voltage sags, which are two most common utility voltage quality problems, can affect micro grid power quality [12], [13]. 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. When critical loads are connected to an inverter, severe unbalanced voltages are not generally acceptable, and the inverter should be disconnected from the utility grid. Only when the voltage imbalance is not so serious or the local load is not very sensitive to it can the inverter remain connected. Since the controllers designed in the dq or αβ frames under unbalanced situations become noticeably complex [14], it is advantageous to design the controller in the natural reference frame. Another power quality problem in microgrids is the total harmonic distortion (THD) of the inverter local load voltage and the current exchanged with...
the grid (referred to as the grid current in this paper), which needs to be maintained low according to industrial regulations.

It has been known that it is not a problem to obtain low THD either for the inverter local load voltage [15], [16] or for the grid current [17], [18]. However, no strategy has been reported in the literature to obtain low THD for both the inverter local load voltage and the grid current simultaneously. This may even have been believed impossible because there may be nonlinear local loads. 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 [16]–[18], 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. For three-phase inverters, the same individual controller can be used for each phase in the natural frame when the system is implemented with a neutral point controller, e.g., the one proposed in [19]. As a result, the inverter can cope with unbalanced local loads for three-phase applications. In other words, harmonic currents and unbalanced local load currents are all contained locally and do not affect the grid. Experimental results are presented to demonstrate the excellent performance of the proposed control scheme.

It is worth stressing that the cascaded current–voltage 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.

This is different from the conventional voltage–current control scheme [12], where the (inner) current loop is used to regulate the filter inductor current of the inverter (not the grid current), so it is impossible to achieve simultaneous improvement of the THD in the grid current and the inverter local load voltage. An inner current loop can still be added to the proposed structure inside the voltage loop without any difficulty to perform the conventional function, if needed. The H∞ repetitive control strategy [16]–[18] is adopted in the paper to design the controllers, but this is not a must; other approaches can be used as well. Repetitive control [20], which is regarded as a simple learning control method, provides an alternative to perfectly track periodic signals and/or to reject periodic disturbances in dynamic systems, using the internal model principle [21].

The 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 [22]–[26], grid-connected inverters [15], [27], and active filters [28], [29] to obtain very low THD. The multi loop control strategies analyzed in [30] indicated that it was impossible to stabilize an inverter with a proportional feedback of the capacitor voltage and that the performance with an inner loop proportional–derivative voltage controller was not good either.

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.

![Fig. 1. Sketch of a grid-connected single-phase inverter with local loads.](image-url)
excellent performance in reducing THD.

The main functions of the voltage controller are the following: to deal with power quality issues of the inverter, local load voltage even under unbalanced and/or nonlinear local loads, to generate and dispatch power to the local load, and to synchronize the inverter with the grid. When the inverter is synchronized and connected with the grid, the voltage and the frequency are determined by the grid. 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 \(i_{\text{ref}}\) (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 \(u_g\) is fedforward 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.

II. 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 current \(i_1\) flowing through the filter inductor is called the filter inductor current in this paper, and the current \(i_2\) 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 \(u_o\) and, simultaneously, for the grid current \(i_2\). As a matter of fact, the system can be regarded as two parts, as shown in Figs. 2 and 3, cascaded together. 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 \(u_o\) and an outer current loop to regulate the grid current \(i_2\). 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., \(u_o = u_{o\text{ref}}\). 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

III. 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 \(P_u\)

The corresponding control plant shown in Fig. 2 for the voltage controller consists of the inverter bridge and the LC filter \((L_f, C_f)\). The filter inductor is modeled with a series winding resistance. The PWM block, together with the inverter, is modeled by using an average voltage approach with the limits of the available dc-link voltage [15] so that

- the average value of \(u_t\) over a sampling period is equal to \(u_{\text{ref}}\).

