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Modular *Plug'n'Play* Control Architectures for Three-phase Inverters in UPS Applications

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***Abstract*— In this paper a control strategy for the parallel operation of three-phase inverters in a modular online uninterruptable power supply (UPS) system is proposed. The UPS system is composed of a number for DC/ACs with *LC* filter connected to the same AC critical bus and an AC/DC that forms the DC bus. The proposed control is designated in two layers, individual layer and recovery layer. In individual layer, virtual impedance concept is employed in order to achieve active power sharing while individual reactive power is calculated to modify output voltage phases to achieve reactive power sharing among different modules. Recovery layer is mainly responsible for guaranteeing synchronization capability with the utility and voltage recovery. With the proposed control, improved voltage transient performance can be achieved and also DC/AC modules are allowed to be plugged in and out flexibly while controlling the AC critical bus voltage. Detailed control architecture, regarding individual layer and recovery layer, are presented in this paper. Also an experimental setup was built to validate the proposed control approach under several scenarios-case study.**

***Keywords*— Modular UPS system, *Plug'n'Play*, voltage restoration.**

I. Introduction

Nowadays, along with rapid development of advanced technologies in communication and data processing, a large number of modern equipment that require continuous and reliable power supply are encompassing into our everyday life [1]. Power reliability issues related to the utility have led to the increasing attention to different kinds of UPS systems.

Based on the International Electrotechnical Commission Standard 62040-3, a UPS system can be categorized in three types, namely offline UPS, online UPS and line-interactive UPS. Online UPS system is receiving more and more interest from both research and industrial fields due to its outstanding capability of suppressing the utility distortion [2]. Consequently, a cluster of online UPS structure has been proposed in [3]-[5].

Conventionally, an online UPS system is made up of an AC/DC, a DC/AC, a battery pack, a static bypass switch and isolating transformer, as shown in Fig. 1. In addition to controlling DC bus in the UPS system, the AC/DC also acts as the charger for the battery pack in normal condition (*Normal*). Otherwise, the battery pack will start to regulate the DC bus. In case of power failure (*Power Failure*), the static bypass

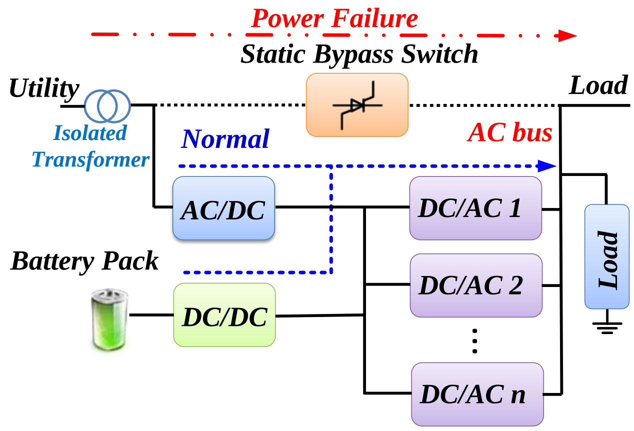

Fig. 1. Proposed Modular Online UPS Structure.

switch will be turned on in order to allow the utility to support the load directly [3].

Modular online UPS system (Fig. 1), as a kind of flexible, reliable architecture, is becoming more and more attractive in in both academic and industrial field [6]. Several inverter modules are operating at the same time to work as inverter stage of the online UPS system. Numbers of the parallel control technologies, such as centralized control [7], master-slave control [8], [9], averaged load sharing [10], allow the possibility of allowing inverter modules share both active power and reactive power of the load. Nevertheless, critical lines are mandatory in these control algorithms. Consequently, wireless droop controls methods [11]-[13] were proposed to avoid such kind of lines among the inverter modules. Normally, wireless droop control will modify the output voltage frequency or phase and voltage amplitude. As a result, actual output voltage of the UPS system will have some deviations compared to the given reference. Thus a recovery layer controller [14], [15] is required to recover the output voltage according to the given reference. Local data of each inverter module is required to transfer through the CAN bus network since the mature DSP technology offers a smaller communication network delay [16].

