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IMPROVING THE POWER QUALITY OF A GRID CONNECTED INVERTER BY CASCADED CURRENT-VOLTAGE CONTROL

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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 also the current exchanged with the grid. It also allows seamless transfer of the operation mode from stand-alone to grid-connected or vice versa. The control strategy includes an inner voltage loop and an outer current loop, with both controllers designed using the H∞ repetitive control strategy. This results in a very low total harmonic distortion in both the inverter local load voltage and also the current exchanged with the grid at an equivalent time. The presented control strategy will be employed to single-phase inverters and three-phase four-wire inverters. It allows 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 under different scenarios, with comparisons made to the current repetitive controller replaced with a current proportional–resonant controller, are proposed to demonstrate the excellent performance of the proposed strategy.

Index Terms—H∞ control, microgrids, power quality, repetitive control, seamless transfer, total harmonic distortion (THD).

I. INTRODUCTION

Microgrids are increasing as a consequence of rapidly growing distributed power generation systems. up the management capabilities and operational options of microgrids brings environmental and economic advantages. The introduction of microgrids results in improved power quality, reduces transmission congestion, decreases emission and energy losses, and effectively facilitates the use of renewable energy. Microgrids are usually operated within the grid-connected mode; but, it's also expected to provide sufficient generation capacity, controls, and operational ways to provide a minimum of a part of the load after being disconnected from the distribution system and to remain operational as a stand-alone (islanded) system [1]–[6]. Traditionally, the inverters utilized in microgrids behave as current sources after 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's advantageous to operate inverters as voltage sources as a result of 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 presented in [8] to attain seamless transfer via changing the references to the controller without changing the controller. Another necessary 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 will represent a high proportion of the full load in small-scale systems, the problem with power quality may be a particular concern in microgrids. Moreover, unbalanced utility grid voltages and utility voltage sags, which are 2 most common utility voltage quality issues, will affect microgrid power quality. The electrical converter controller ought to be ready to address unbalanced utility grid voltages and voltage sags, that are among the vary given by the waveform quality needs of the local loads and/or microgrids. When critical loads are connected to an inverter, severe unbalanced voltages are not usually acceptable, and also the inverter ought to be disconnected from the utility grid. Only if the voltage imbalance isn't therefore serious or the local load isn't very sensitive to it will the inverter remain connected. Since the controllers designed in the dq or αβ frames under unbalanced situations become noticeably advanced it’s advantageous to design the controller within the natural reference frame.

Another power quality problem in microgrids is the total harmonic distortion (THD) of the inverter local load voltage and also the current exchanged with the grid (referred to as the grid current during this paper), which has to be maintained low according to industrial regulations. It’s been known that it's not a problem to obtain low THD either for the inverter local load voltageor for the grid current. However, no strategy has been reported within the literature to obtain low THD for both the inverter local load voltage and also the grid current simultaneously. This could even are believed not possible as a result of there is also nonlinear local loads. During this paper, a cascaded control structure consisting of an inner-loop voltage controller and an outer-loop current controller is presented to achieve this, when spotting that the inverter LCL filter will be split into 2 separate components (which is, of course, obvious however nobody has taken advantage of it). The LC part will be employed to design the voltage controller, and also the grid interface inductor may be used to design the present controller. The voltage controller is responsible for the power quality of the inverter native load voltage and power distribution and synchronization with the grid, and also the current controller is responsible for the power quality of the grid current, the power exchanged with the grid, and also the over current protection. With the help of the H∞ repetitive control the presented strategy is able to maintain low THD in both the inverter local load voltage and also the grid current at an equivalent time. When the inverter is connected to the grid, both controllers are active; once the inverter isn't connected to the grid, the current controller is functioning under zero current reference. Hence, no additional effort is required 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. As a result, the inverter can cope with unbalanced local loads for three-phase applications. In other words, harmonic currents and unbalanced native load currents are all contained locally and don't affect the grid. Experimental results are given 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 native load voltage and also the grid current at an equivalent time and achieves seamless transfer of the operation mode. The outer-loop current controller provides a reference for the inner-loop voltage controller that is the key to permit the simultaneous improvement of the thd within the grid current and also the inverter local load voltage and to attain the seamless transfer of operation mode. this can be different from the conventional voltage–current control strategy wherever the (inner) current loop is employed to regulate the filter inductor current of the electrical converter (not the grid current), thus it's not possible to attain synchronous improvement of the thd in the grid current and also the inverter local load voltage.

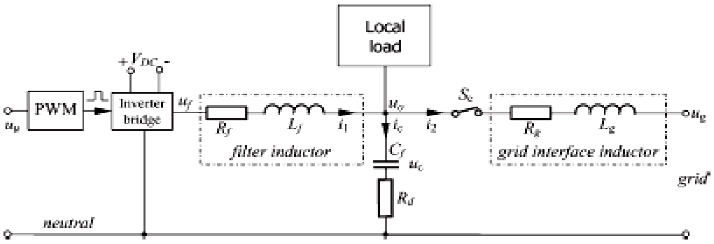

Fig. 1.Sketch of a grid-connected single-phase inverter with local loads.

