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Improvement of Power Quality Using Cascaded Voltage and Current Control for Inverter in Microgrids

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Abstract

This paper proposes cascaded voltage and current control strategy for inverter in micro grids. This strategy gives excellent performance of THD (total harmonic distortion)for both inverter local load voltage and grid current and it improves the power quality. It consists of inner voltage loop and outer current loop. When non linear and unbalanced loads are connected to the inverter in the grid. This strategy significantly improves the THD of inverter local load voltage and grid current. This control schemes is designed by using H^{∞} repetitive control strategy which gives seamless transfer between stand alone and grid connected modes. This strategy is used for single phase and three phase systems.

Index Terms—H^{∞} control, micro grids, power quality, repetitive control, seamless transfer, total harmonic distortion (THD).

I.INTRODUCTION

Microgrids significant entities in the development of smart grids.A micro grids consists of energy components including the active loads such as air conditioning, renewable power generators [1].Due to the intermitted production of renewable power and the time varying power demand, the micro grid energy surplus, either positive or negative vary overtime grid reduce the power demand from power plants and reduce the losses due to the plants long distance power transportation in the substation transformer[2].

A parallel control structure consisting of an output voltage controller and a grid current controller was proposed to achieve seamless transfer via changing the reference to the controller without changing the controller. The inverters used in micro grids behave as current source when they are connected to the grid and as voltage when they are autonomously[3].The grid connected inverter should operate in grid tied and off grid modes in order to provide power to emergenency load during system outages. Moreover the transition between the two modes should be seamless to minimize any sudden voltage change across emergenency load or any sudden current change to the grid.

A seamless transfer between both modes has been proposed in [4]. However, the grid currents controller and the output voltage controller must be switched between the two modes. So the outputs of both controllers may not be equal during transfer instant which will cause the current or voltage spikes during switching process. On other hand as the grid interactive inverter should operate in OFF grid mode, the filter capacitor is necessary[5].It is worth stressing that the cascaded current-voltage control structure improves the quality of the both the inverter local load voltage and grid current at the same time and achieves seamless transfer of the operation mode.

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. Experimental results are presented and discussed in Section V. An Extension for fuzzy controller designed in section VI. Finally, conclusions are made in Section VII.

II SYSTEM DISCRIPTION

The structure of a single phase inverter connected to the grid is shown in fig.1.

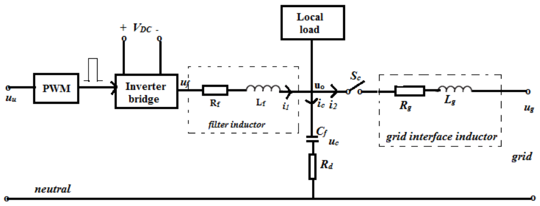


Fig.1 sketch of a grid-connected single phase inverter with local loads

It consists of an inverter bridge, an LC filter, and a grid interface inductor connected with a circuit breaker. It is worth nothing 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 and the current i_2 flowing through the grid interface inductor is called the grid current.

The control objective is to maintain low THD for the inverter local load voltage μ_0 and, simultaneously, for the grid current i_2.Hence, a cascaded controller can be adopted and designed. The controller consists of two loops an inner voltage loop to regulate the inverter local load voltage μ_0 and an outer to regulate the grid current i_2 as shown in fig 2.

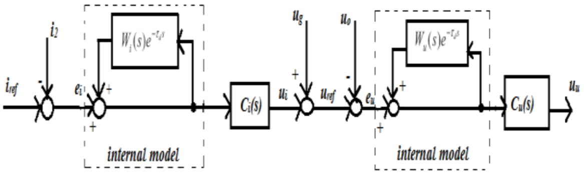


Fig.2.Cascaded current–voltage controller for inverters, where both controllers adopt the H^∞ repetitive strategy

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 assumptions that the inner loop is already in the steady state i.e., $\mu_0=\mu_{ref}$. 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 both controllers are designed using the H^∞ repetitive control strategy because of its excellent performance in reducing THD.

The voltage controller functions are the following:

1. To deal with power quality issues of the inverter local load voltage even under unbalanced and/or nonlinear local loads,

2. To generate and dispatch power to the local load, and
3. To synchronized the inverter with the grid.

When the inverter synchronized and connected with the grid, the voltage and the frequency are determined by the grid.

The current controller functions are as follow:

- 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.

