Hybrid Control of Multiple Inverters in an Island-Mode Distribution System

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Abstract **– Inverter-interfaced distributed generation (DG) offers the possibility of introducing power quality functions such as suppression of harmonic distortions. However, the traditional voltage- and frequency-droop methods of achieving load sharing work on average values and do not address waveform quality. This paper proposes a hybrid scheme for an island-mode system with many inverters. Inverters in close proximity operate in master-salve mode whereas load sharing between distant groups uses frequency droop. Communication between inverters is used within one group but not between groups, as such links would be impractical. The master inverter uses repetitive voltage control at the common node to suppress harmonic distortion. Slave inverters within a group also use repetitive control but in current mode. A simulation study, using EMTDC, has shown that the control system achieves good power quality and satisfactory coordinated operation.**

Keywords: island-mode distribution system, distributed generation, repetitive control, H^{∞} control

I INTRODUCTION

Distributed generation (DG) is of increasing importance as new forms of generation and new ownership of generation is encouraged by policy makers and market opportunities [1]. Many of the newer forms of generation need power electronic based interfaces. Photo-voltaic arrays and fuel cells require DC to AC inverters. Variable speed wind-turbines require AC to DC to AC conversion as do high speed gas-turbine driven generators.

An inverter has a quite different characteristic to a conventional electrical machine. Power export and waveform quality can be controlled with a relatively high bandwidth in an inverter. Indeed, control is necessary since an inverter has little short-time overload rating and close sharing must be enforced. Further, the inverter will have at least an inductive filter. This filter will have been chosen to present a high impedance to current emissions from the inverter at the switching frequency. However, this filter will still have a relatively large impedance to low-order harmonic distortion and so harmonic currents drawn by a non-linear load will cause voltage distortion to appear across this filter which will be common to other loads in the vicinity.

An electrical machine, on the other hand, has a power export that is controlled with modest bandwidth and waveform quality is set at design stage by the winding configuration. A low source impedance is used to ensure that fault current can be supplied (to clear faults) and to avoid harmonic current causing large harmonic voltage drops.

When the distributed generators are exporting into a large, strong grid then power export from a small DG unit can be set at will. In an island situation (a physical island or de-synchronisation because of a problem in a main grid) there is a need to match load and supply and provide a mechanism for sharing load between generating sets. For traditional electrical machines this is achieved through a governor (or control) setting that has a defined frequency droop as a function of real power supplied and a voltage droop with reactive power. For an inverter-interfaced system, it would be attractive, from a control point of view, to distribute reference signals to all of the inverters to ensure that the desired power matching and power sharing was achieved.

There have been several proposals for parallel operation of inverters in application areas such as UPS [2,9] and photovoltaic power supply system [3]. For inverters in close proximity there are methods such as: central mode, master-slave mode and distributed logic mode [4]. The close proximity has allowed control signals to be communicated between inverters.

There are communication-based sharing and control methods using a PLL to provide synchronisation and communication to provide sharing [5, 6]. Communication has the potential to provide a better degree of control; better in terms of response to load changes and better in terms of providing low distortion. However, with DG units spread over some physical distance this would require communication links with a degree of robustness that is not thought to be practical or economic at present.

To avoid communication, the frequency droop method has been adapted for inverter use [7, 8, 9]. The common system frequency is used to indicate the degree of load on the system. Some low bandwidth communication may well be used to supplement the system so that the load sharing can be adjusted (by setting the parameters of the droop characteristic) and to allow generators to be scheduled.

Communication should be used to whatever extent is practicable in a given environment. Thus, inverters connected to the same node of a distribution system could have inter-inverter communication of demand signals to provide rapid response sharing and suppression of harmonic distortion. But the impracticality of communication between inverters at remote nodes is recognised and the sharing between these groups is accomplished through more traditional means. Thus, a hybrid control scheme can be developed that uses as much of the potential of the inverter as can be realised in practice an at reasonable cost.