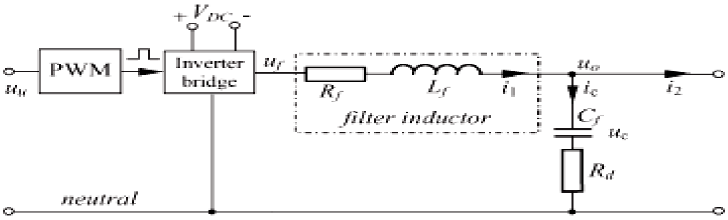

Fig. 2. Control plant *Pu*for the inner voltage controller.

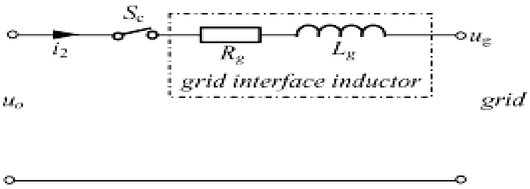

Fig. 3. Control plant *Pi* for the outer current controller.

An inner current loop will still be added to the presented structure inside the voltage loop without any difficulty to perform the conventional function, if needed. The H∞ repetitive control strategy is adopted within the paper to design the controllers, however this is} not a must; different approaches can be used as well. Repetitive control which is regarded as an easy learning control technique provides an alternate to perfectly track periodic signals and/or to reject periodic disturbances in dynamic systems, employing the internal model principle.

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's value 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 also 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. As a matter of fact, the system will be regarded as 2 components, as shown in Figs. 2 and 3, cascaded together. Hence, a cascaded controller will be adopted and designed. The presented controller, as shown in Fig. 4, consists of 2 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 fundamental 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 will be designed individually. As a result, the outer-loop controller may be designed under the assumption that the inner loop is already within the steady state, i.e., uo = uref .It's also value stressing that the current controller is in the outer loop and also the voltage controller is in the inner loop. This can be contrary to what is usually done. In this paper, both controllers are designed using the H∞ repetitive control strategy because of its excellent performance in reducing thd.

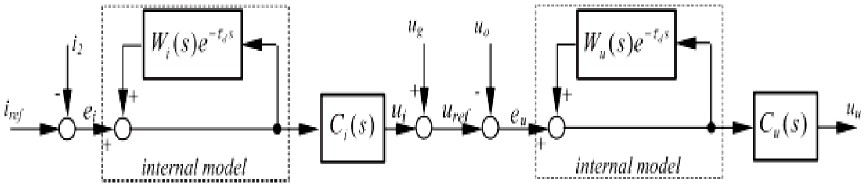

Fig. 4. Proposed cascaded current–voltage controller for inverters, where both controllers adopt the *H*∞ repetitive strategy.

The main functions of the voltage controller are the following:to deal with power quality issues of the inverter localload voltage even under unbalanced and/or nonlinear localloads, to generate and dispatch power to the local load, andto synchronize the inverter with the grid. When the inverter issynchronized and connected with the grid, the voltage and thefrequency 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 is used for over current protection, but usually, it's included in the drive circuits of the inverter bridge. A phase-locked loop (PLL) is used to provide the phase information of the grid voltage, that is required to generate the current reference iref (see Section V for an example). because the control structure described here uses only one inverter connected to the system and also the inverter is assumed to be powered by a constant dc voltage source, no controller is required to regulate the dc-link voltage (otherwise, a controller is 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 can be used as a synchronization mechanism, and it doesn't have an effect on the design of the controller, as are seen later.

III. DESIGN OF THE VOLTAGE CONTROLLER

The design of the voltage controller will be outlined hereinafter,following the detailed procedures proposed. Aprominent feature different from what is known is that thecontrol 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 P0075

The corresponding control plant shown in Fig. 2 for thevoltage controller consists of the inverter bridge and the LCfilter (Lf and Cf). The filter inductor is modeled with a series winding resistance. The PWMblock, together with the inverter,is modeled by using an average voltage approach with the limitsof the available dc-link voltage so that the average value ofufover a sampling period is equal to uu. As a result, the PWMblock and the inverter bridge can be ignored when designingthe controller.

The filter inductor current *i*1 and the capacitor voltage *uc*are chosen as state variables *xu*= [*i*1 *uc*]*T*. The external input*wu*= [*i*2 *u*ref]*T*consists of the grid current *i*2 and the referencevoltage *u*ref . The control input is *uu*. The output signal fromthe plant *Pu*is the tracking error *eu*= *u*ref− *uo*, where *uo*=*uc*+ *Rd*(*i*1 − *i*2) is the inverter local load voltage. The plant*Pu*can be described by the state equation

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

and the output equation

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

with

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

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

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

$$D_{u1} = [\,R_d \quad 1\,] \quad D_{u2} = 0.$$

The corresponding plant transfer function is then

$$P_u = \left[\begin{array}{c|cc} A_u & B_{u1} & B_{u2} \\ \hline C_{u1} & D_{u1} & D_{u2} \end{array}\right]. \qquad (3)$$

B. Formulation of the Standard H∞ Problem

In order to guarantee the stability of the inner voltage loop,an H∞ control problem, as shown in Fig. 5, is formulatedto minimize the H∞ norm of the transfer function T˜zu˜ wu=Fl(˜ Pu, Cu) from ˜ wu= [vu wu]T to ˜zu= [zu1 zu2]T, afteropening the local positive feedback loop of the internal modeland introducing weighting parameters ξuand μu. The closedloopsystem can be represented asto be designed. The generalized plant ˜ *Pu*consists of the original plant *Pu*, together with the low-pass filter *Wu* =_*AwuBwuCwuDwu*_, which is the internal model for repetitivecontrol. The details of how to select *Wu* can be found.

