IMPROVING THE QUALITY OF POWER FOR GRID CURRENT BASED VOLTAGE CONTROLLER

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ABSTRACT

In this paper, a cascaded current–voltage 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. The control scheme includes an inner voltage loop and an outer current loop, with both controllers designed using the fuzzy logic control and H∞ repetitive control strategy. 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. 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 under different scenarios, with comparisons made to the current repetitive controller replaced with a current proportional–resonant controller, is presented to demonstrate the excellent performance of the proposed strategy.

I. INTRODUCTION

THE application of distributed power generation has been increasing rapidly in the past decades. Compared to the conventional centralized power generation, distributed generation (DG) units deliver clean and renewable power close to the customer’s end [1]. Therefore, it can alleviate the stress of many conventional transmission and distribution infrastructures. As most of the DG units are interfaced to the grid using power electronics converters, unbalanced utility grid voltages and voltage sags, which are they have the opportunity to realize enhanced power generation through a flexible digital control of the power converters. On the other hand, high penetration of power electronics based DG units also introduces a few issues, such as system resonance, protection interference, etc. In order to overcome these problems, the microgrid concept has been proposed, which is realized through the control of multiple DG units. Compared to a single DG unit, the microgrid can achieve superior power management within its distribution networks. In addition, the islanding operation of microgrid offers high reliability power supply to the critical loads. Therefore, microgrid is considered to pave the way to the future smart grid [1].

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 micro grids 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 stressing that the cascaded current–voltage control 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 micro grids 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] and fuzzy 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. 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. Simulation results are presented to demonstrate the excellent performance of the proposed control scheme.

Fig. 2. Control plant Pu for the inner voltage controller. 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 multi loop control strategies analyzed in [20] 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 for current and fuzzy logic control for voltage.

II. PROCEDURE FOR 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 i1 flowing through the filter inductor is called the filter inductor current in this paper, and the current i2 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 uo and, simultaneously, for the grid current i2.

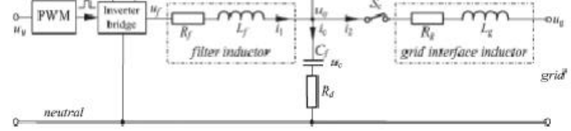


Fig. 1. Sketch of a grid-connected single-phase inverter with local loads

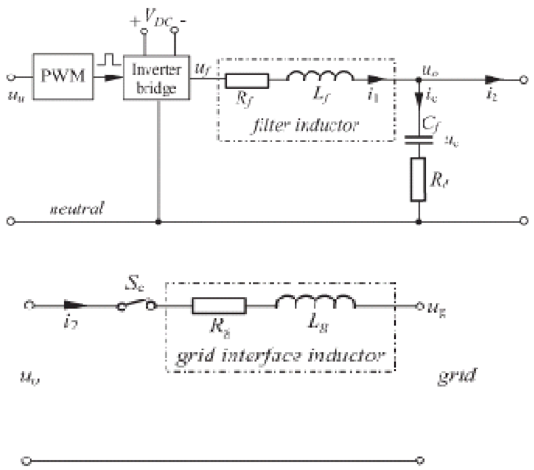


Fig. 3. Control plant Pi for the outer current controller.

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 uo 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., uo = uref . It is also worth stressing that the current controller is in the outer loop and the voltage controller is in the inner loop.

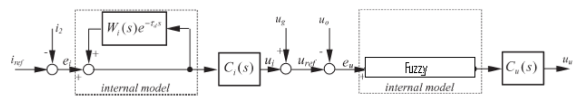


Fig. 4. Proposed cascaded current–voltage controller for inverters, where both controllers adopt the H∞ repetitive and fuzzy strategy.

This is contrary to what is normally done. In this paper, both controllers are designed using fuzzy and H∞ repetitive control strategy because of its 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 ref.

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 A rule base can be defined throughout different 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.

III. VOLTAGE CONTROLLER DESIGN

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. Lineal control theory uses mathematical models of a process and some specifications of the expected behavior in close loop, to design a controller [9]. These control strategies are highly used in systems that can be assumed as linear in certain range of their operation. Besides, it is absolutely necessary to obtain a linear model that represents the relationship between input and output in order to design the controller [17].

However, for some systems it is difficult to find out that linear model. Sometimes, it is necessary to use sophisticated tools of identification in order to find out a linear input-output transfer function [8]. Despite this, the found out model only describes the system in a narrow range accurately. In addition, when the system does not have constant parameters or has interdependence with others parameters the found out model is less accurate.