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 µg 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 voltage controller design will be outlined hereinafter, following the detailed procedures proposed in [9]. The control plant of the voltage controller is no longer the whole LCL filter but just the LC filter, as shown in fig.3.

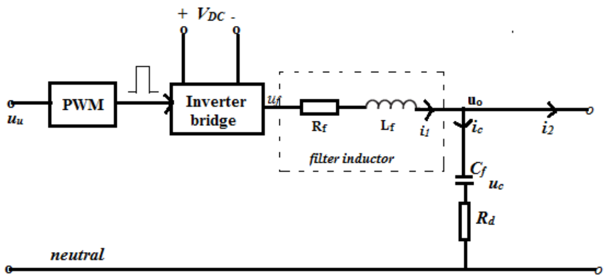


fig.3.Control plant P_u for the inner voltage controller

A. State-Space Model of the plant P_u

The corresponding control plant shown in fig.3.for the voltage controller consists of the inverter bridge and the filter (L_f and C_f). The filter inductor is modeled with a series winding resistances. 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_f over a sampling period is equal to u_u. 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 variable $x_u= [i_1 \mu_c]^T$. The external input $w_u= [i_2 u_{ref}]^T$ 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 $e_u=u_{ref}-u_0$, where $u_0= u_c + R_d(i_1-i_2)$ is the inverter local load voltage. The plant P_u can be described by the state equation

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

And the output equation

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

with,

$$A_u = \begin{bmatrix} -\frac{Rf+Rd}{Lf} & -\frac{1}{Lf} \\ \frac{1}{Cf} & 0 \end{bmatrix}$$

$$B_{u1}=\begin{bmatrix}\frac{Rd}{Lf} & 0\\ -\frac{1}{Cf} & 0\end{bmatrix}\ B_{u2}=\begin{bmatrix}\frac{1}{Lf} & 0\\ o & 0\end{bmatrix}$$

$$C_{u1}=\begin{bmatrix}-Rd & -1\\ 0 & 0\end{bmatrix}$$

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

The corresponding plant transfer function is then

$$P_u=\begin{bmatrix}Au & Bu1\ Bu2\\ Cu1 & Du1\ Du2\end{bmatrix} \tag{3}$$

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

In order to guarantee the stability of inner voltage, an H$^\infty$ control problem, as shown in fig.4.

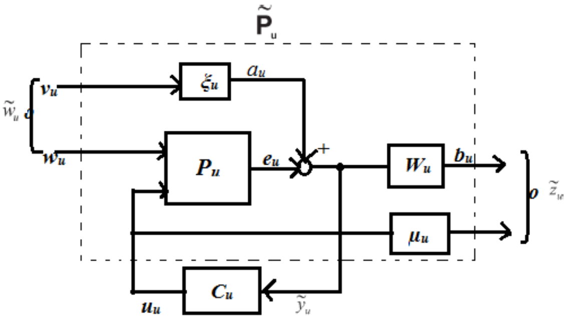


Fig.4.Formulation of the H$^\infty$ control problem for the voltage controller

is formulated to minimize the H norm of the transfer function $T_{\tilde{z}_u \tilde{w}_u}=F_1(\tilde{P}_u,C_u)$ from $\tilde{w}_u=[V_u\ W_u]^T$ to $\tilde{z}_u=[z_{u1}\ z_{u2}]^T$, after opening the local positive feedback loop of the internal model and introducing weighing parameters ξ_u and μ_u. the closed loop system can be represented as

$$\begin{pmatrix}\tilde{z}u\\ \tilde{y}u\end{pmatrix}=\tilde{P}_u\begin{pmatrix}\tilde{w}u\\ \tilde{u}u\end{pmatrix}$$

$$u_u = C_u \tilde{y}_u \ (4)$$

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 $w_u=\begin{bmatrix}Awu & Bwu\\ Cwu & Dwu\end{bmatrix}$, which is the internal model for repetitive control. A weighting parameter ξ_u is added to adjust the relative importance of v_u with respect to w_u, and another weighting parameter μ_u is added to adjust the relative important of μ_u with respect to b_u. The parameter ξ_u and μ_u also play a role in guaranteeing the stability of the system; see more details in[9] and [10].it can be found out that generalized plant $\tilde{P}_u$ is realized as The controller C_u can then be found according to the generalized plant $\tilde{P}_u$ using the H$^\infty$ control theory. E.g. by using the function hinfsyn provided in MATLAB.

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

IV CURRENT CONTROLLER DESIGN

In the current controller design, 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. 5.