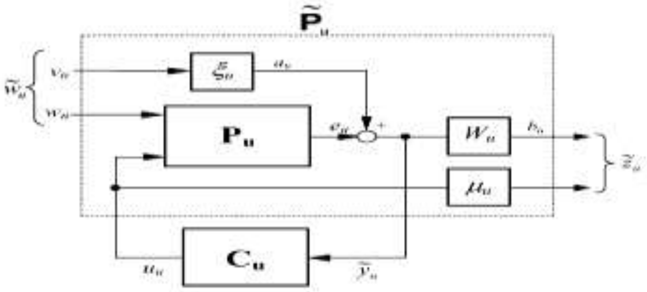

Fig. 5.Formulation of the *H*∞ control problem for the voltage controller.

$$\begin{bmatrix} \tilde{z}_u \\ \tilde{y}_u \end{bmatrix} = \tilde{P}_u \begin{bmatrix} \tilde{w}_u \\ u_u \end{bmatrix}$$
$$u_u = C_u \tilde{y}_u \qquad (4)$$

where ˜ *Pu*is the generalized plant and *Cu* is the voltage controller

A weighting parameter *ξu*is added to adjust the relativeimportance of *vu* with respect to *wu*, and another weightingparameter *μu*is added to adjust the relative importance of *uu*with respect to *bu*. The parameters *ξu*and *μu*also play a rolein guaranteeing the stability of the system.

IV. DESIGN OF THE CURRENT CONTROLLER

As explained before, when designing the outer-loop currentcontroller, it can be assumed that the inner voltage loop tracksthe reference voltage perfectly, i.e., *uo*= *u*ref . Hence, the controlplant for the current loop is simply the grid inductor, asshown in Fig. 3. The formulation of the *H*∞ control problemto design the *H*∞ compensator *Ci*is similar to that in the caseof the voltage control loop shown in Fig. 5 but with a differentplant *Pi* and the subscript *u* replaced with *i*.

A. State-Space Model of the Plant Pi

Since it can be assumed that uo= uref , there is uo= ug+uior ui= uo − ugfrom Figs. 3 and 4, i.e., uiis actuallythe voltage dropped on the grid inductor. The feedforwardedgrid voltage ugprovides a base local load voltage for theinverter. The same voltage ugappears on both sides of thegrid interface inductor Lg, and it does not affect the controllerdesign. Hence, the feedforwarded voltage path can be ignored during the design process. This is a very important feature. Theonly contribution that needs to be considered during the designprocess is the output uiof the repetitive current controller.

TABLE I
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 $i2$ flowing through the grid interface inductor$Lg$is chosen as the state variable $xi = i2$. The externalinput is $wi= i$ref , and the control input is ui. The output signalfrom the plant Pi is the tracking error $ei= i$ref− $i2$, i.e., thedifference between the current reference and the grid current.