As a result, the PWM block and the inverter bridge can be ignored when designing the controller. The filter inductor current \(i_1\) and the capacitor voltage \(u_c\) are chosen as state variables \(x = [i_1 u_c]^T\). The external input \(w_e = [i_2 u_{\text{ref}}]\) T consists of the grid current \(i_2\) and the reference voltage \(u_{\text{ref}}\). The control input is \(u_i\). The output loop tracks the reference voltage perfectly, i.e., \(u_i = u_{\text{ref}}\).
signal from the plant $P_g$ is the tracking error $e_u = u_{ref} - u_o$, where $u_o = u_i + R_d (i_1 - i_2)$ is the inverter local load voltage. The plant $P_g$ can be described by the state equation

$$\dot{x}_u = A_u x_u + B_{u1} w_u + B_{u2} u_u$$  \hspace{1cm} (1)$$

and the output equation

$$y_u = e_u = C_{u1} x_u + D_{u1} w_u + D_{u2} u_u$$  \hspace{1cm} (2)$$

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

$$B_{u1} = \begin{bmatrix} R_f \\ \frac{1}{L_f} \\ \frac{1}{C_f} \end{bmatrix}$$

$$C_{u1} = [-R_d \ \ 1]$$

$$D_{u1} = [R_d \ \ 1]$$

The corresponding plant transfer function is then

$$R_u = \begin{bmatrix} A_u & B_{u1} \\ C_{u1} & D_{u1} \\ 0 & 0 \end{bmatrix}$$  \hspace{1cm} (3)$$

B. Formulation of the Standard $H^\infty$ Problem

In order to guarantee the stability of the inner voltage loop, an $H^\infty$ control problem, as shown in Fig. 5, is formulated to minimize the $H^\infty$ norm of the transfer function $T = z_u \tilde{w}_u = F_1(P_u, C_u)$. From $\tilde{w}_u = [v_u \ w_u]^T$ to $z_u = [z_{u1} \ z_{u2}]^T$ after opening the local positive feedback loop of the internal model and introducing weighting parameters $\zeta_u$ and $\mu_u$. The closed loop system can be represented as

$$\begin{bmatrix} \tilde{z}_u \\ \tilde{y}_u \end{bmatrix} = \tilde{P}_u \begin{bmatrix} \tilde{w}_u \\ u_u \end{bmatrix}$$  \hspace{1cm} (4)$$

Where $\tilde{P}_u$ is the generalized plant and $C_u$ is the voltage controller to be designed. The generalized plant $\tilde{P}_u$ consists of the original plant $P_u$, together with the low-pass filter which is the internal model for repetitive control. The details of how to select $\tilde{w}_u$ can be found in [16] and [18]. A weighting parameter $\zeta_u$ is added to adjust the relative importance of $v_u$ with respect to $w_u$, and another weighting parameter $\mu_u$ is added to adjust the relative importance of $u_u$ with respect to $b_u$. The parameters $\zeta_u$ and $\mu_u$ also play a role in guaranteeing the stability of the system; see more details in [16] and [18].

IV. DESIGN OF THE CURRENT CONTROLLER

As explained before, when designing the outer-loop current controller, it can be assumed that the inner voltage 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 of the repetitive current controller. The grid current $i_2$ flowing through the grid inductor $L_g$ is chosen as the state variable $x_3 = i_2$. The external input is $w_u = i_{ref}$, and the control input $u_i$ is the voltage error $e_i = i_{ref} - i_2$, i.e., the difference between the current reference and the grid current. The plant $P_i$ can then be described by the state equation

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

and the output equation

$$y_i = e_i = C_i x_i + D_i w_i + D_{i2} u_i$$

VI. FUZZY LOGIC CONTROLLER
Where
\[ A_1 = -\frac{R_g}{L_g}, \quad B_{ll} = 0, \quad B_{l2} = \frac{1}{L_g}, \]
\[ C_{ll} = -1, \quad D_{l1} = 1, \quad D_{l2} = 0. \]

V. DESIGN EXAMPLE

As an example, the controllers will be designed in this section for an experimental setup, which consists of an inverter board, a three-phase LC filter, a three-phase grid interface inductor, a board consisting of voltage and current sensors, a step-up wye-wye transformer (12 V/230 V/50 Hz), a dSPACE DS1104 R&D controller board with Control Desk software, and MATLAB Simulink/Simpower software package. The inverter board consists of two independent three-phase inverters and has the capability to generate PWM voltages from constant 42-V dc voltage source. One inverter was used to generate a stable neutral line for the three-phase inverter.