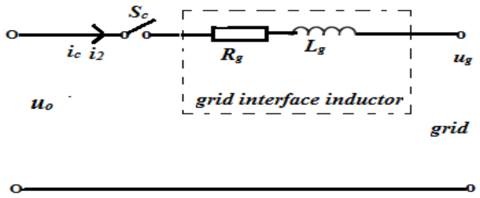


Fig.5. Control plant Pi for the outer current controller.

A. State- Space Model of the Plant Pi

Since it can be assumed that $u_o = u_{ref}$, there is $u_o = u_g + u_i$ or $u_i = u_o - u_g$ from Figs. 2 and 6, 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 *ug* appears on both sides of the grid interface inductor L_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 *ui* of the repetitive current controller.

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 P_i is the tracking 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

$$\dot{x}_i = A_i x_i + B_{i1} w_i + B_{i2} u_i \qquad (5)$$

and the output equation

$$y_i = e_i = C_{i1} x_i + D_{i1} w_i + D_{i2} u_i \qquad (6)$$

where

$$A_i = -\frac{Rg}{Lg} \; B_{i1} = 0 \; B_{i2} = \frac{1}{Lg}$$

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

The corresponding transfer function of P_i is

$$\text{Pi} = \begin{bmatrix} Ai & Bi1\ Bi2 \\ Ci1 & Di1\ Di2 \end{bmatrix} \qquad (7)$$

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

In order to guarantee the stability of outer current, an H$^\infty$ control problem, as shown in fig.7.

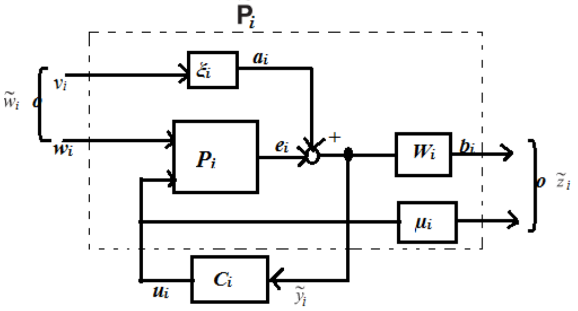


Fig.6.Formulation of the H$^\infty$ control problem for the current controller.

The resulting generalized plant can be obtained as

$$\tilde{P}_i = \begin{bmatrix} A_i & 0 & 0 & B_{i1} & B_{i2} \\ B_{wi}C_{i1} & A_{wi} & B_{wi}\xi_i & B_{i1}D_{i1} & B_{wi}D_{i2} \\ D_{wi}C_{i1} & C_{wi} & D_{wi}\xi_i & D_{wi}D_{i1} & D_{wi}D_{i2} \\ 0 & 0 & 0 & 0 & \mu_i \\ C_{i1} & 0 & \xi_i & D_{i1} & D_{i2} \end{bmatrix}$$

with weighting parameters ξ_i and μ_i and low-pass filter $W_i = \begin{bmatrix} Awi & Bwi \\ Cwi & Dwi \end{bmatrix}$ which can be selected similarly as the corresponding ones for the voltage controller.

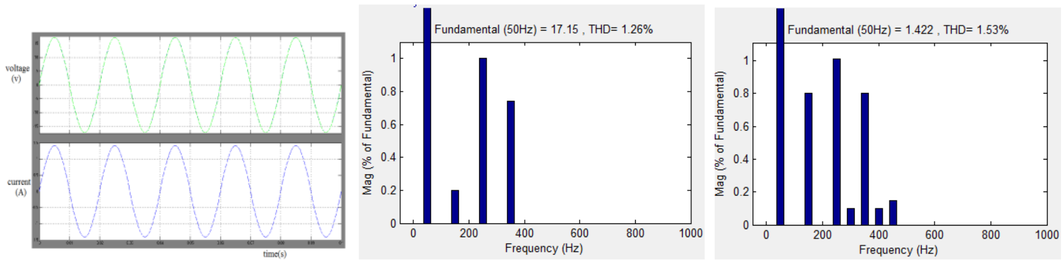
The controller C_i can then be found according to the generalized plant $\tilde{P}_i$ using the H^∞ control theory, e.g., by using the function *hinfsyn* provided in MATLAB.