V. SIMULATION RESULTS

A. In the Stand-Alone Mode:

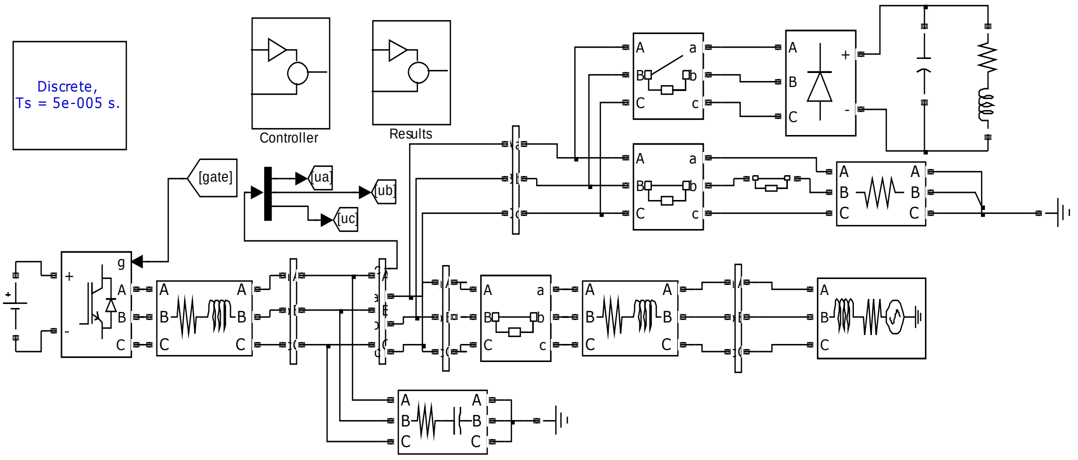

Fig 6. Simulation model for Stand- Alone mode

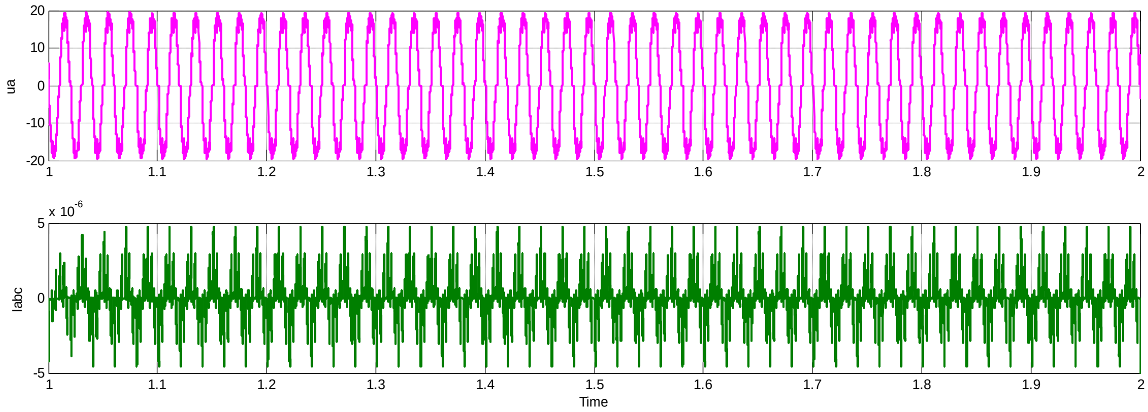

Fig.7 Simulation results for Stand-alone mode. (a) *ua*and its reference *u*ref and current *iabc*.

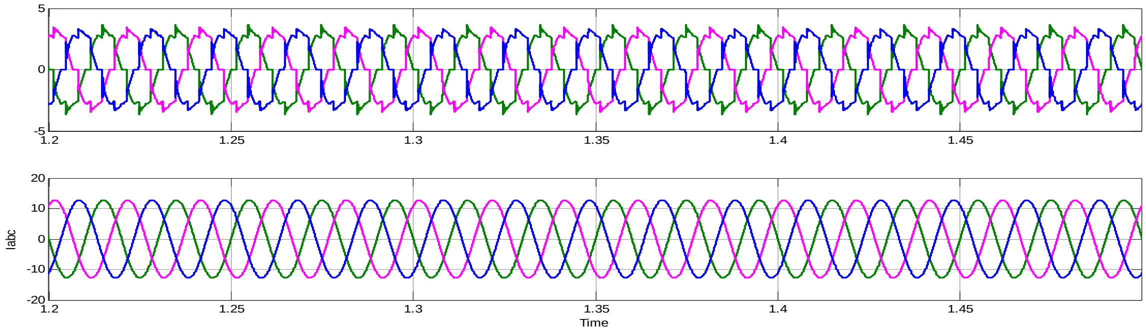

Fig 8. Simulation results for Stand-alone mode with a nonlinear load. (a) *uA*and its reference *u*ref and current *iabc*.

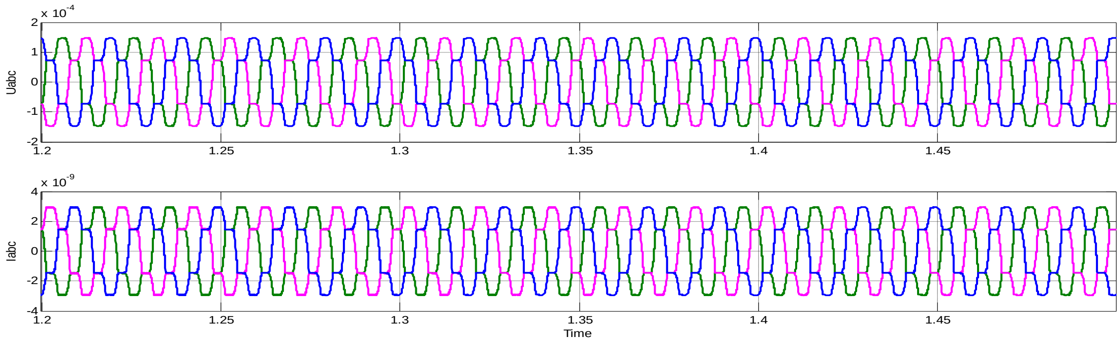

Fig 9. Simulation results for Stand-alone mode with an unbalanced load. (a) Inverter local load voltage and local load currents.