In this paper, a modular structure is employed with a number of inverter modules operating in parallel as shown in Fig. 1. Each inverter module is connected with the same AC bus with *LC* filter. System control is divided into two layers, namely individual layer (each inverter module) and recovery layer (UPS output voltage recover). Each individual layer controller for inverter module utilizes virtual impedance approach to achieve active power sharing among different modules. Inductor current and capacitor voltage are measured to achieve the proposed control. Moreover, regarding reactive power sharing issues, each DC/AC individual reactive power is calculated each phase respectively in order to modify phase angle of its own output, which is called "*phase-equal loop*". Consequently, UPS systems output voltage will have voltage drop and phase shift compared with the given voltage references (utility) and this is an undesired condition for an online UPS system. Hence a recovery layer controller is added in order to compensate voltage amplitude and phase errors by monitoring the proposed online UPS system AC bus voltage amplitude and phase angle information. Therefore, phase angle synchronization capability with the utility is finally achieved and the output voltage amplitude is tightly controlled under different load condition. On the other hand, this proposed control strategy allows any of the inverter modules to plug in or plug out at any time with small voltage oscillation. In order to validate the proposed control algorithm under several case-study scenarios, an experimental setup with dSPACE 1006 was built.

This paper is organized as follows. Section II presents the proposed system's structure and detailed control algorithm while Section III analyzed the system's stability. Section IV discusses the simulation results and experimental results are presented in Section V to validate the control algorithm feasibility. Finally, conclusions are given in Section VI.

II. Proposed Control Scheme for Online Modular UPS System

Compared with conventional online UPS system, each inverter module in the proposed modular online UPS system has a smaller power rate, which is an important issue that will reduce the system cost. Moreover, improved system expandability contributes to the low maintain cost of the system. On the other hand, the *LC* filter used avoids the resonance brought by *LCL* filter [17]-[19].

The proposed modular online UPS system, shown in Fig. 1, uses a three-phase-three-wire AC/DC to control the DC bus. The control is carried out in *dq* frame, which is presented in [20] detailed. And the phase angle detected by the AC/DC is also the phase reference for the inverter modules, which is transferred through the CAN bus network.

A. Individual Layer for Singel Inverter Module

The individual layer control is considered in $\alpha\beta$ frame, which is a typical double loop (voltage and current) control architecture as show in Fig. 2,

$$G_v(s) = k_{pv} + \frac{k_{rv}s}{s^2+\omega_o^2} + \sum_{h=5,7}\frac{k_{hrv}s}{s^2+(\omega_o h)^2} \qquad (1)$$

$$G_c(s) = k_{pc} + \frac{k_{rc}s}{s^2+\omega_o^2} + \sum_{h=5,7}\frac{k_{hrc}s}{s^2+(\omega_o h)^2} \qquad (2)$$

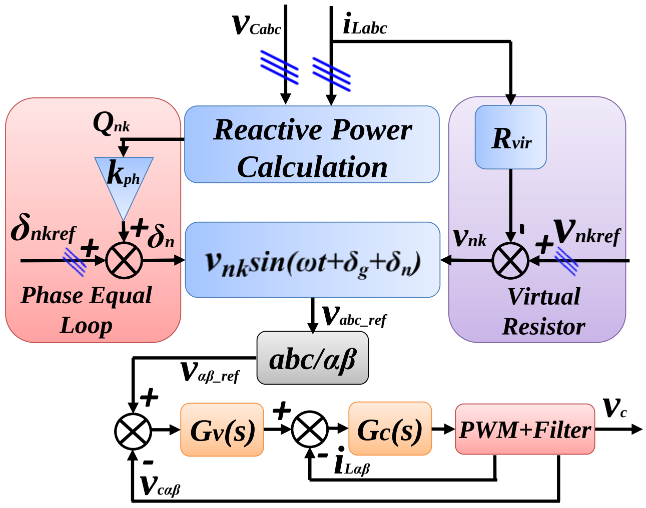

Fig. 2. Inverter Module individual layer control loop diagram.

being k_{pv}, k_{rv}, ω_o, k_{hrv}, h, k_{pc}, k_{rc} and k_{hrc} as voltage proportional term, fundamental frequency voltage resonant term, fundamental frequency, the h^{th} harmonic voltage compensation term, harmonic order, current proportional term, fundamental frequency current resonant term and the h^{th} harmonic current compensation term respectively. Hereby, nonlinear load condition is taken into consideration since PR controller has the ability to eliminate the voltage distortion due to the nonlinear load [21], [22]. Only 5^{th} and 7^{th} have been taken into consideration.

Moreover, virtual impedance and "*phase-equal loop*", referring to (3) and (4), are used to achieve parallel operation and active, reactive power sharing (shown in Fig. 2).

$$V_{nk} = V_{nkref} - R_{vir} i_{nLk} \qquad (3)$$

$$\delta_n = \delta_{utility\_k} + k_{ph} Q_{nk} \qquad (4)$$

Here n is the number of DC/AC module (1, 2, 3…N), k is the phase order (a, b, c), V_{nkref} is the nominal voltage reference, R_{vir} is the virtual resistor, $\delta_{utility}$ is the utility phase information of phase k, k_{ph} is the phase regulating coefficients and Q_{nk} is the reactive power of each phase of each inverter module.