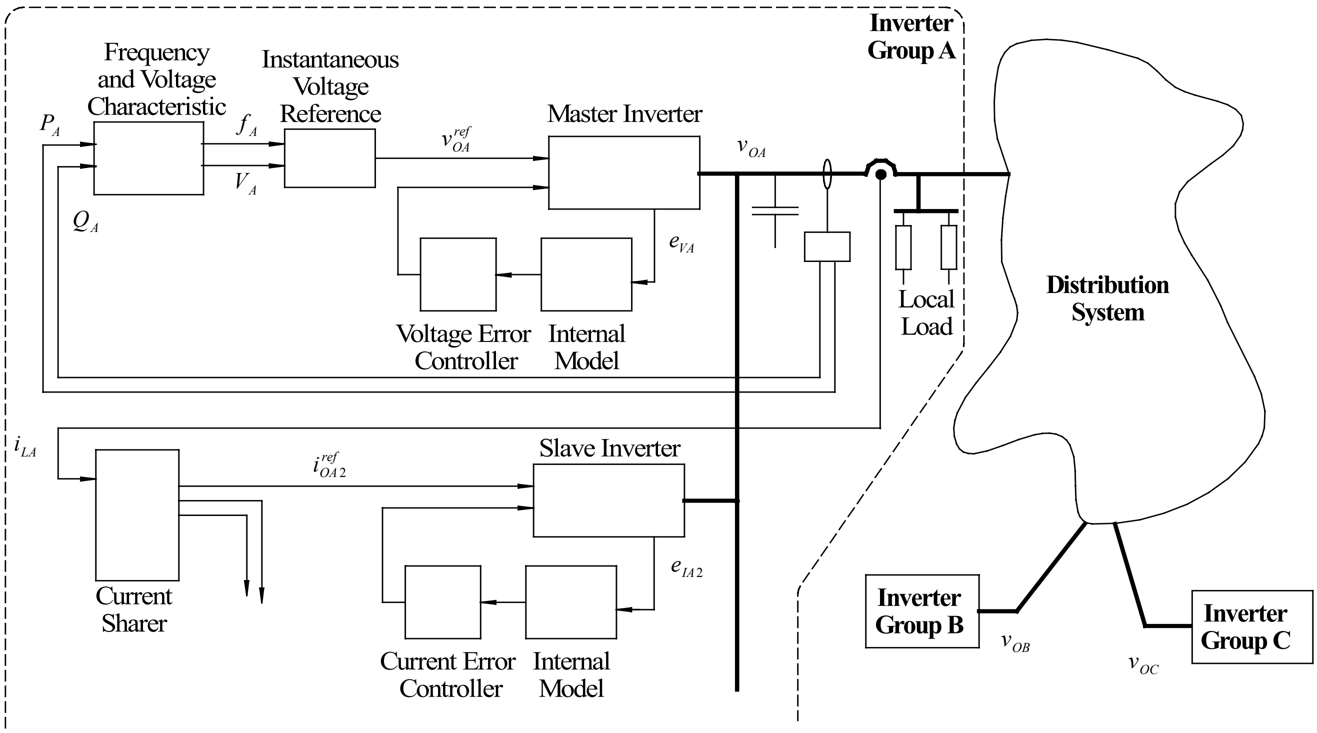


Figure 1 A multi-inverter system with inverters arranged in groups.

This paper will develop and test a hybrid, hierarchical, control scheme. It will employ droop characteristics between inverter groups and master-slave current sharing within groups. An inverter group is defined as those inverters connected to the same distribution system node. Within the group, voltage control will operate in a high bandwidth loop so that good waveform quality is ensured and current control will operate with tracking performance with the internal model based repetitive control technique. The loop will be designed to be robust to disturbances and plant uncertainty.

II A MULTIPLE INVERTER SYSTEM

Figure 1 illustrates the proposed arrangement of inverter groups with three groups, A, B and C. Group A is shown in detail. It consists of a master inverter and a number of slave inverters. The distinction between master and slave only applies to the control function allocated to the inverter. Technologically, the inverters are identical. Because the inverters of a group are physically close and connected to a common node, they can not all have control of their output voltage. Instead, one inverter is allowed to control the node voltage and is designated the master. This task need not be allocated to the same inverter at all times. The other inverters operate as slaves that inject current into the common node in order to take a share of the power generation.

III CONTROL SYSTEM DESIGN

A. Inter-Group Power Control

Inter-group power control is achieved through a droop characteristics. A conventional droop method is described as:

$$\omega_i = \omega_0 - m_i P_i \qquad V_i = V_0 - n_i Q_i$$

where ω_0 is the no-load frequency, V_0 the no-load voltage magnitude.

To provide equal (per unit) sharing, the slopes m_i and n_i are chosen to match the frequency and voltage differences between zero and full load for each node:

$$\Delta\omega = m_1\, P_{01} = m_2\, P_{02} = \dots$$
$$\Delta V = n_1\, Q_{01} = n_2\, Q_{02} = \dots$$

where P_{0i} & Q_{0i} are the total real and reactive power ratings of the set of inverters at node *i.* The droop characteristic provides voltage references for the inverters in phasor form which are converted to instantaneous voltage references in the normal way.

The conventional scheme will provide equal sharing of power generation between inverter groups but this may not be the best solution for the distribution system. Part of the rational for DG is that loads can be supplied by local generation and losses through distribution networks reduced. The proposal here is to modify the droop characteristic such that generation at nodes with a large local load is increased so that power exchanges through the distribution system are reduced. If the objective was for a node to meet its local load in full and then export power in proportion to its remaining capacity then the slope could be modified to:

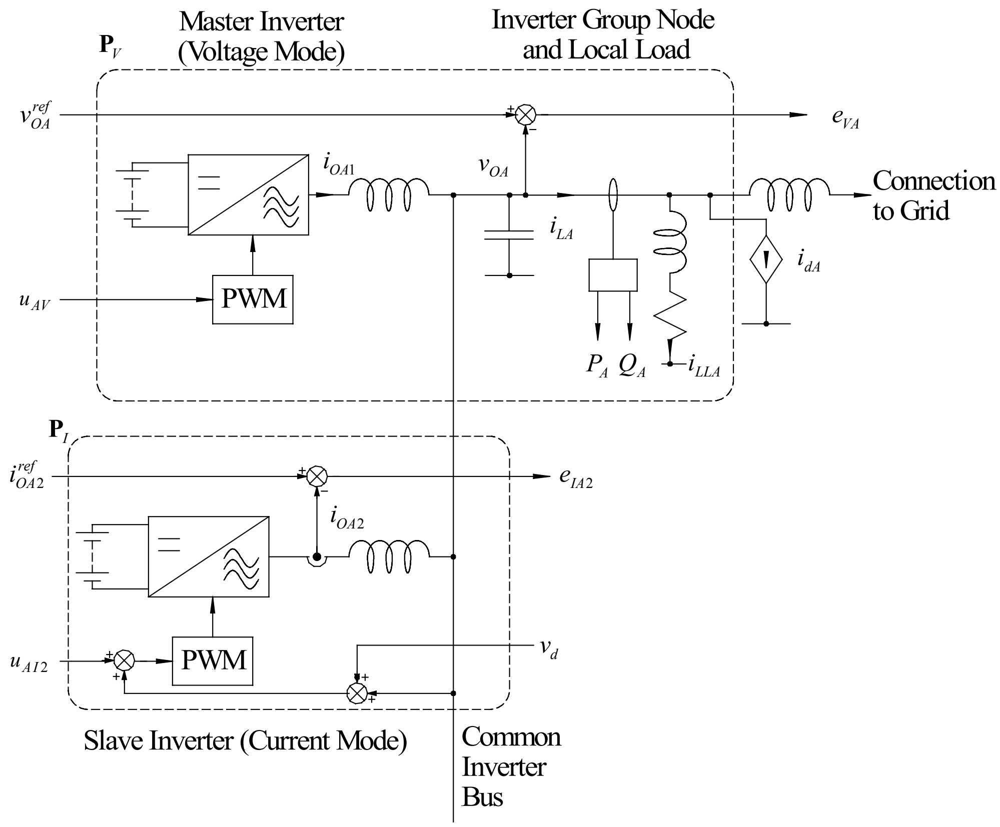


Figure 2 An inverter group comprising one master and several slaves connected to a common node.

$$m_i' = \frac{\Delta\omega}{P_{0i}} \cdot f(P_{Li})$$

where $f(P_{Li})$ is a descending linear function of load power P_{Li}. $f(P_{Li})$ is 1 at the normal load. Values of slope smaller than *m* indicate a preferred group that should produce more power to meet its local load.