B. In the Grid-Connected Mode

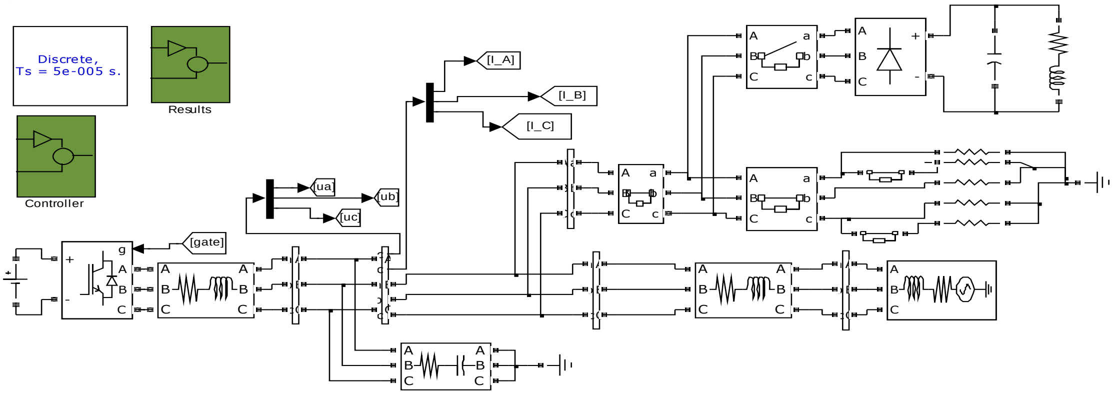

Fig.10 Simulation model for Grid connected mode

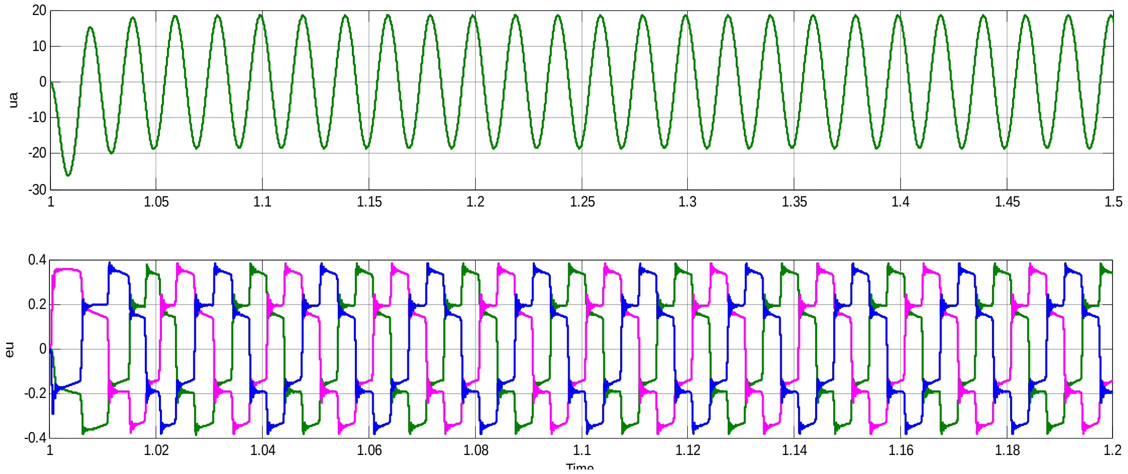

Fig .11 Simulation results for Grid-connected mode with unbalanced loads: Inverter local load voltage, the filter inductor currents, and the grid currents for *H*∞ repetitive current–voltage controller.

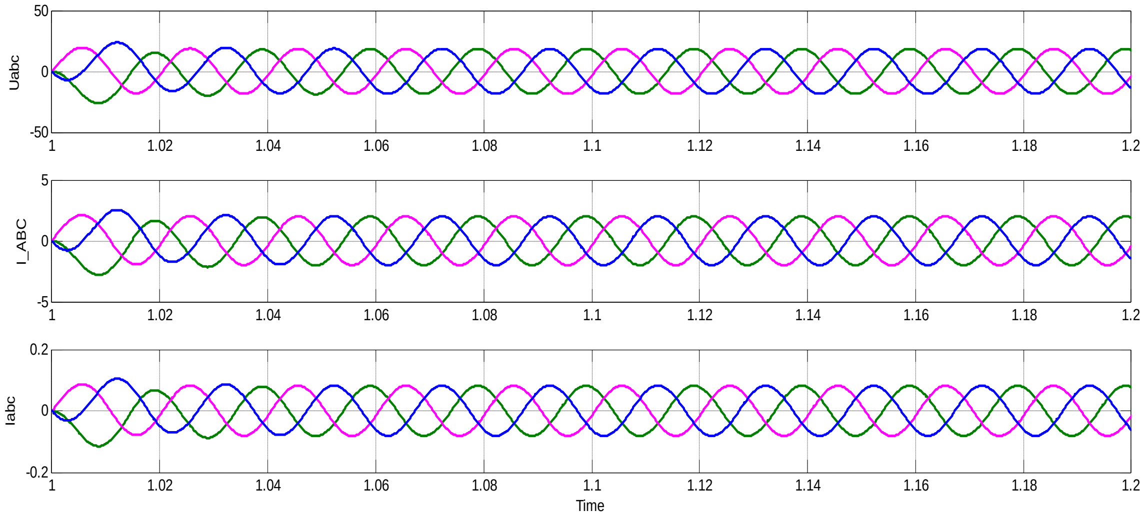

Fig.12. Simulation results for Grid-connected mode with unbalanced loadsInverter local load voltage and the grid current in the grid-connected mode with resistive load PR-current-*H*∞-repetitive-voltage controller.