V RESULTS AND DISCUSSION

In both stand-alone and grid-connected modes with different loads to evaluate its performance are discuss in the above-designed controller. It also carried out the operation modes of seamless transfer. The H^∞ repetitive current controller was replaced with a proportional–resonant (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), the experimental results with both the repetitive current controller and the PR current controller are similar, and hence, no comparative results are provided for the stand-alone mode.

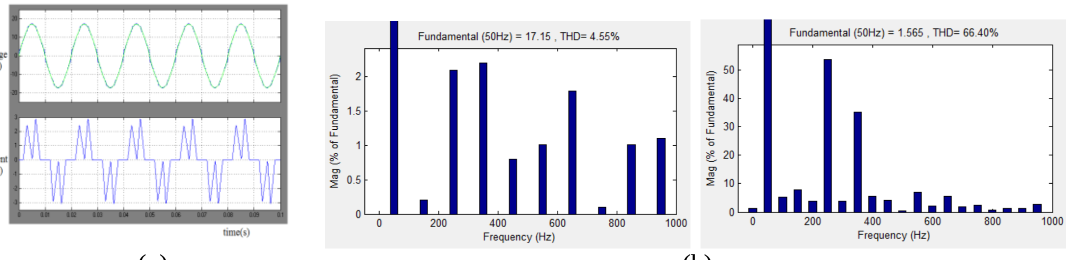
A. In the Stand-Alone Mode

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, a nonlinear load, and an unbalanced load.



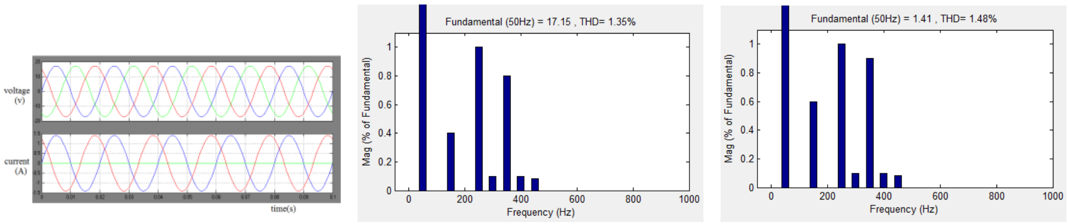
(a) (b)

Fig.7 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.



(a) (b)

Fig.8 Stand-alone mode with a nonlinear load. (a) (Upper) u_A and its reference u_{ref} and (lower) current i_A. (b) (Upper) Voltage THD and (lower) current THD.

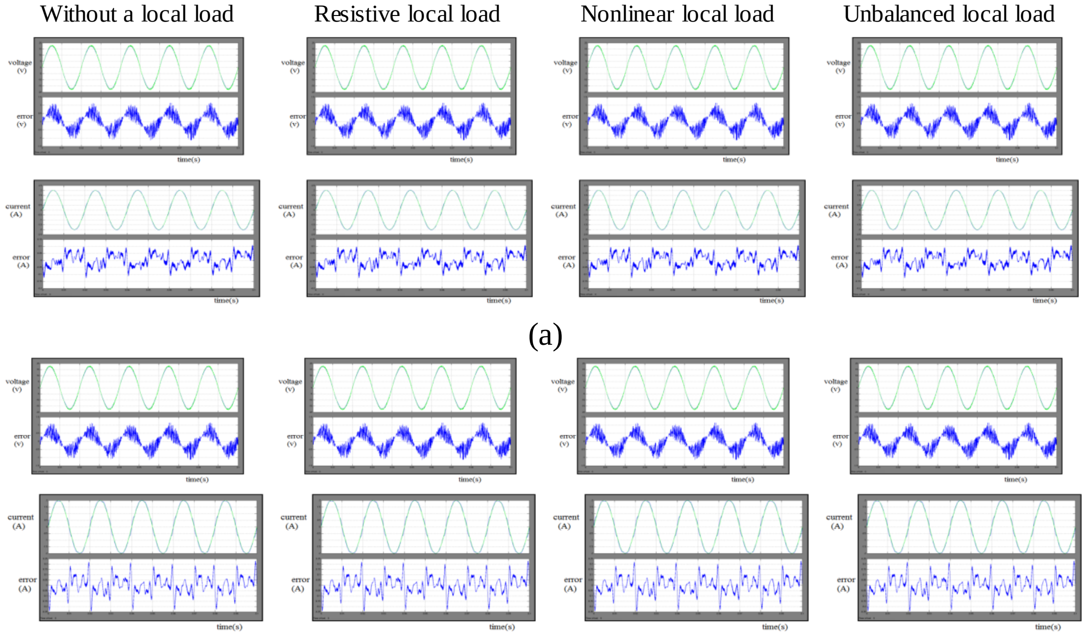


(a) (b)

Fig.9 Stand-alone mode with an unbalanced load. (a) (Upper) u_A and its reference u_{ref} and (lower) current i_A. (b) (Upper) Voltage THD and (lower) current THD.