B. Intra-Group Power Control

Inverters within a group share a common voltage node and are connected to it by an inductance. The inductance allows the current between the voltage source inverter and the voltage node to be controlled and also forms part of the filter to attenuate switching frequency current emissions. The filter is formed with the capacitor at the node. The electrical connections of the inverters and filters are shown in figure 2. Only one element can have control of the node voltage and so one inverter is designated as the master and operates with a voltage control loop. The voltage controller acts to follow the references set by the inter-group power controller. The intra-group power sharing is assured by making other inverters at the node slaves to the master. For this the overall output current is measured and each slave is controlled to provide a proportion of this current.

C. Voltage Controller Design

Good dynamic control of voltage in a three-phase system is often achieved by controlling in a rotating reference frame. A key advantage is that positive sequence fundamental frequency voltage and current terms appear stationary once transformed and therefore a *PI* controller can reduce the steady-state error to zero. However, negative sequence terms (arising from unbalance) appear as a double frequency term and completely eliminating error in this term is not possible. Similarly, a standard *PI* controller may not sufficiently suppress harmonic terms.

For unbalanced systems, a controller with a high gain at fundamental frequency operating in a stationary reference frame can be used. This controller will ensure that phase voltages remain balanced even when unbalanced currents are drawn through significant impedance. The gain can be formed by a second order transfer function. Although this second order function provides the gain necessary to provide good tracking of the fundamental term, it does not provide good rejection properties at harmonic frequencies. For this repetitive control can be used. Repetitive control offers good tracking performance for periodic references and good rejection of periodic disturbances [10,11].

The schematic diagram of figure 1 includes within the local control loops for voltage and current an internal model block in order to implement repetitive control. The internal model operates on the error term and provides a series of poles-pairs at multiples of a chosen frequency. The first several pole-pairs are close to the imaginary axis but at higher multiples the poles-pairs are brought into the left half-plane. The internal model can be implemented from a delay element (equal to the period of concern) in a positive feedback loop. Including a low pass filter in the loop provides the necessary shift to the left of the higher poles.

Figure 3 shows the arrangement of the control-loop and the internal model.

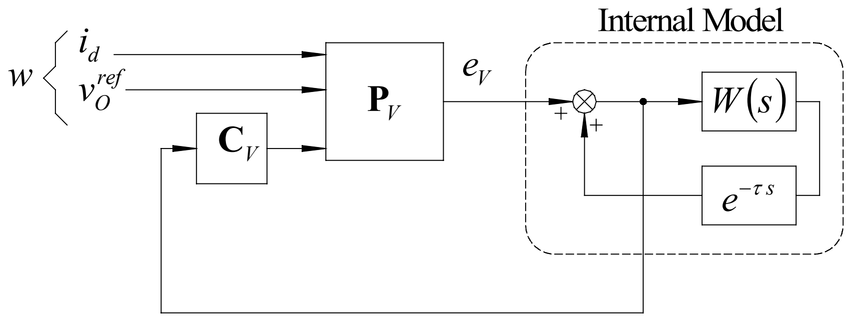


Figure 3 A repetitive control system, including internal model, for control of voltage of master inverter.

The delay element is in fact chosen to provide a delay of just less than the period of interest. Here a delay of τ = 19.9 ms was chosen (for a 50 Hz system) and combined with a first order low-pass filter.

$$W(s) = \frac{\omega_C}{\omega_C + s} \qquad \omega_C = 10^4 \text{ rad/s}$$

The plant, $\mathbf{P}_V$, is a state-space representation of the plant shown in figure 2.

$$\dot{x}_V = A_V x_V + B_V \begin{bmatrix} w_V \\ u_V \end{bmatrix}$$
$$y_V = C_V x_V + D_V \begin{bmatrix} w_V \\ u_V \end{bmatrix}$$

where

$$\begin{aligned} x_V &= \begin{bmatrix} i_{O1} & i_{LL} & v_O \end{bmatrix}^T \\ \begin{bmatrix} w_V \mid u_V \end{bmatrix}^T &= \begin{bmatrix} i_d & v_O^{ref} \mid u_V \end{bmatrix}^T \\ y_V &= \begin{bmatrix} e_V \end{bmatrix} \end{aligned}$$

The voltage tracking error is defined as $e_V = v_O^{ref} - v_O$.

The state-space model (A_V, B_V, C_V, D_V) was obtained in the normal way. The inductors were modelled with both series and parallel internal resistance to include core losses and properly characterise them at harmonic frequencies. The linear portion of the local load is included in the plant but subject to uncertainty. The non-linear portion of the local load is treated as a disturbance current.

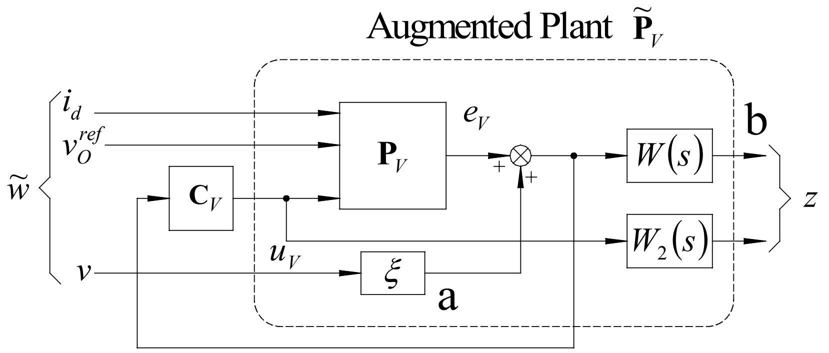


Figure 4 The standard H^∞ problem for the repetitive control system.

The controller, $\mathbf{C}_V$, that stabilises this loop must be robust to disturbance and plant uncertainty. For this reason the H^∞ design procedure is used to design the controller [12]. An augmented plant model, $\widetilde{\mathbf{P}}_V$, is formed, figure 4. This has an exogenous input, $\widetilde{w}$ and an external output, $\widetilde{z}$. An additional input, v and a scaling parameter, ξ are introduced. The low-pass feature of $W(s)$ results in a design with a small output voltage error in the low frequency range. $W_2(s)$ is chosen as a high-pass filter so as to reduce control gain in the high frequency range so that the controller practicable, $W_2(s) = \dfrac{0.02s}{s+10^5}$.