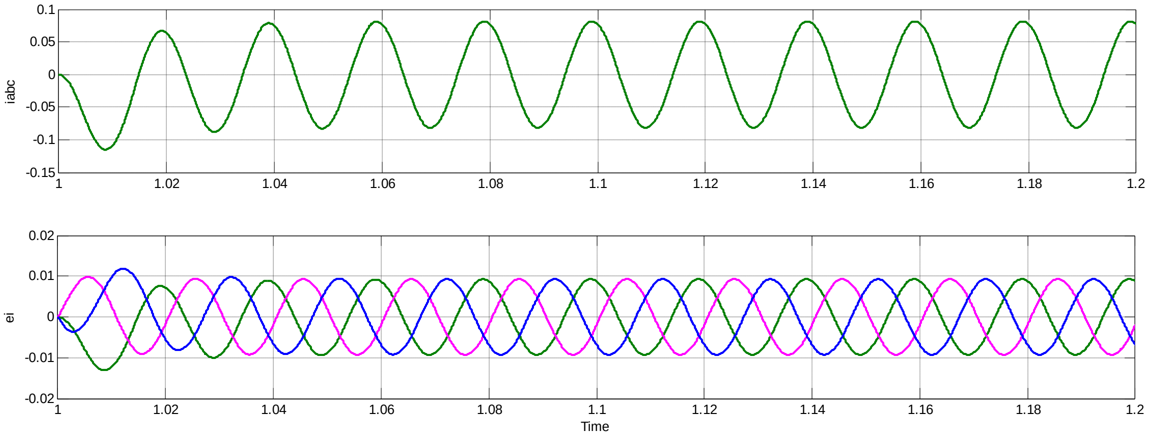

Fig .13. Simulation results for Inverter local load voltage and the grid current in the grid-connected mode with nonlinear load

C. Transient Performance:

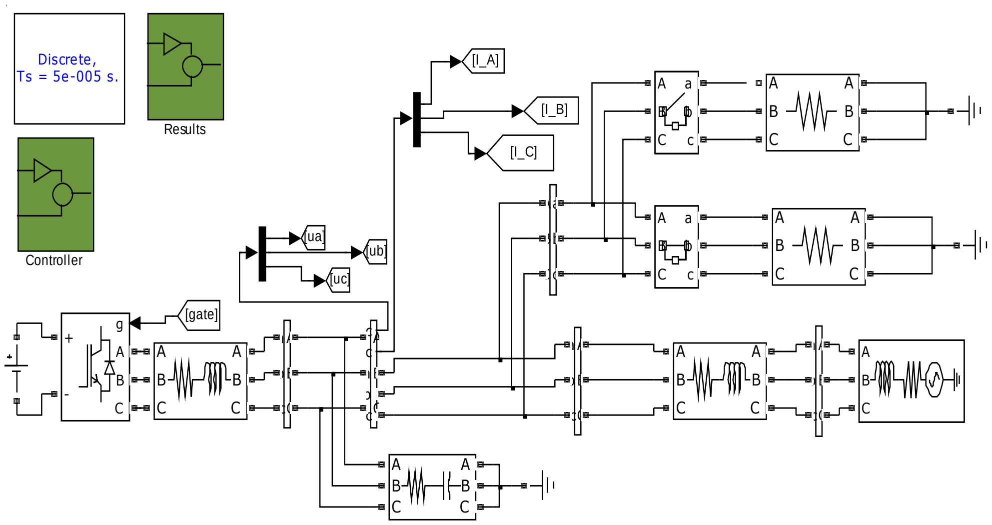

Fig.14. Simulation model for Transient Performance

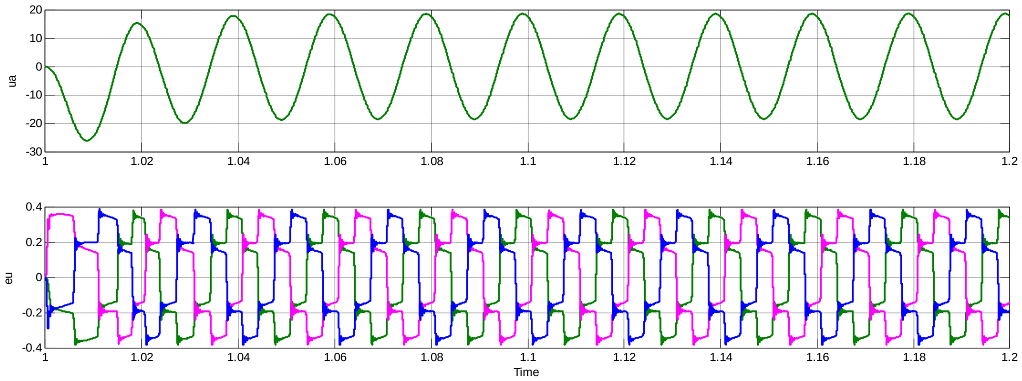

Fig.15. Simulation results for Transient response in the grid-connected mode without local load to 1-A step change in I*d Grid current *ia*and its reference *i*ref and current tracking error *ei* for *H*∞ repetitive current–voltage controller and PR-current-*H*∞-repetitive-voltage controller.