Given the above points, linear control strategies could be limited in design and performance. On the other hand, non-linear strategies such as knowledge Based Fuzzy Control (KBFC) [10], outperform linear controllers in many of the cases exposed above. KBFC is based on human knowledge which adds several types of information and can mix different control strategies that cannot easily be added through an analytical control law. On top of that, like human knowledge, KBFC does not need an accurate mathematical model in order to work out a control action [9]. What is more, KBFC uses the experience and the knowledge of an expert about the behavior of the system in order to work out the control action.

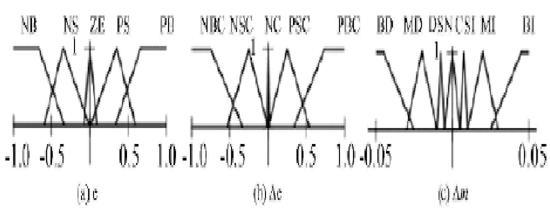
A kind of KBFC is the rule-based fuzzy control, where the human knowledge is approximated by means of linguistic fuzzy rules in the form if then. Each rule describes the control action in a particular condition of the system [9]. Control action that would be done by a human operator [9]-Therefore, under a specific condition of the system (if condition1) can be specified an action (then action1).

A. State-Space Model of the Plant Pi

Since it can be assumed that uo = uref , there is uo = ug + ui or ui = uo − ug from Figs. 3 and 4, i.e., ui is actually the voltage dropped on the grid inductor. The feed forwarded grid voltage ug provides a base local load voltage conditions of a system in which each rule defines an action for a specific condition. In the same way, both condition and action are represented by linguistic terms such as (large, medium, small) for condition and (increase a few, increase a lot) for actions, those linguistic terms belong to fuzzy sets with overlapped boundaries.

Therefore, by means of fuzzy sets it is possible to get smooth interpolation between different rules, in order to describe completely the behavior of the system with few rules [9]. That characteristic allows the fuzzy control to represent the qualitative knowledge of a human expert [9].

The controllers are based on a Mamdani fuzzy inference system, that kind of controllers are usually used into feedback systems because the rule base represents a static mapping between antecedents and consequents



Membership functions

Paramet	Value	Paramet	Value
Lf	150μH	Rf	0.045
Lg	450μH	Rg	0.135
Cf	22μF	Rd	1Ω

Δe/e	NB	NS	ZE	PS	PB
NBC	BD	MD	SD	SD	NC
NSC	MD	SD	NC	NC	SI
NC	SD	SD	NC	SI	SI
PSC	SD	NC	NC	SI	MI
PBC	NC	SI	SI	MI	BI

IV. CURRENT CONTROLLER DESIGN

As explained before, when designing the outer-loop current controller, it can be assumed that the inner voltage loop tracks the reference voltage perfectly, i.e., uo = uref .

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 Ci is similar to that in the case of the voltage control loop shown in Fig. 5 but with a different plant Pi and the subscript u replaced with I for the inverter. The same voltage ug appears on both sides of the grid interface inductor Lg, 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 ui of the repetitive current controller. The grid current i2 flowing through the grid interface inductor Lg is chosen as the state variable xi = i2. The external input is wi = iref , and the control input is ui.

The output signal from the plant Pi is the tracking error ei = iref − i2, i.e., the difference between the current reference and the grid current. The plant Pi can then be described by the state equation as follows:

TABLE I PARAMETERS OF INVERTER

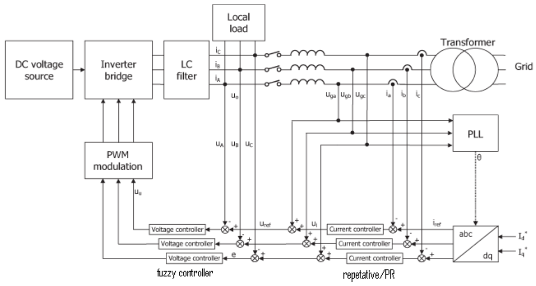


Fig. 6. Sketch of a grid-connected three-phase inverter using the proposed strategy.

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 Ω), a nonlinear load (a three-phase uncontrolled rectifier loaded with an LC filter with L = 150 μH and C = 1000 μF and a resistor R = 20 Ω), and an unbalanced load (RA = RC = 12 Ωand RB = ∞).

1) With the Resistive Load: 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 0.63%, while the grid voltage THD was 0.89%. 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.