The standard H^∞ problem for $\widetilde{\mathbf{P}}_V$ is to find a stabilizing compensator such that the H^∞ norm of the transfer function from $\widetilde{w}$ to $\widetilde{z}$, $\left\|T_{\widetilde{z}\,\widetilde{w}}\right\|_\infty$, is smaller than a given bound and the H^∞ norm of the transfer function from a to b, $\left\|T_{ba}\right\|_\infty = \gamma$, must be smaller than 1. Moreover, $\gamma_O / (1-\gamma)$, where $\left\|T_{ew}\right\|_\infty = \gamma_O$, is minimized so as to obtain a small steady-state error. The standard H^∞ design tools in the Matlab toolbox were used to choose a stabilizing compensator $\mathbf{C}_V$ to meet these criteria.

D. Current Controller Design

Design of the controller for the current controlled inverters follows a procedure similar to the voltage controlled case. The plant, $\mathbf{P}_I$, shown in figure 2, includes a feed-forward term for the node voltage, v_O. It is considered that this term will not, in practice, be a perfect representation of the node voltage and so a disturbance voltage, v_d is included in the model. The current tracking error is defined as $e_I = i_O^{ref} - i_O$ and the state-space model of the plant is formulated as:

$$\dot{x}_I = A_I x_I + B_I \begin{bmatrix} w_I \\ u_I \end{bmatrix}$$

$$y_I = C_I x_I + D_I \begin{bmatrix} w_I \\ u_I \end{bmatrix}$$

where
$$x_I = [i_{O2}]$$
$$[w_I \mid u_I]^T = [v_d \quad v_I^{ref} \mid u_I]^T$$
$$y_I = [e_I]$$

The H^∞ design method is again applied to an augmented plant model and a stabilising controller, $\boldsymbol{C_I}$, found.

IV SIMULATION STUDY

The proposed hybrid control system was assessed through a series of time-step simulation studies using PSCAD/EMTDC. Two inverter groups were modelled each with 3 inverters. The system is shown in Fig. 5. Group A was composed of identical 30 kVA inverters (to give a total power of 90 kVA) and group B had similar inverters but with ratings of 15 kVA (to give a group total of 45 kVA). After an uncontrolled three-phase rectifier, output voltage of a high frequency three-phase AC generator (driven by a micro-gas turbine) has been converted to DC voltage. Thus DG model is not given in Fig.5. The switching frequency was chosen as 20 kHz. A four wire LC filter is formed at each node and a set of local loads provided. The filter inductors are modelled with a series winding resistance and a parallel core loss resistance. The load has a linear element (a star connected set of resistors) and a non-linear element (an uncontrolled diode rectifier and resistor). Between the two nodes is an interconnection line. The no-load frequency was set to 50.05Hz. No-load voltages were set to 330V for the Group A and 326V for the Group B. Other control coefficient were chosen as: m_A=0.0005Hz/kW, m_B=0.001Hz/kW, n_A=0.125V/kVar, n_B=0.25V/kVar, $f(P_{LA}) = 1.6 - 0.0075 \cdot P_{LA}$ and $f(P_{LB}) = 1.6 - 0.012 \cdot P_{LB}$. Two stabilizing controllers for the voltage control and the current control are designed as

$$\mathbf{C_V} = \frac{2.102\times10^5\ \mathrm{S}^5 + 2.313\times10^{10}\ \mathrm{S}^4 + 2.229\times10^{14}\ \mathrm{S}^3 + 1.264\times10^{18}\ \mathrm{S}^2 + 4.087\times10^{21}\ \mathrm{S} + 2.164\times10^{24}}{\mathrm{S}^6 + 1.013\times10^5\ \mathrm{S}^5 + 4.852\times10^9\ \mathrm{S}^4 + 1.233\times10^{14}\ \mathrm{S}^3 + 1.552\times10^{18}\mathrm{S}^2 + 7.761\times10^{21}\ \mathrm{S} + 6.277\times10^{24}}$$

and

$$\mathbf{C_I} = \frac{2.034\times10^5\ \mathrm{S}^2 + 2.045\times10^{10}\ \mathrm{S} + 1.088\times10^{13}}{\mathrm{S}^3 + 4.822\times10^4\mathrm{S}^2 + 6.589\times10^8\mathrm{S} + 6.541\times10^{10}}$$

respectively.