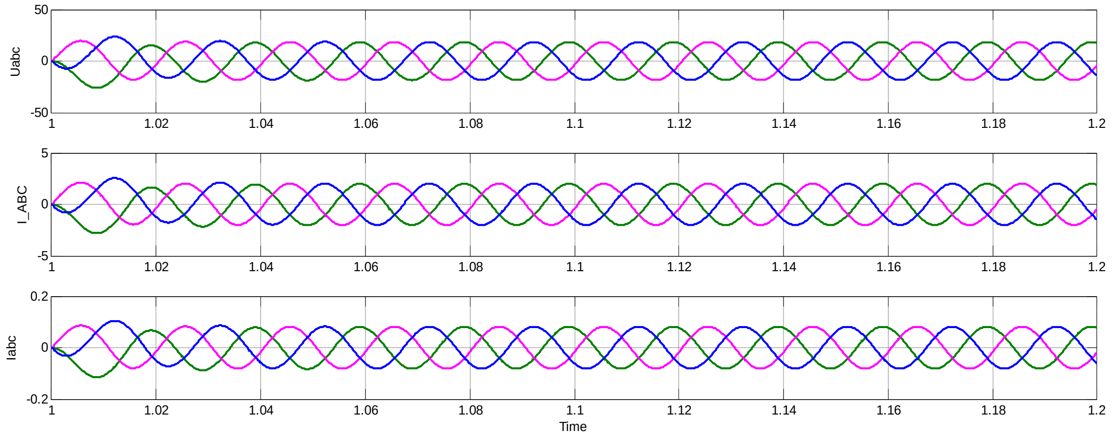

Fig .16. Simulation results for Transient Performance Transient response in the grid-connected mode local load was changed from 12 to 100 Ω at *t* = 1.88 s. *ia*, its reference *i*ref , and the current tracking error *ei* and *uA*, its reference *u*ref , and the voltage tracking error *eu*.

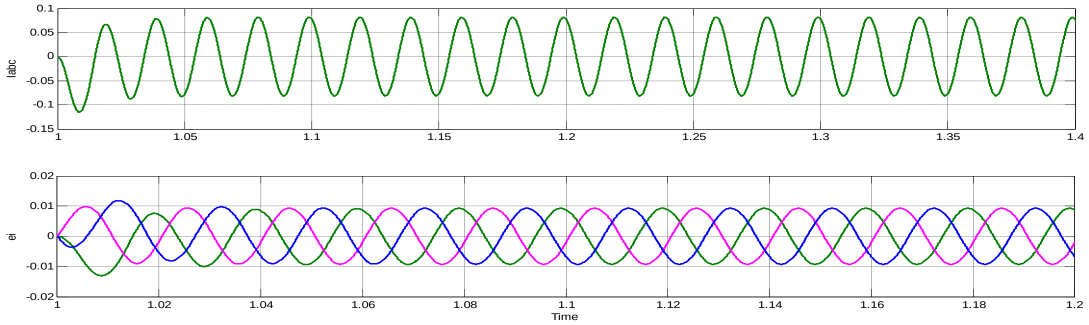

Fig .17. Simulation results for Transient Performance Transient response in the grid-connected mode local load was changed back from 100 to 12 Ω at *t* = 6.61 s. *ia*, its reference *i*ref , and the current tracking error *ei* and *uA*, its reference *u*ref , and the voltage tracking error *eu*.