B. In the Grid-Connected Mode

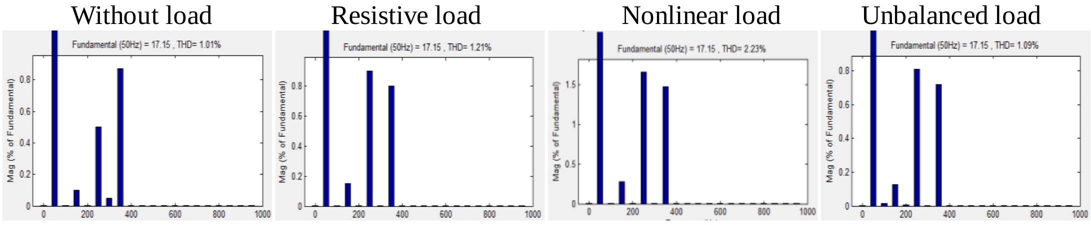
In grid connected mode the comparison for H^{∞} repetitive current controller and a proportional–resonant (PR) current controller. The current reference of the grid current I^*_d was set at 2A (corresponding to 1.41 A rms), after connecting the inverter to the grid. The reactive power was set at 0var ($I^*q = 0$). 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.



(a)

(b)

Fig. 10. Inverter local load voltage and the grid current in the grid-connected mode with (left column) no load, (middle column) resistive load (middle-left column), (middle-right column) nonlinear load, and (right column) unbalanced load (a) H∞ repetitive current–voltage controller. (b) PR-current-H∞-repetitive-voltage controller.



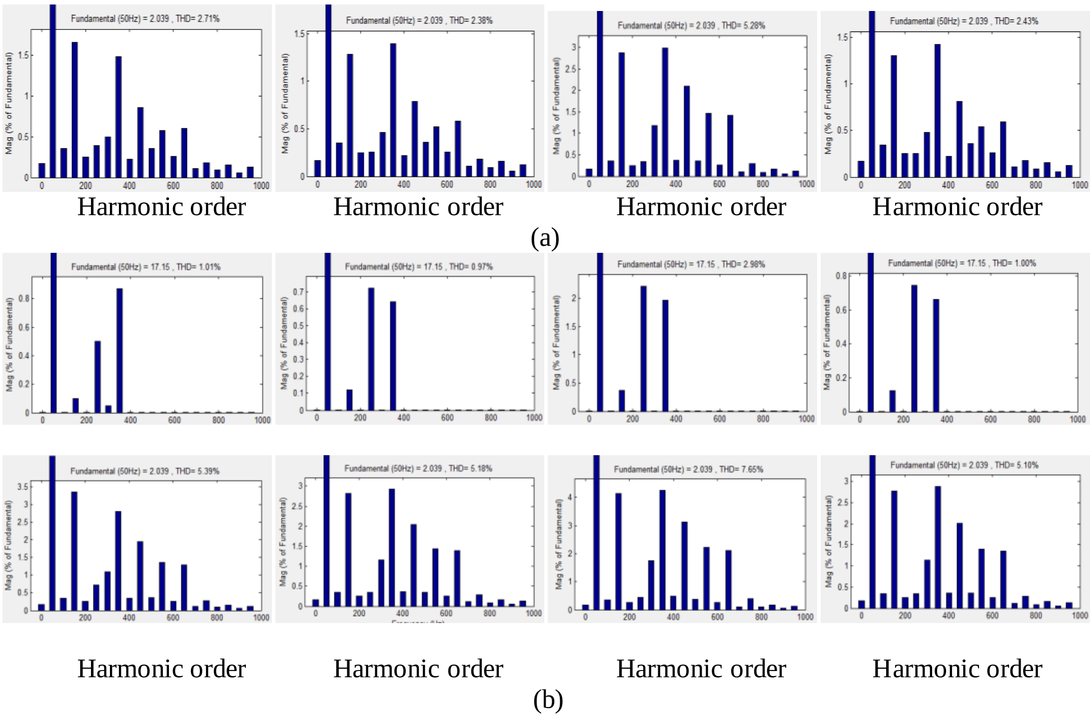
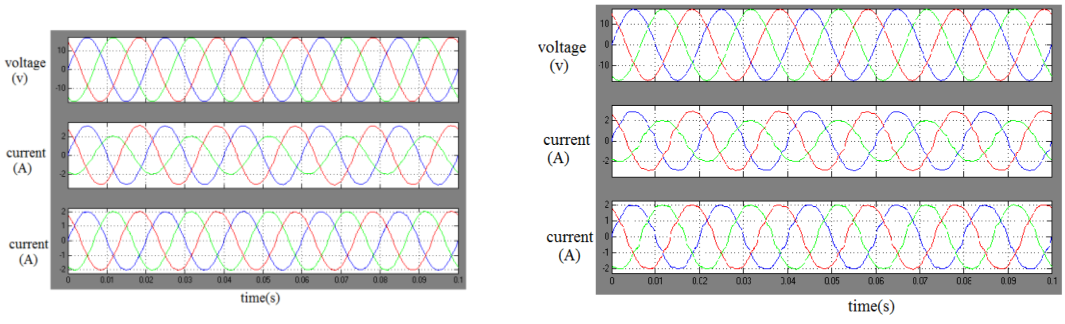