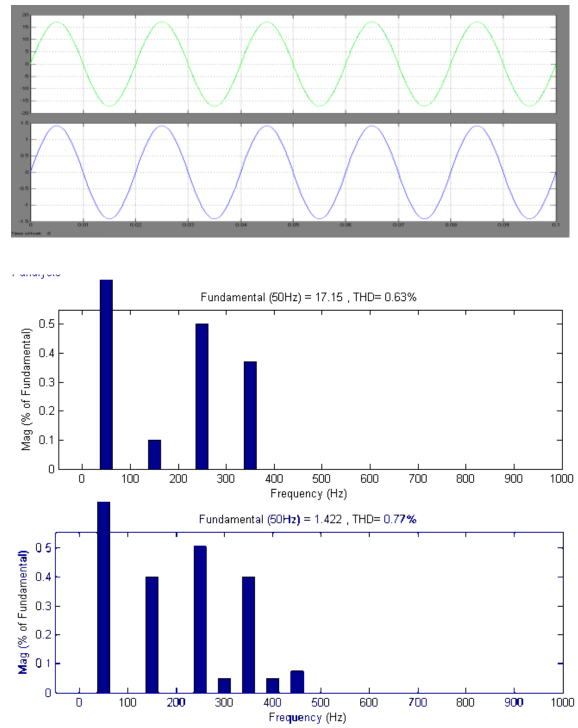


Fig. 7. Stand-alone mode with a resistive load. (a) (Upper) uA and its reference uref and (lower) current iA. (b) (Upper) Voltage THD and (lower) current THD.

2) With the Nonlinear Load: The local load voltage uA, voltage reference uref , and filter inductor current iA are shown in Fig. 8(a). The spectra of the inverter
local load voltage and the local load current are shown in Fig. 8(b). The recorded local load voltage THD was 2.27%, while the grid voltage THD was 1.78%. The simulation 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. 9(a) with their spectra shown in Fig. 9(b). The recorded local load voltage THD was 0.68%, while the grid voltage THD was 0.50%.

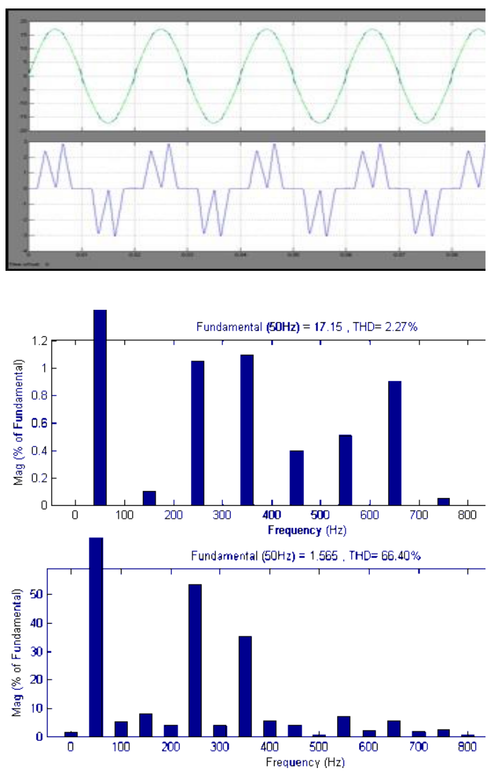
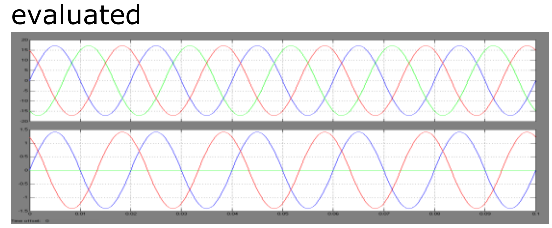


Fig. 8. Stand-alone mode with a nonlinear load.
(a) (Upper) uA and its reference uref and (lower) current iA.
(b) (Upper) Voltage THD and (lower) current THD.

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* 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



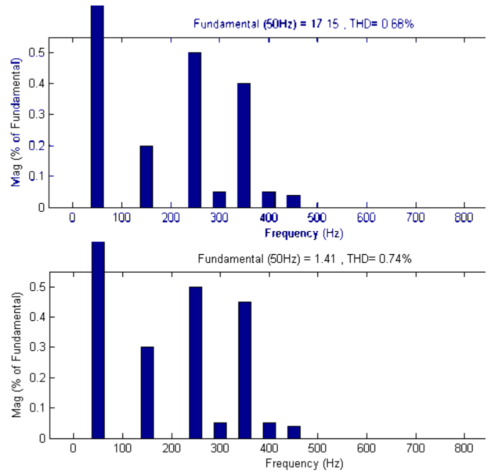


Fig. 9. Stand-alone mode with an unbalanced load. (a) (Upper) Inverter local load voltage and (lower) local load currents. (b) (Upper) Voltage THD and (lower) current THD.