Each phase voltage references are calculated and modified respectively, referring to (5), (6) and (7), making preparations for unbalance load compensation,

$$v_a = (V_{aref} - R_{vir} i_{La}) \cdot \sin(\omega t + \delta_{utility\_a} + k_{ph} Q_a) \qquad (5)$$

$$v_b = (V_{bref} - R_{vir} i_{Lb}) \cdot \sin(\omega t + \delta_{utility\_b} + k_{ph} Q_b) \qquad (6)$$

$$v_c = (V_{cref} - R_{vir} i_{Lc}) \cdot \sin(\omega t + \delta_{utility\_c} + k_{ph} Q_c) \qquad (7)$$

B. Recovery Layer for the Online UPS System

Due to virtual impedance, output voltage amplitude and phase angle of the UPS system is load type dependent. That means the deviations between UPS output voltage and the utility is varying in different load condition. So voltages must be recovered to the nominal value and synchronized with the

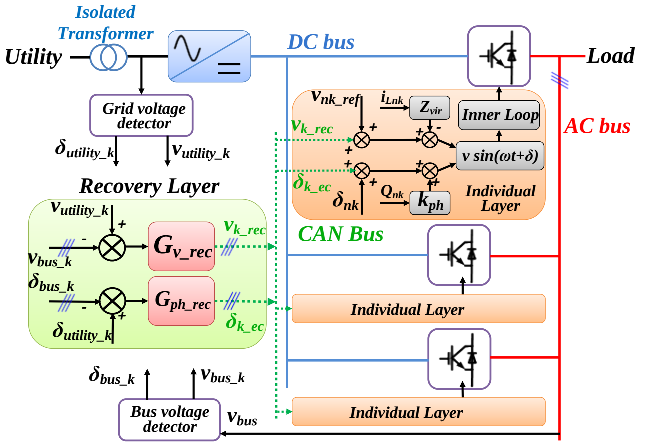

Fig. 3. Overall control diagram for the online UPS system.

utility without causing any voltage oscillation according to International Electrotechnical Commission Standard 62040-3. So a high-level controller, called "*recovery layer*" control is chosen to eliminate the deviations between UPS output voltage and the utility. Through the "*recovery layer*" control loop, compensated value for voltage references are obtained and broadcast through the CAN bus network. Considering that each phase may be faced with different load condition, the voltage references compensating values are calculated each phase respectively.

The overall control diagram is shown in Fig. 3. Instead of implementing the voltage recover control in each inverter module, the AC bus voltage of the UPS system is used,

$$v_{k\_rec} = \left(V_{utility\_k} - V_{bus\_k}\right) \cdot G_{v\_rec}(s) \tag{8}$$

$$\delta_{k\_rec} = \left(\delta_{utility\_k} - \delta_{bus\_k}\right) \cdot G_{ph\_rec}(s) \tag{9}$$

being v_{k_rec}, k, $V_{utility\_k}$, V_{bus_k}, G_{v_rec}, δ_{k_rec}, $\delta_{utility\_k}$, δ_{abus_k} and G_{ph_rec} as restoration value of voltage amplitude, phase order (a, b, c), RMS voltage reference of phase k in central controller (utility voltage amplitude), AC bus voltage RMS value of phase k, voltage compensation block transfer function, phase restoration value of voltage phase, phase reference in central controller of phase k (utility phase angle), AC bus voltage phase angle of phase k and phase compensation blocks transfer function respectively.

It can be seen that the recovery layer controller is only monitoring the AC bus voltage amplitude and phase angle all the time. Although without knowing the exact operating numbers of the inverter module, it can still calculate the recovered voltage amplitude value for each inverter module.

In this scenario, the compensation blocks are implemented by using two typical *PI*s, shown in (10) and (11),

$$G_{v\_rec}(s) = k_{pv\_rec} + \frac{k_{iv\_rec}}{s} \tag{10}$$

$$G_{ph\_rec}(s) = k_{p\delta\_rec} + \frac{k_{i\delta\_rec}}{s} \tag{11}$$

with k_{pv_rec} being the voltage proportional term, k_{iv_rec} being the voltage integral term, $k_{p\delta\_rec}$ being the phase proportional term and $k_{i\delta\_sec}$ being the phase integral term.