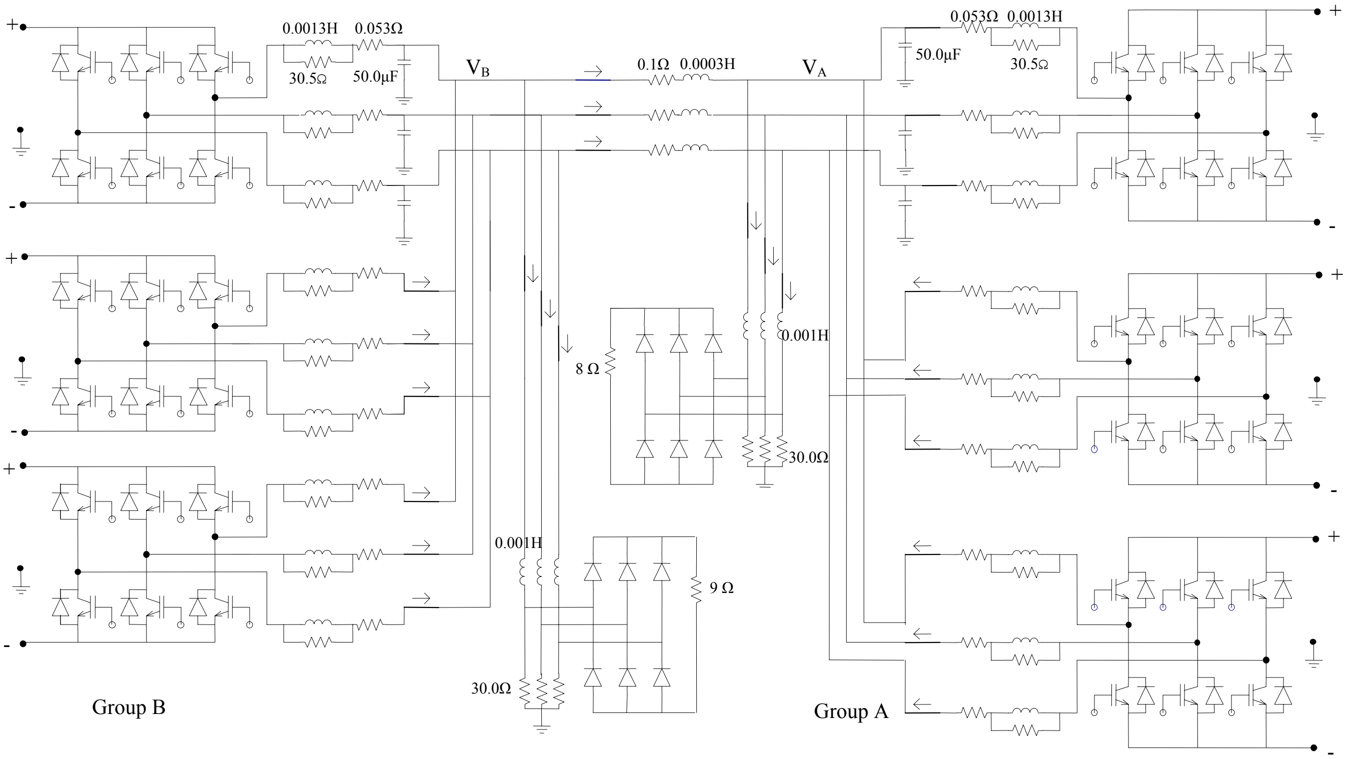


Figure 5 Circuit diagram of complete distribution system model

A. Voltage and Current tracking performance

Figure 6 shows the tracking performance of the voltage (master) controller during the start-up operation. It takes the repetitive controller around 5~6 cycles to reduce the voltage tracking error to a very small value and then the voltage follows its reference value with no phase-lag and very little distortion (caused by the non-linear load). Total harmonic distortion (THD, 2^{nd} to 31^{st} harmonics) at both nodes is kept below 0.6%. The current (slave) controller has a faster control response as shown in figure 7. The inverter current accurately follows the harmonic-rich current references. The current also includes some switching frequency components which are absorbed by the filter capacitors. Figure 8 shows that the two inverter groups supply different waveforms (different combinations of harmonic and fundamental current to their local loads) but that exchange between inverter groups occurs with fundamental current only. This is important for restricting power losses and occurs because the two node voltages are maintained as sinusoidal by the voltage controllers.

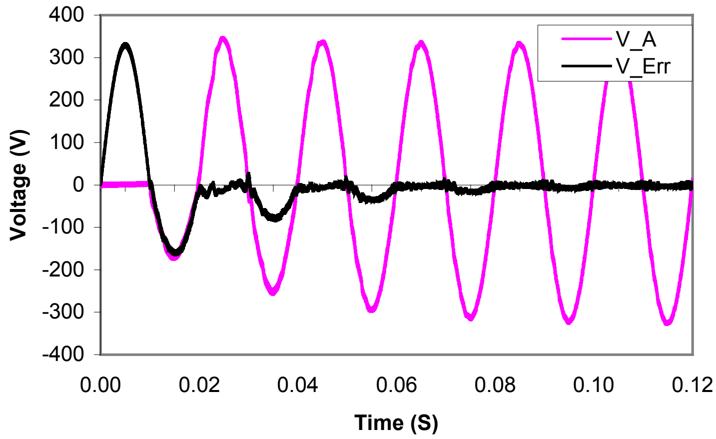


Figure 6 Voltage tracking performance

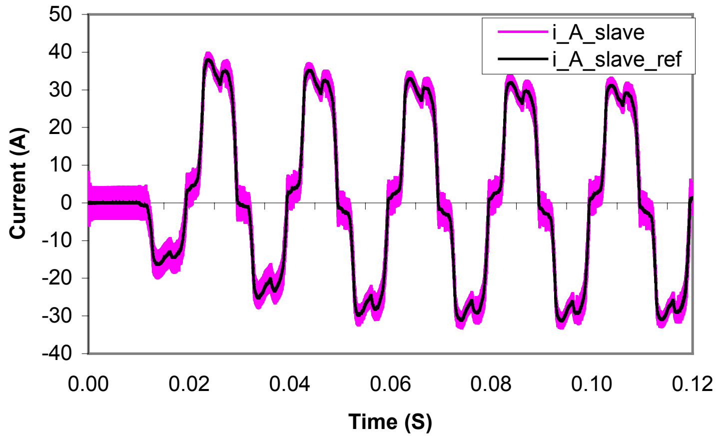


Figure 7 Current tracking performance

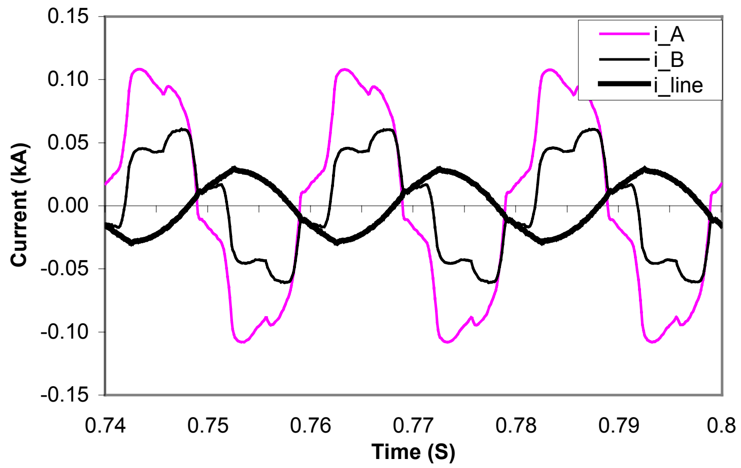
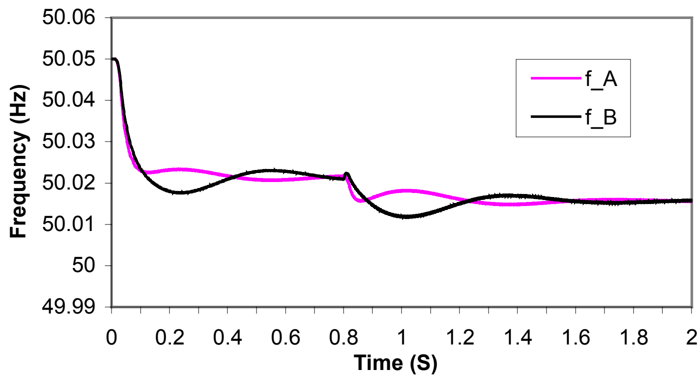