The generated three-phase voltage was connected to the grid via a controlled circuit breaker and a step-up transformer. The PWM switching frequency was 12 kHz. A Yokogawa power analyzer WT1600 was used to measure the THD.

The parameters of the inverter are given in Table I. Three sets of identical controllers were used for the three phases because there was a stable neutral line available. The control structure for the three-phase system is shown in Fig. 6.

A traditional dq PLL was used to provide the phase information needed to generate the three-phase grid current references via adq/abc transformation from the current references \( I_d \) and \( I_{q} \).

The internal model was implemented according to [16], with the capability to adapt to the frequency change in the grid.

It is worth noting that it is quite a challenge to work with low-voltage inverters to improve the voltage THD, because, in general, the higher the voltage, the bigger the value of the fundamental component.

Moreover, the impact of noises and disturbances is more severe for low-voltage systems than for high-voltage ones. Hence, it should be easy to apply the strategy proposed in this paper to inverters at higher voltage and higher power ratings.

Unlike Boolean logic, fuzzy logic allows states (membership values) between 0 or 1. Its major features are the use of linguistic variables rather than numerical variables. Linguistic variables, defined as variables whose values are sentences in a natural language (such as small and big), may be represented by fuzzy sets. The general structure of an FLC is represented in Fig. 5 and comprises four principal components:

- a fuzzification interface which converts input data into suitable linguistic values;
- a knowledge base which consists of linguistic definitions and control rule set;
- a decision making logic which, simulating a human decision process, infers fuzzy control action from the knowledge of the control rules and linguistic definitions; and
- a defuzzification interface which yields a non-fuzzy control action from an inferred fuzzy control action.

In this paper, two FL controller block are used for error signal-d and error signal-q as shown in Fig. 5. The process also same as before except the controller now is Fuzzy Logic. For both blocks the FL controller consists of five linguistic variables from input which is: Negative Big (NB), Negative Small (NS), Zero Equivalent (ZE) and Positive Small (PS), Positive High (PH). Each parameter from linguistic variables for error signal is shown in Fig. 6.

For delta error, therefive linguistic variables from input which is: Negative High (NH), Negative Medium (NM), Negative Small (NS), Zero Equivalent (ZE) and Positive Small (PS), Positive Medium (PM), Positive Big (PB) Both variables can be depicted as in Fig. 7.
VII. SIMULATION RESULTS

The above-designed controller was implemented to evaluate its performance in both stand-alone and grid-connected modes with different loads.

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 ($RA=RB=RC=12\Omega$), a nonlinear load (a three-
phase uncontrolled rectifier loaded with an LC filter with $L = 150\mu H$ and $C = 1000\mu F$ and a resistor $R = 20\Omega$, and an unbalanced load ($R_A = R_C = 12\Omega$ and $R_B = \infty$).

1) With the Resistive Load: The local load voltage $u_A$, voltage reference $u_{\text{ref}}$, and filter inductor current $i_A$ are shown in Fig. 9(a). Fig. 9(b) shows the spectra of the inverter local load voltage and the local load current. The recorded local voltage THD was 0.63%, while the grid voltage THD was 0.77%. 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.

2) With the Nonlinear Load: The local load voltage $u_A$, voltage reference $u_{\text{ref}}$, and filter inductor current $i_A$ are shown in Fig. 10(a). The spectra of the inverter local load voltage and the local load current are shown in Fig. 10(b). The recorded local load voltage THD was 2.27%, while the grid voltage THD was 66.40%. The experimental results demonstrate satisfactory performance of the voltage controller for nonlinear loads.

3) With the Unbalanced Load: The inverter local load voltage and the local load currents are shown in Fig. 11(a) with their spectra shown in Fig. 11(b). The recorded local load voltage THD was 0.68%, while the grid voltage THD was 0.74%. Since the proposed control structure adopts separate controllers for each phase, the unbalanced loads had no influence on the voltage controller performance, and the inverter local load voltages remained balanced.