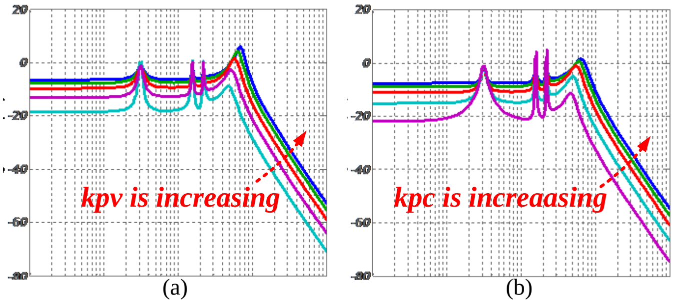

Fig. 4. Bode diagram of inner loop. (a) Bode diagram with variable k_{pv}. (b) Bode diagram with variable k_{pc}.

III. Stabilty Analysis

Since the system control is carried out mainly on two layers, critical parameters used in these two layers are analyzed respectively, namely individual layer control parameter and recover layer control parameter.

A. *Analysis of Individual Layer Control Parameter*

Based on Fig. 2, the voltage and current inner loop is considered in $\alpha\beta$ frame, whose transfer function is derived. In order to make the model more accurate, a delay block due to PWM and control is given,

$$G_{PWM}(s) = \frac{1}{1.5T_s s + 1} \tag{12}$$

where T_s is the PWM period. So by combining (1), (2) and (12), transfer function from reference voltage to output capacitor voltage is derived,

$$G(s) = \frac{d}{as^2 + bs + c} \tag{13}$$

with $a = LR_{Load}C$, $b = L + G_{current}G_{PWM}R_{Load}C$, $c = R_{Load} + G_{current}G_{PWM} + G_{voltage}G_{current}G_{PWM}R_{Load}$,

where L, C and R_{Load} are filter inductance, filter capacitance and load respectively. Consequently, *bode* diagram of the system is presented in Fig. 4. It can be observed that 0 dB is achieved on both fundamental frequency and harmonic frequency (5^{th} and 7^{th}). With the proportional term k_{pv} increasing, 0dB is guaranteed while bandwidth of the controller is increased. A similar performance is observed in the current loop, as shown in Fig. 4(b).

Since output voltage amplitude of the UPS system is decreased proportionally to the inductor current while considering a fixed virtual resistor value. According to the full load working condition, the virtual resistor value can be chosen as,

$$\left|\frac{i_L R_{vir}}{V_{\max}}\right| \le 0.1 \tag{14}$$

being i_L, V_{max} as the inductor current under full load condition and nominal output voltage amplitude respectively. Normally, the voltage oscillation should be limited under 10%. As for the "*phase equal loop*", it is analyzed together with the phase restoration loop since it is tightly related with output voltage's phase angle.

B. Analysis of Recover Layer Control Parameter

The control diagram shown in Fig. 3 is able to be represented by Fig. 5. By assuming that inner loop of each DC/AC module is well tuned and operated. $\boldsymbol{v}$ can be treated the same as $\boldsymbol{v_{bus\_k}}$. Similarly, $\boldsymbol{\delta}$ is able to be seen the same as $\boldsymbol{\delta_{bus\_k}}$. consequently, the control diagram is simplified as shown in Fig. 6(a).

$$v_{bus\_k} = \frac{G_{v\_rec}G_{delay}v_{utility\_k} + v_{nk\_ref} - R_{vir}i_{Lnk}}{1 + G_{v\_rec}G_{delay}} \quad (15)$$

Considering the dynamic performance of the system, the closed loop function is expressed as follows,

$$G_{voltage\_rec}(s) = -\frac{1.5R_{vir}T_s s^2 + s}{1.5T_s s^2 + (1 + k_{pv\_rec})s + k_{iv\_rec}} \quad (16)$$

Fig. 7(a) shows the *pz* map of voltage amplitude restoration control block. While k_{pv_rec} is moving from 0 to 2, one dominating pole moves obviously towards origin point while the second one tends to move inconspicuously towards boundary of stable area. Similarly, a simplified control diagram for phase restoration is derived as shown in Fig. 6(b), from which a mathematical model is able to be derived,

$$\delta_{bus\_k} = \frac{G_{ph\_rec}G_{delay}\delta_{ref\_r} + \delta_{ref} + G_{LPF}k_{ph}Q}{1 + G_{ph\_rec}G_{delay}} \quad (17)$$

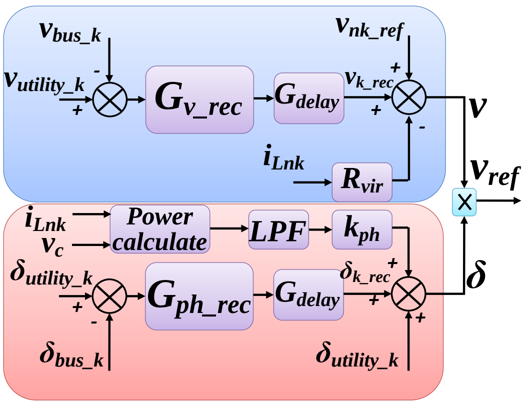

Fig. 5. Control loops for voltage restoration and phase restoration.