D. Seamless Transfer of the Operation Mode

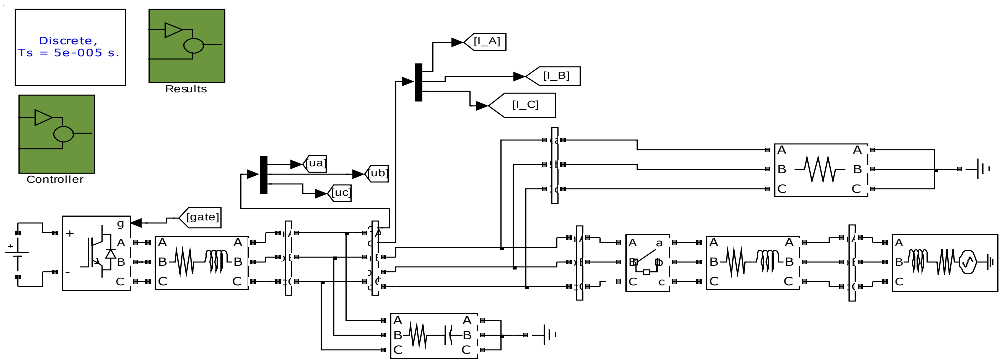

Fig.18 Simulation model for seamless transfer of the operation mode

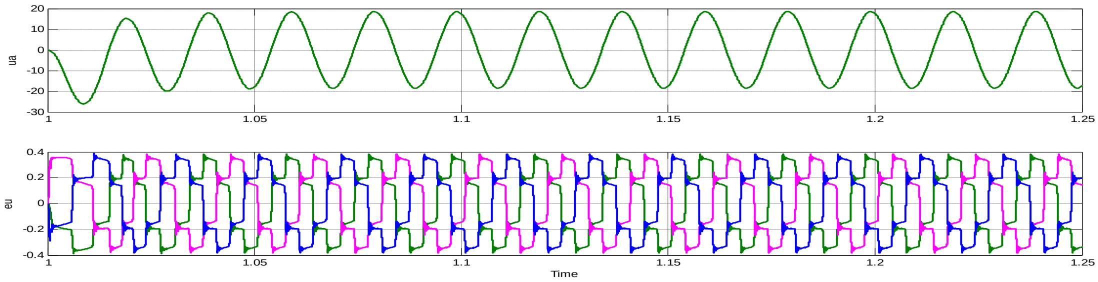

Fig .19 Simulation results for the stand-alone mode to the grid-connected mode at *t* = 1s.*ia*, its reference *i*ref , and the current tracking error *ei* and *uA*, its reference *u*ref , and the voltage tracking error *eu*.

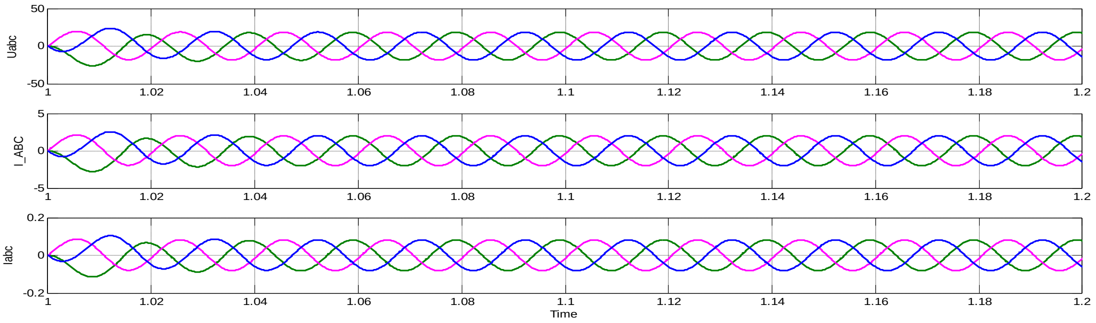

Fig .20. Simulation results for grid current reference *I*d* from 0 to 1.5 A at *t* = 3s. *ia*, its reference *i*ref , and the current tracking error *ei*. (b) *uA*, its reference *u*ref , and the voltage tracking error *eu*.

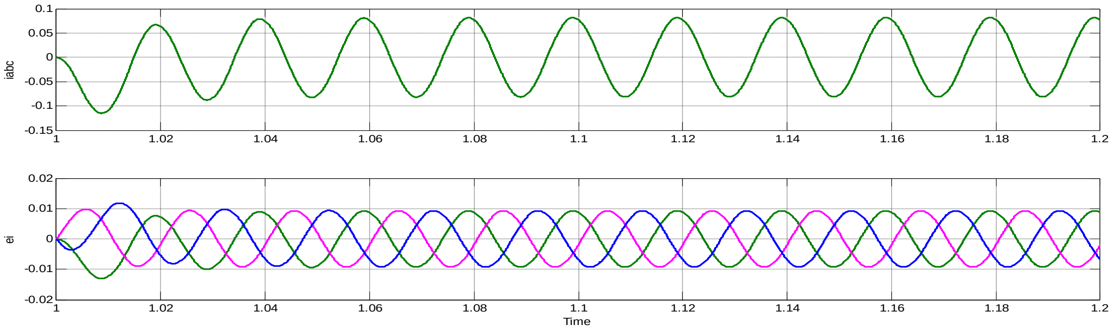

Fig .21. Simulation results for grid-connected mode to the stand-alone mode at *t* = 7.08 s. *ia*, its reference *i*ref, and the current tracking error *ei* and *uA*, its reference *u*ref , and the voltage tracking error *eu*.

VII. CONCLUSION

The cascaded current–voltage control strategy has been presented for inverters in microgrids. It consists of an inner voltage loop and an outer current loop and offers excellent performance in terms of thd for both the inverter native load voltage and also the grid current. Especially, when nonlinear and/or unbalanced loads are connected to the inverter in the grid-connected mode, the presented strategy significantly improves the thd of the inverter native load voltage and also the grid current at the same time. The controllers are designed using the H∞ repetitive control in this paper but will be designed using different approaches also. The presented strategy also achieves seamless transfer between the stand-alone and also the grid-connected modes. The strategy is 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 don't affect the grid. Simulation results under various situations have demonstrated the excellent performance of the proposed strategy.

VIII.ACKNOWLEDGEMENT

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