1) Without a Local Load: The spectra of the inverter local load voltage and the grid current of both controllers are shown in the left column of Fig. 11. The recorded THD of the local voltage was 0.51% for the proposed controller and 0.51% for the PR controller, while the grid voltage THDs were 0.51% and 0.51%, respectively. The THD of the grid current was 1.38% for the proposed controller and 2.73% for the PR controller. In this simulation, the proposed controller outperforms the PR-current–fuzzy voltage controller. Note that the grid was cleaner when the PR-current- fuzzy based voltage controller was tested.

2) With the Resistive Load: The spectra of the inverter local load voltages and grid currents are shown in the middle-left column of Fig. 11. When the resistive local load is connected, the recorded local load voltage THD was 0.60% for the proposed H∞ controller and 0.47% for the PR controller, while the grid voltage THDs were 0.60% and 0.47%, respectively. The grid current THD was 1.19% for the proposed H∞ controller and 2.58% for the PR controller. The performance of both controllers remains almost unchanged with comparison to the previous simulation without a local load. The proposed controller again outperforms the PR current–fuzzy-voltage controller. Note that the grid was cleaner again when the PR-current-fuzzy-voltage controller was tested.

3) With the Nonlinear Load: The spectra of the inverter local load voltage and the grid current are shown in the middle- right column of Fig. 11. The recorded THD of the local voltage was 1.10% for the proposed H∞ controller and 1.18% for the PR controller, while the grid voltage THDs were 1.10% and 1.18%, respectively. The THDs of the grid current were 2.64% and 3.84%, respectively. The proposed controller again clearly outperforms the PR current–fuzzy based voltage controller.

4) With the Unbalanced Load: 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 H∞ current controller and 0.49% in the case with the PR controller, while the grid voltage THDs were 0.53% and 0.49%, respectively. The grid current THDs were 1.20% 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 ∗ reference from 2

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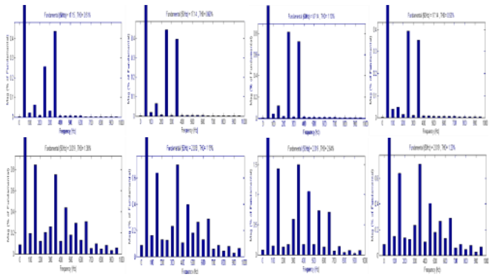

simulation, the proposed controller

2) outperforms the PR-current–fuzzy voltage controller. Note that the grid was cleaner when the PR-current- fuzzy based voltage controller was tested.

2) With the Resistive Load: The spectra of the inverter local load voltages and grid currents are shown in the middle-left column of Fig. 11. When the resistive local load is connected, the recorded local load voltage THD was 0.60% for the proposed H∞ controller and 0.47% for the PR controller, while the grid voltage THDs were 0.60% and 0.47%,

A (1.41 A rms) to 3 A (2.12 A rms) was applied(while keeping I∗ = 0). The grid current i , its reference iref , and the current tracking error ei are shown in Fig. 13. The proposed controller took about 12 cycles to settle down, and the PR-current–fuzzy based voltage 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 with the reference current and the tracking error, when the three-phase resistive local load was changed from RA = RB = RC = 12 Ω to RA = RB = RC = 100 Ω and back, are shown in Fig. 14.

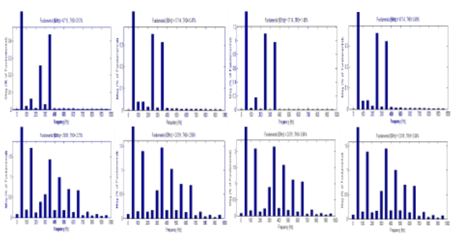

Fig. 11. Spectra of the inverter local load voltage and the grid current with (left column) no load, resistive load (middle-left column), (middle-right column) nonlinear load, and (right column) unbalanced load. (a) H∞ repetitive current–fuzzy based voltage controller. (b) PR-current-fuzzy based voltage controller.

D. Seamless Transfer of the Operation Mode

The transient response of the grid current when the inverter was changed from the stand-alone mode to the grid connected mode and back is shown in Fig

VI. CONCLUSION

The cascaded current–voltage 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 in terms of THD for both the inverter local load voltage and the grid current. In particular, when nonlinear and/or unbalanced loads are connected to the inverter in the grid-connected mode, the proposed strategy significantly improves the THD of the inverter local load voltage and the grid current at the same time. The controllers are designed using the H∞ repetitive current control and fuzzy based voltage control in this paper. 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. Simulation results under various scenarios have demonstrated the excellent performance of the proposed strategy.

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