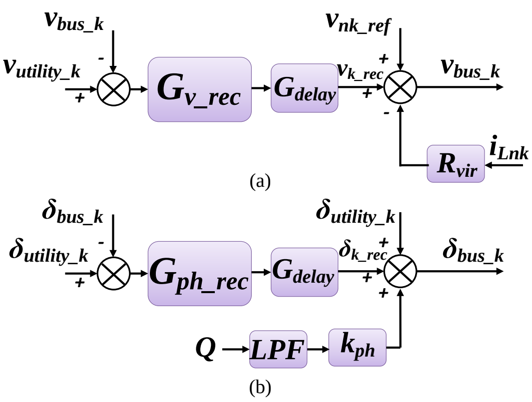

Fig. 6. Simplified recovery level control. (a) Amplitude recover. (b) Phase recover.

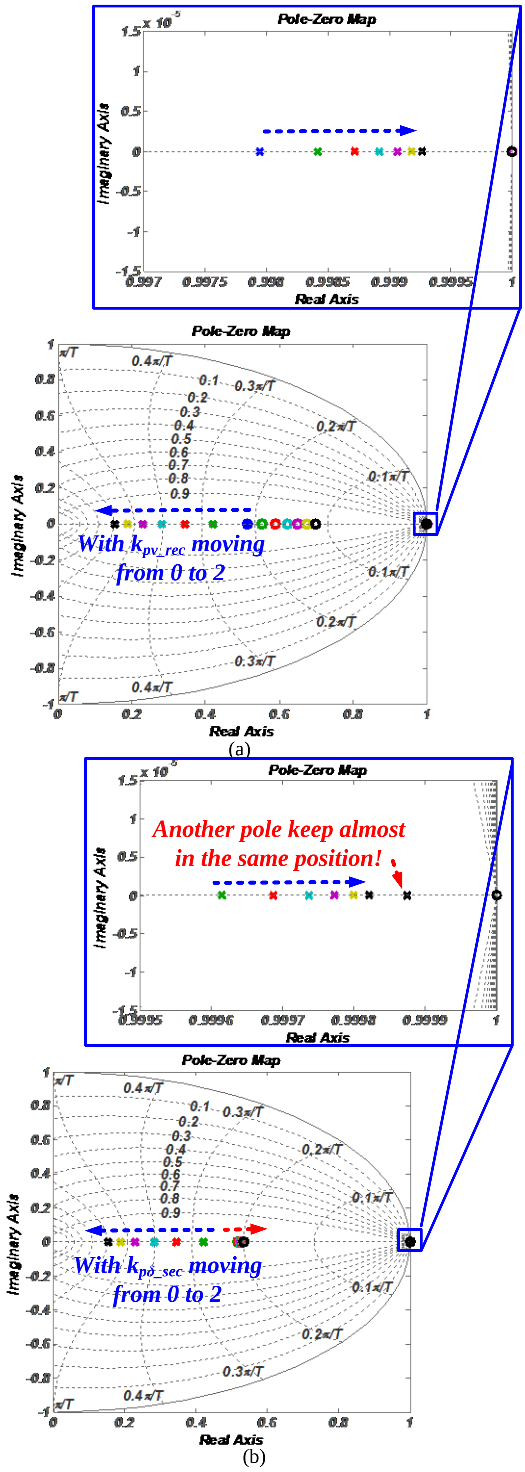

Fig. 7. *PZ* map for recovery control. (a) *PZ* map for variable k_{pv_rec}. (b) *PZ* map for variable $k_{p\delta\_rec}$.

Consequently, the dynamic system mathematical model is expressed as follows,

$$\delta = \frac{G_{LPF}k_{ph}}{1 + G_{ph\_rec}G_{delay}}Q \quad (18)$$

$$G_{LPF} = \frac{\omega_c}{s+\omega_c} \tag{19}$$

$$\frac{\delta}{Q} = \frac{ds^2+es}{fs^3+gs^2+hs+i} \tag{20}$$

$$G_{delay}(s) = \frac{1}{T_c s+1} \tag{21}$$

with the following parameters:

$d = 1.5T_c\omega_c k_{ph}$, $e = \omega_c k_{ph}$, $f = 1.5T_c$

$g = 1.5T_c\omega_c + k_{p\delta\_rec} + 1$, $h = \omega_c + k_{i\delta\_rec} + k_{p\delta\_rec}\omega_c$,

$i = k_{i\delta\_rec}\omega_c$, where ω_c and T_c are cut off frequency of power calculation low pass filter and communication delay time respectively. The phase regulation coefficient k_{ph} is on the numerator, which means that it doesn't affect system stability. Under different control parameters for phase restoration, *PZ* map in *Z* domain is presented in Fig. 7(b). It can be observed that a similar poles and zeros movements performance is obtained.