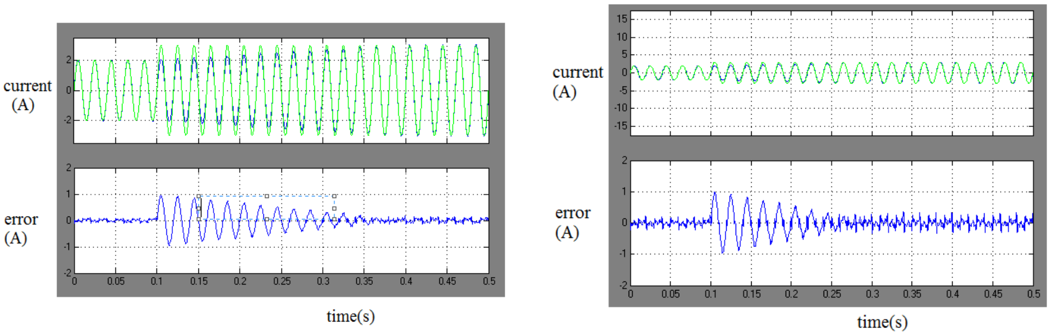
Fig. 11. Spectra of the inverter local load voltage and the grid current with (left column) no load, resistive load (middle-left column), (middle-right column) nonlinear load, and (right column) unbalanced load. (a) H∞ repetitive current–voltage controller. (b) PR-current-H∞-repetitive-voltage controller.



(a) (b)

Fig. 12. Grid-connected mode with unbalanced loads: (Upper) Inverter local load voltage, (middle) the filter inductor currents, and (lower) the grid currents.(a) H^{∞} repetitive current–voltage controller. (b) PR-current-H^{∞}-repetitive voltage controller.

C. Transient Performance



(a) (b)

Fig.13.Transient response in the grid-connected mode without local load : (a) H^{∞} repetitive current–voltage controller. (b) PR-current-H^{∞}-repetitive-voltage controller.

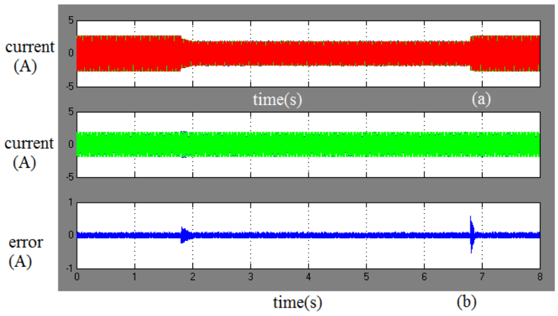


Fig. 14. Transient responses of the inverter and grid currents when the local load was changed. (a) Filter inductor current i_A. (b) Grid current i_a, its reference i_{ref}, and the current tracking error e_i.