B. In the Grid-Connected Mode

The current reference of the grid current $I^*_{d}$ 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. 9. Stand-alone mode with a resistive load. (a) (Upper) $U_a$ and its reference $u_{ref}$ and (lower) current $i_A$. (b) (Upper) Voltage THD and (lower) current THD.

1) Without a Local Load: The local load voltage $u_A$, the voltage tracking error $e_u$, the grid current $i_a$, and the current tracking error $e_i$ are shown. The spectra of the inverter local load voltage and the grid current of both controllers are shown in the left column of Fig. 12. The recorded THD of the local voltage was 0.99% for the proposed controller and 0.99% for the PR controller, while the grid voltage THDs were 1.58% and 0.96%, respectively. The THD of the grid current was 2.27% for the proposed $H_\infty$ controller and 5.09% for the PR controller. In this experiment, the proposed controller outperforms the PR-current–$H_\infty$-voltage controller. Note that the grid was cleaner when the PR-current $H_\infty$-voltage controller was tested.
2) With the Resistive Load: The experimental results of the grid-connected inverter with the balanced resistive local load connected to the system are shown in Fig. 12. When the resistive local load is connected, the grid current THD was 0.60% for the proposed controller and 5.24% for the fuzzy controller. The performance of both controllers remains almost unchanged with comparison to the previous experiment without a local load. The proposed controller again outperforms the fuzzy controller. Note that the grid was cleaner again when the PR-current-H∞ -voltage controller was tested.
Fig. 11. Stand-alone mode with an unbalanced load. (a) (Upper) Inverter local load voltage and (lower) local load currents. (b) (Upper) Voltage THD and (lower) current THD.

3) With the Nonlinear Load: The local load voltage $u_A$, the voltage tracking error $e_u$, the grid current $i_a$, and the current tracking error $e_i$ are shown in Fig. The spectra of the inverter local load voltage and the grid current are shown in the middle-right column of Fig. 12 while the grid voltage THDs were 1.10% and 0.93%, respectively. The THDs of the grid current were 1.48% and 3.84%, respectively.

![FFT analysis](image1)

**Fig 12a (resistive load)**
Fig 12a (nonlinear load)
Fig 12a (unbalanced load)

Fig 12a (without load)
Fig 12b (resistive load)
Fig 12b (nonlinear load)
4) With the Unbalanced Load: The inverter local load voltage, the filter inductor current, and the grid current are shown. The spectra of the inverter local load voltage and the grid current are shown in the right column of Fig. 11. The recorded local load voltage THD was 0.53% in the case with the fuzzy current controller and 1.20% in the case with fuzzy controller, while the grid voltage THDs were 0.49% and 0.92%, respectively. The grid current THDs were 0.49% and 2.54%, respectively. Both strategies can inject balanced clean currents to the grid although the local load is not balanced.

C. Transient Performance
1) Transient Response to the Change of the Grid Current Reference (No Local Load Connected): A step change in the grid current $I^* d$ reference from 2 A (1.41 A rms) to 3 A (2.12 A rms) was applied (while keeping $I^* q = 0$). The grid current $i_a$, its reference $i_{ref}$, and the current tracking error $e_i$ are shown in Fig. 13. The proposed controller took about 12 cycles to settle down, and the fuzzy controller took about eight cycles to settle down. This is reasonable because each repetitive controller takes about five cycles to settle down. This reflects the tradeoff between low THD and system response speed.
2) Transient Response to the Change of the Resistive Local Load: The filter inductor current and the grid current, together

VII. CONCLUSION
The fuzzy logic control strategy has been proposed for inverters in micro grids. The proposed strategy significantly improves the THD of the inverter local load voltage and the grid current at the same time. The proposed strategy also achieves seamless transfer between the stand-alone and the grid-connected modes. The strategy can be used for single-phase systems or three-phase systems. As a result, the nonlinear harmonic currents and unbalanced local load currents are all contained locally and do not affect the grid. Experimental results under various scenarios have demonstrated the excellent performance of the proposed strategy.

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