Figure 8 Inverter output current and interconnection line current

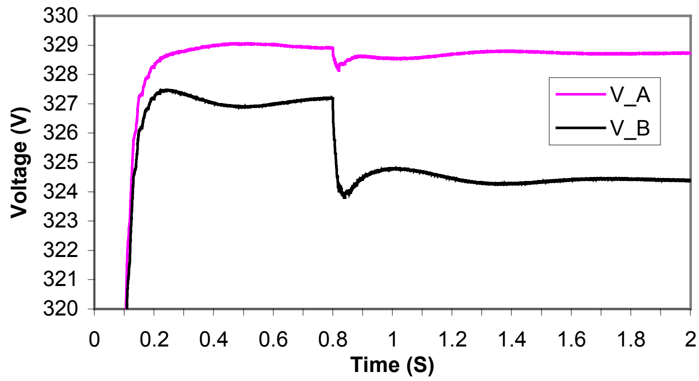
B. Dynamics of power sharing

A series of tests were conducted to test the dynamic performance of the real and reactive power sharing controllers. The example simulation shown here begins with a load of 39kW at Node A and a load of 36 kW at Node B. For the first test the resistance of the of the rectifier load at Node B is suddenly decreased so that the load at node B increases to 60 kW (the accompanying reactive power increases from 9kVar to 17kVar. Figure 9(a) shows that the frequencies of the two nodes initially converge to 50.022Hz after 0.7s and then, after the load is increased, the two frequencies fall to 50.015 Hz with a slightly oscillatory trajectory with a settling time of around 1s. Figure 9(b) shows how the voltage magnitudes at the two nodes settle after the increase in real and reactive power. Figure 9(c) shows how the power generation is shared between the two inverter groups. With conventional sharing, Group A should provide twice the power because it has twice the capacity of Group B but here the sharing has been modified to reduce the power exchange between nodes. There is an 11 kW exchange through the line. When the local load at Node B increases by 24 kW, it would be expected under conventional sharing that ⅔rd (16 kW) of that increase would be met by a transfer from the remote Group A but the modified sharing means most of the increase is met locally and the transfer only increases by only 11 kW.

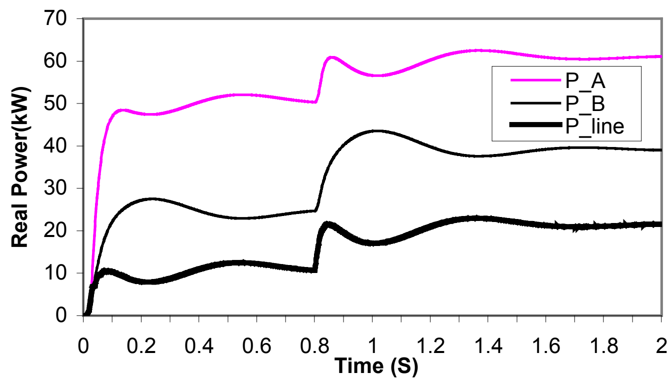
Reactive power sharing does not strictly follow the relative power ratings of the groups because of the line impedance. Also, voltage difference between two nodes is partly determined by the real power current. Thus in (d), when load reactive power at Node B increases, the reactive power output from inverters at the node decreases