D. Seamless Transfer of the Operation Mode

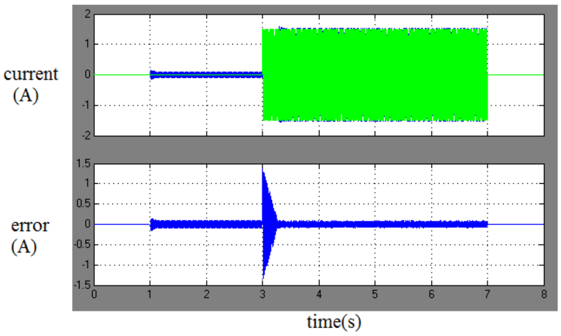
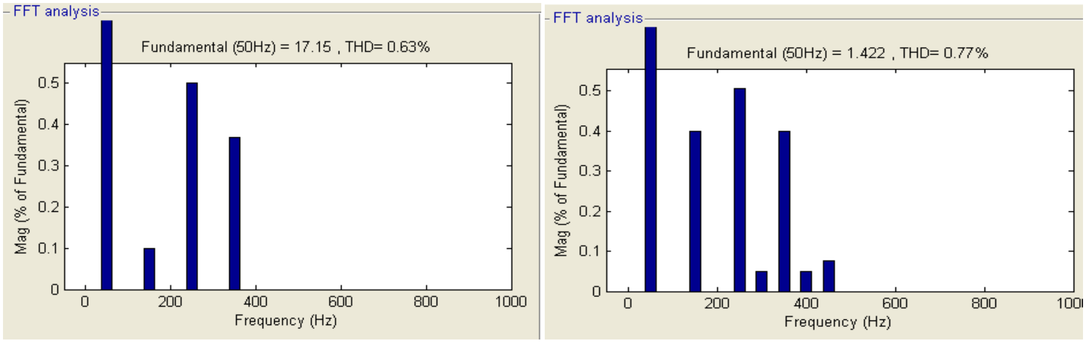


Fig.15. Transient response of the inverter when transferred from the standalone mode to the grid-connected mode and then back.

VI EXTENSION RESULTS

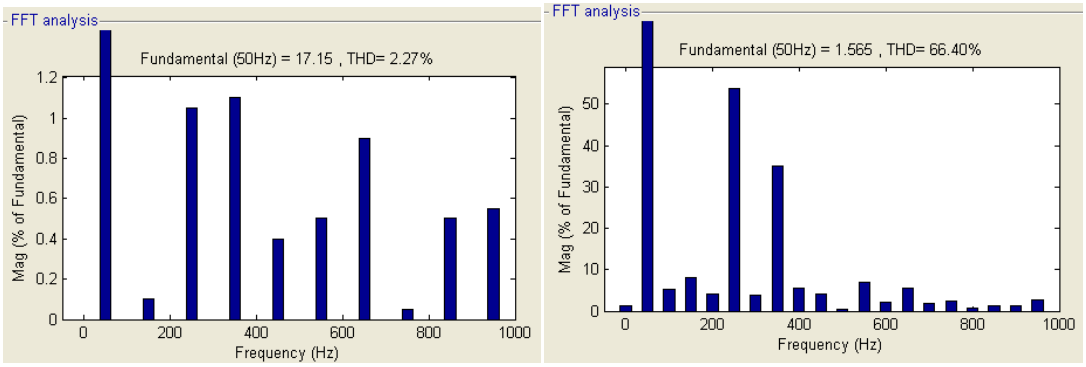
In both stand-alone and grid-connected modes with different loads to evaluate its performance are discuss in the fuzzy-designed controller. It also carried out the operation modes of seamless transfer. The H^∞ repetitive current controller was replaced with a proportional–resonant (PR) current controller 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), the experimental results with both the repetitive current controller and the PR current controller are similar, and hence, no comparative results are provided for the stand-alone mode.

In the Stand-Alone Mode



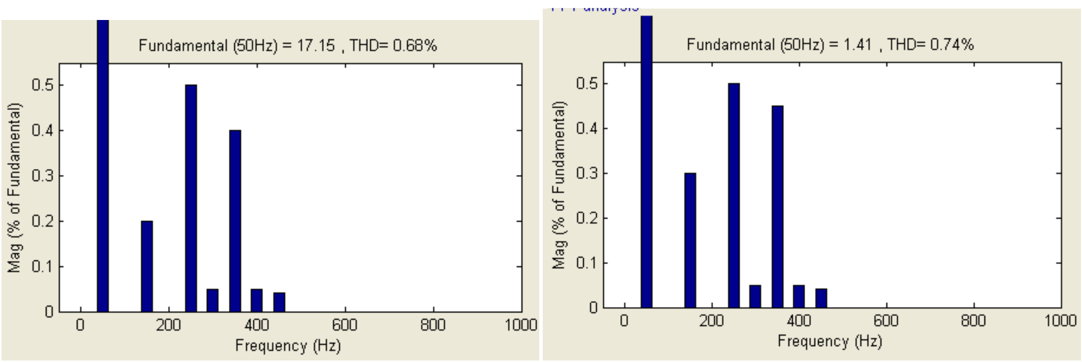
(a)

Fig.16. Stand-alone mode with a resistive load. (a)(Upper) Voltage THD and (lower) current THD.