On the other hand, the communication delay T_c impacts on system stability is also analyzed. With increasing T_c, one dominating pole of phase restoration tends to move outside of stable region. And one zero is moving out of the unit circle, which means a slow transient performance, as shown in Fig. 8(a). Fig. 8(b) presents the *PZ* map for amplitude recovery. The same phenomenon is obtained.

IV. Simualtiong Results

A three-inverter-module online UPS system, as shown in Fig. 1, was established in the PLECS. The power sharing performance of the different modules is shown in Fig. 9. It can be see that with the modules plugging in and out, small oscillation in the AC bus voltage is observed. The AC bus voltage is tightly controlled. As mentioned in IEC 62040-3, the output voltage oscillation of an UPS system should be kept to minimum 10% compared with the nominal value. It can be observed that when any of the inverter modules is ordered to plug in or out, there is around 10V voltage overshoot or dip on AC bus, which is around 5% of the nominal RMS voltage value of the AC bus.

On the other hand, the phase synchronization capability of the system is also tested in the simulation, which is shown in Fig. 10. And the signals of phase *a* of both the utility and the UPS output voltage are monitored in the simulation. At the same time, errors between them are also calculated, which are shown in Fig. 10. Because of the recovery level control, the errors are eliminated gradually until it reaches zero as shown in Fig. 10.

V. Experimental Results

A modular online UPS system shown in Fig. 1 was built in the intelligent MicroGrids laboratory (Fig. 11) [23] with four *Danfoss* converters, shown in Fig. 11. Three were working as inverter modules and the last one is AC/DC. The control algorithm was established in MATLAB/SIMULINK and compiled into a dSPACE 1006 platform for real-time control of the experimental setup. A list of critical parameters that have significant effect on the system performance is presented in Table I. Experiments, including both steady and transient operation, were carried out to prove the proposed approach feasibility.

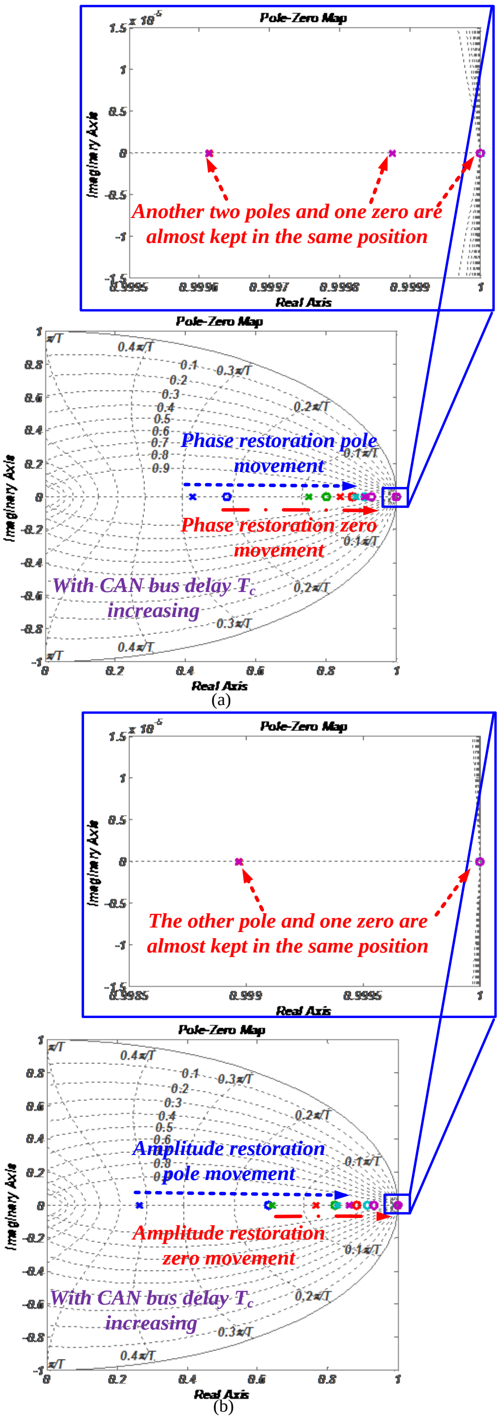

Fig. 8. Communication delay impact on voltage amplitude and phase restoration control. (a) Phase restoration. (b) Amplitude restoration.