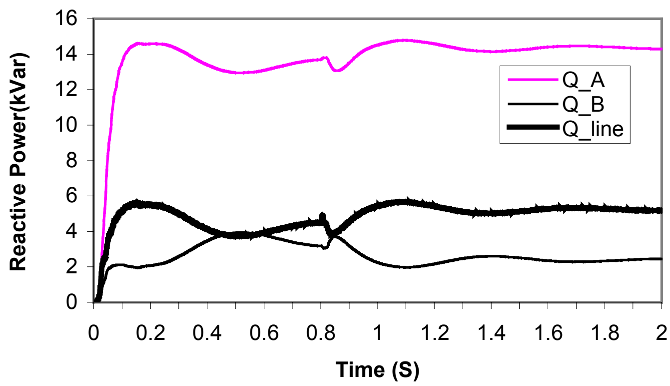
(a) frequency



(b) voltage magnitude

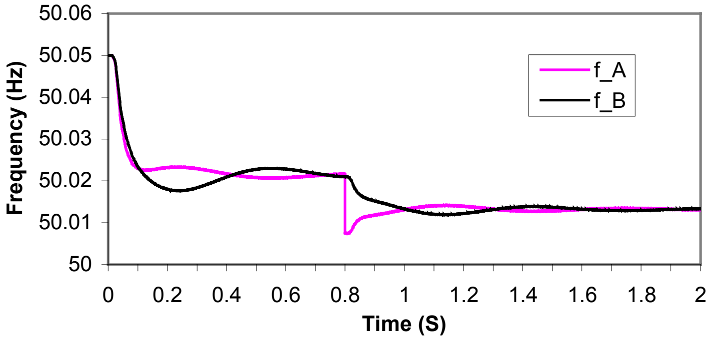


(c) real power

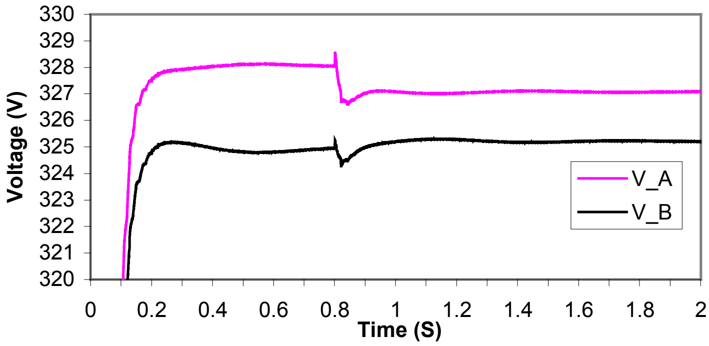


(d) reactive power

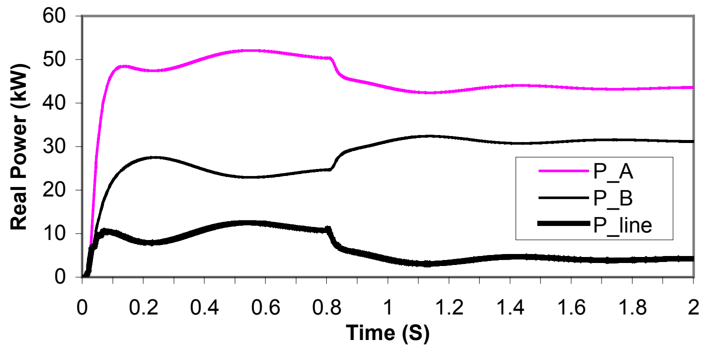
Figure 9 System response to nonlinear load increase.



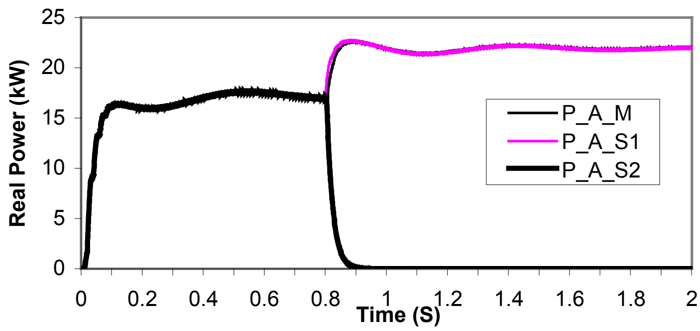
(a) frequency



(b) voltage magnitude



(c) real power

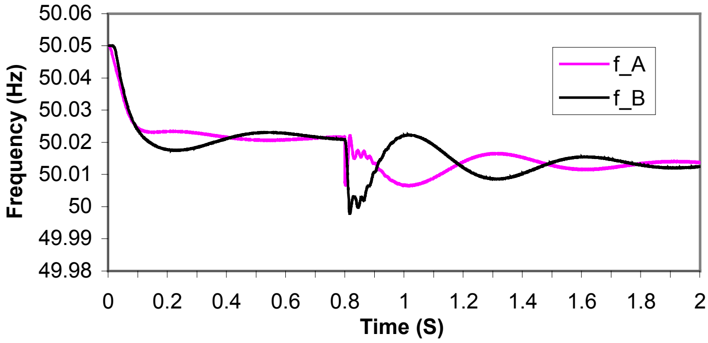


(d) real power of inverters of group A

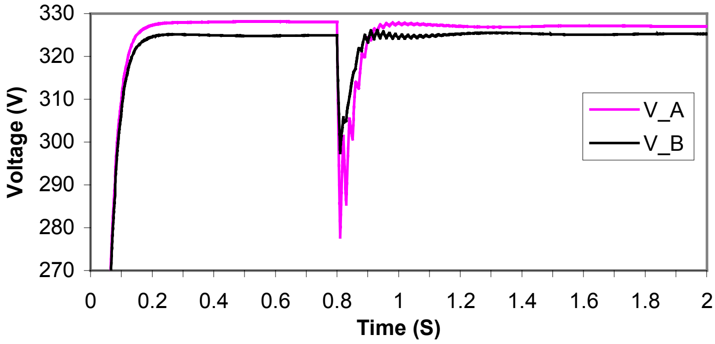
Figure 10 Shut down of a slave inverter of group A

Figure 10 give system response to the shut down of a slave inverter at group A. Since the total power rating available of group A has reduced with the loss of one inverter, power sharing is reallocated. Real power output from group A decreases from 50.4kW to 43.6kW while real power output from group B increases from 25.4kW to 31.8kW. Inside the group A, power output from two remain inverters increases from about 16.9kW to 21.8kW each.

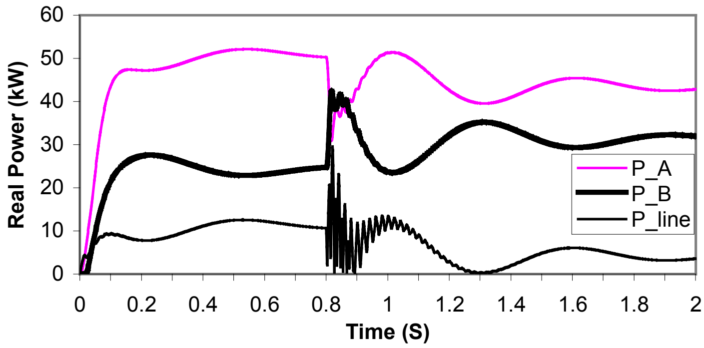
If a master inverter is taken out of service, a slave inverter can switch its operation from current control mode to voltage mode so that it can act as a master. However, it will take certain time for the internal model of the repetitive controller to establish a converged error (there will also be a delay in actually executing a change of controller but this is relatively small). Also, during the transient process, power sharing has a relatively higher frequency oscillation. There is, therefore, a considerable disturbance to the system following the shut down of a master inverter as shown in Figure 11.