(a)

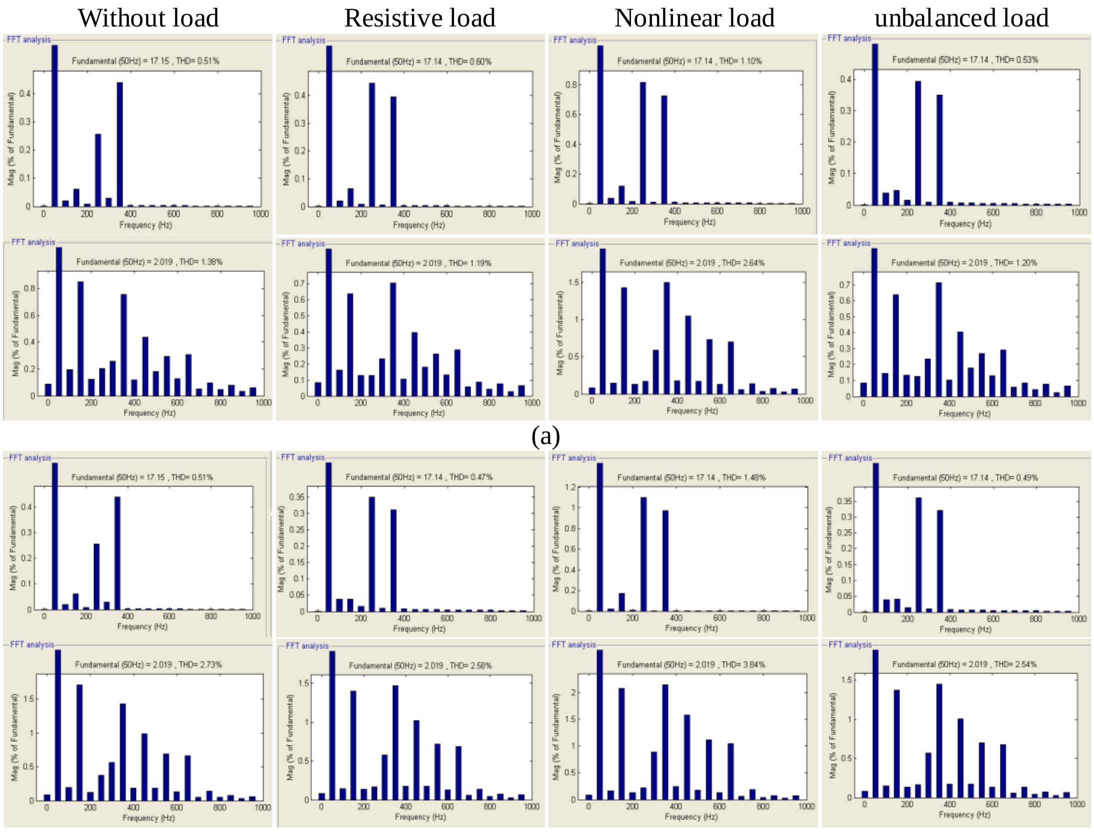
Fig.17 Stand-alone mode with a nonlinear load. (a) (Upper) Voltage THD and (lower) current THD.



(a)

Fig.18 Stand-alone mode with an unbalanced load. (a)(Upper) Voltage THD and (lower) current THD.

B. In the Grid-Connected Mode



(a)

(b)

Fig. 19. Spectra of the inverter local load voltage and the grid current (a) H$^{\infty}$ repetitive current–voltage controller. (b) PR-current-H$^{\infty}$-repetitive-voltage controller.

VII CONCLUSION

The cascaded current–voltage control strategy has been proposed for inverters which improves the power quality of inverter local load voltage and current. This control strategy includes inner voltage loop and outer current loop. These are designed using the H repetitive control strategy which gives very low total harmonic distortion. When nonlinear and unbalanced loads connected to the inverter in grid connected mode, the proposed strategy improve the THD. This control strategy gives seamless transfer between stand alone and grid connected modes.

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