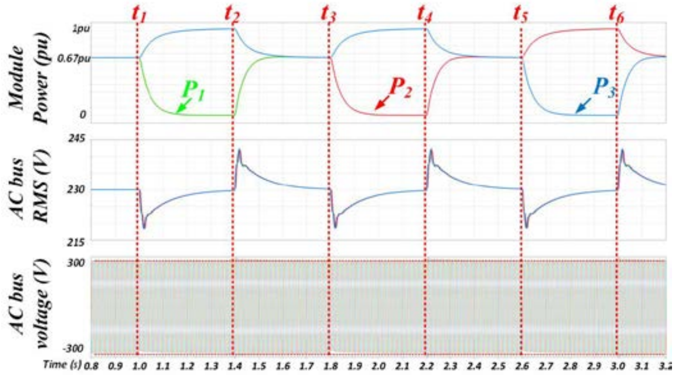

Fig. 9. Power and AC bus voltage performance during the transient process when one module plugs in or out.

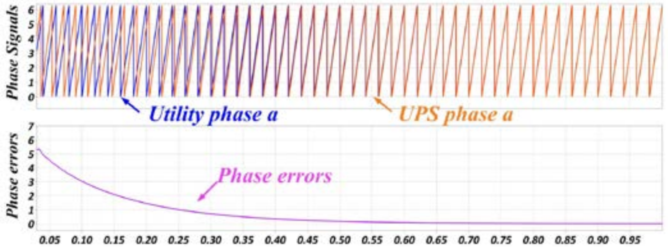

Fig. 10. Synchronization capability with the utility (Phase *a*) in simulation.

TABLE I. PARAMETERS OF EXPERIMENTAL SETUP

Symbol	Parameter	Values
	Converters	
f_{sw}	Switch frequency	10kHz
L	Filter inductance of DC/AC module	1.8mH
C	Capacitor of DC/AC module	27uF
	Inverters Control Parameters	
k_{pv}	Proportional voltage term	0.55
k_{rv}	Resonant voltage term	70
k_{5rv},k_{7rv}	5th, 7th resonant voltage term	100,100
k_{pc}	Proportional current term	1.2
k_{rc}	Resonant current term	150
k_{5rc},k_{7rc}	5th, 7th, resonant current term	30,30
V_{ref}	Reference voltage	230V (RMS)
	Secondary Control	
k_{pv_rec}	Proportional voltage term	3.2
k_{iv_rec}	Integral voltage term	30.5
$k_{p\delta\_rec}$	Proportional phase term	0.2
$k_{i\delta\_rec}$	Integral phase term	9

A. Power Sharing Performance

As show in Fig. 12, in linear load condition, inverter module #3 is ordered to plug in at t_a and plug out at t_b. It can be observed that the active power is well shared among the inverter modules. Furthermore, the power sharing performance under nonlinear load condition was also tested, as shown in Fig. 13. With module plugging in or out, both active power and reactive are shared equally among the modules in both steady and transient process.

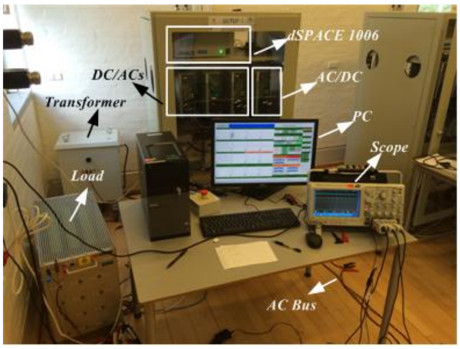

Fig. 11. Experimental setup.

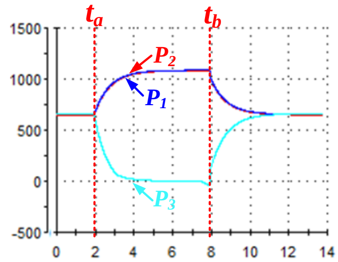

Fig. 12. Active power of 3 inverter modules in linear load condition.

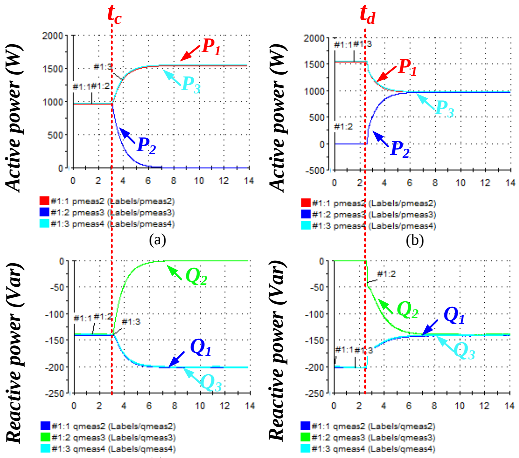

Fig. 13. Power of 3 inverter modules in nonlinear load condition. (a) Inverter module #3 plugs out (active power). (b) Inverter module #3 plugs in (active power). (c) Inverter module #3 plugs out (reactive power). (d) Inverter module #3 plugs in (reactive power).