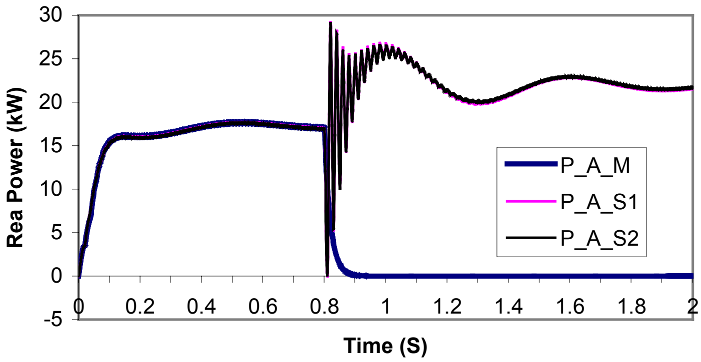
(a) frequency



(b) voltage magnitude



(c) real power



(d) real power of inverters of group A

Figure 11 Shut down of a master inverter of group A

C. Disturbance of voltage tracking

The initial convergence of the voltage controller was demonstrated in section A but it is important to establish how the tracking is disturbed by operation of the outer-loop power controllers that set the reference for the voltage tracking. Figure 12 gives responses of THD of the voltage at Node B to an increase of linear load (parallel impedance deceases from 30Ω to 5+j30Ω) and nonlinear load (resistance after the rectifier decreases from 9Ω to 4.5Ω). The THD converges to about 0.5%. This low value is the advantage by the use of repetitive control. Following the increase in load, there is a period of readjustment of the error stored in the internal model. It takes 5~6 cycles for the voltage to re-converge in both cases but the change of non-linear causes a much larger transient increase in voltage THD as might be expected.

Figure 13 shows that the shut down of the master inverter of group A causes a larger transient increase in voltage THD since a new voltage controller has to be established with an internal model initialised to zero.

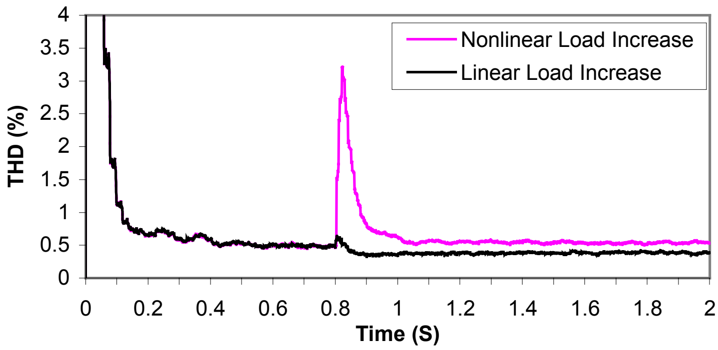


Figure 12 Voltage THD response to load increase

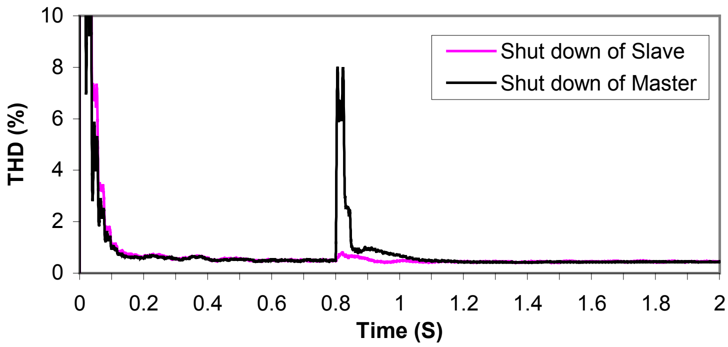


Figure 13 Voltage THD response to inverter shut down

V Conclusions

A hybrid control system has been proposed for an island-mode distribution system containing many inverters, some in close proximity and some not. The key features are that inter-group power sharing avoids communication links by using droop characteristics. These droop characteristics have been modified so that local loads are predominantly met by local generation and the remaining load is shared in proportion to power rating. Sharing between inverters in close proximity and connected to a common node is achieved through a master-slave arrangement. To provide good tracking of the current sharing reference in terms of both fundamental and harmonic current, repetitive control has been used. Repetitive control has also been used in master inverter to provide low distortion voltage waveforms at the common node even in the presence of substantial non-linear local load. A simulation study, using EMTDC, has shown that the control system achieves good power quality and satisfactory coordinated operation.

VI References

[1] N. Jenkins, R. Allan, P. Crossley, D. Kirschen and G. Strbac, *Embedded Generation*, IEE Power and Energy Series, London, 2000.

[2] J.-F. Chen and C.-L. Chu, “Combination voltage-controlled and current controlled PWM inverters for UPS parallel operation”, *IEEE Trans PE*, Vol 10, No.5 1995, pp.547-558.

[3] C.-C. Hua and J.-R. Lin, "Fully digital control of distributed photovoltaic power systems", *IEEE International Symposium on Industrial Electronics*, Vol. 1, 2001, pp.1-6.

[4] M. Prodanovic, T.C. Green and H. Mansir, “A survey of control methods for three-phase inverters in parallel connection”, *IEE Conference on Power Electronics and Variable Speed Drives*, 2000, pp.472-477.

[5] A. P. Martins, A.S. Carvalho and A.S. Araujo, "Design and implementation of a current controller for the parallel operation of standard UPSs", *IEEE IECON 21st International Conference on Industrial Electronics, Control, and Instrumentation*, Vol.1, 1995, pp.584-589.

[6] T. Kawabata, N. Sashida, Y, Yamamoto, K. Ogasawara and Y. Yamasaki, "Parallel processing inverter system", *IEEE Trans PE*, Vol 6, No.3 1991, pp.442-450.

[7] M.C. Chandorkar, D.M. Divan and R. Adapa, "Control of parallel connected inverters in standalone ac supply systems", *IEEE Trans. Industry applications*, Vol. 29. No. 1, 1993, pp.136-143.

[8] A. Tuladhar, H. Jin, T. Unger and K. Mauch, "Control of parallel inverters in distributed AC power systems with consideration of line impedance effect", *IEEE Trans. Industry applications*, Vol.36, No.1, 2000 , pp. 131-137.

[9] S. Duan, Y. Meng, J. Xiong, Y. Kang and J. Chen, "Parallel operation control technique of voltage source inverters in UPS", *IEEE Conference on Power Electronics and and Drive Systems*, 1999, pp.883-887.

[10] G. Weiss, Q.-C. Zhong, T. C. Green, and J. Liang, "H^∞ repetitive control of DC-AC converter in micro-grids", accepted for *IEEE Trans on Power Electronics.*

[11] J. Liang, T. C. Green, G. Weiss and Q.-C. Zhong, "Evaluation of repetitive control for power quality improvement of distributed generation", *IEEE 33rd Power Electronics Specialist Conference*, Vol.4, 2002, pp.1803-1808.

[12] G. Weiss and M. Hafele, "Repetitive control of MIMO systems using H∞ Design", *Automatica*, vol.35, no.7, 1999, pp.1185-1199.

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