B. Voltage Restoration Performance

Fig. 14 presents the voltage amplitude restoration performance of the AC bus in the system due to module plug in and out. It can be observed that when inverter module #3 plugs out, the voltage dip is quite small and recovered fast (Fig. 14 (a)). On the other hand, when it plugs into the system again, there is a voltage overshoot on the AC bus. And after around 1 utility cycle (0.02s), the voltage amplitude is recovered to the nominal value. Furthermore, the voltage recover performance under nonlinear load condition is also tested as shown in Fig. 15. It can be observed that the AC bus voltage is well tightly controlled and it takes a bit more time to recover the voltage when inverter module #3 plugs in, which is around 0.08s.

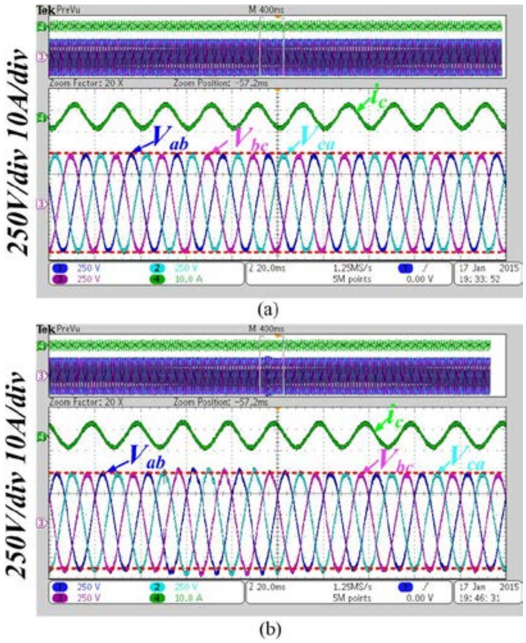

Fig. 14. UPS line to line voltage and phase *c* current under linear load condition. (a) Inverter module #3 plugs out. (b) Inverter module #3 plugs in.

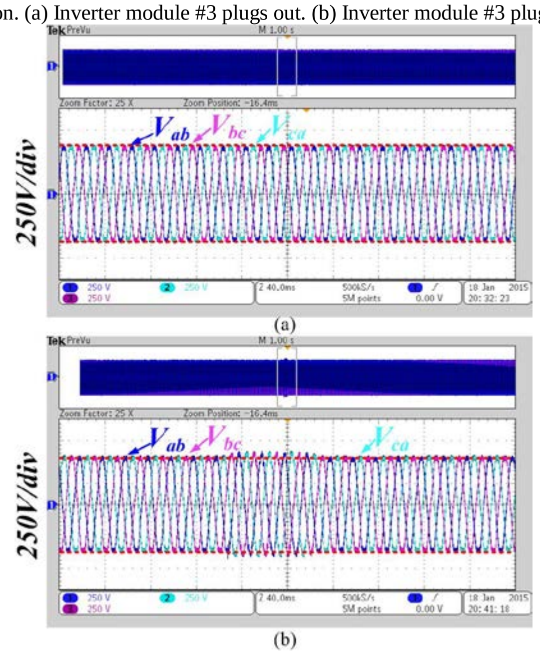

Fig. 15. UPS line to line voltage under nonlinear load condition. (a) Inverter module #3 plugs out. (b) Inverter module #3 plugs in.

C. *UPS Output Terminal Test*

The modular UPS system was also tested as a whole system. Load was connected with the AC bus and a step was carried out in order to test the AC bus control performance. In Fig. 16, at $\boldsymbol{t_e}$, the load was connected to the AC bus suddenly. It can be seen that there is a small voltage dip on the AC bus. After around 20***ms***, the voltage amplitude is recovered. At $\boldsymbol{t_f}$, load was turned off suddenly and around 20***ms*** is requited to recover the voltage amplitude.

D. *Synchronizing Test with the Utility*

In order to have a smooth bypass process for the proposed modular online UPS system, the AC bus voltage must be kept tightly synchronized with the utility. The synchronization performance was tested under linear load condition, which is presented in Fig. 17. It can be observed that during the whole synchronization process, the AC bus voltage is kept stable without any oscillation. Since the initial phase error is set to be π, the error is reduced gradually until it reaches zero as shown in Fig. 17 due to the recover layer control. On the other hand, the synchronization capability was also tested under the nonlinear load condition, which is presented in Fig. 18. It can be seen that a similar performance is obtained.

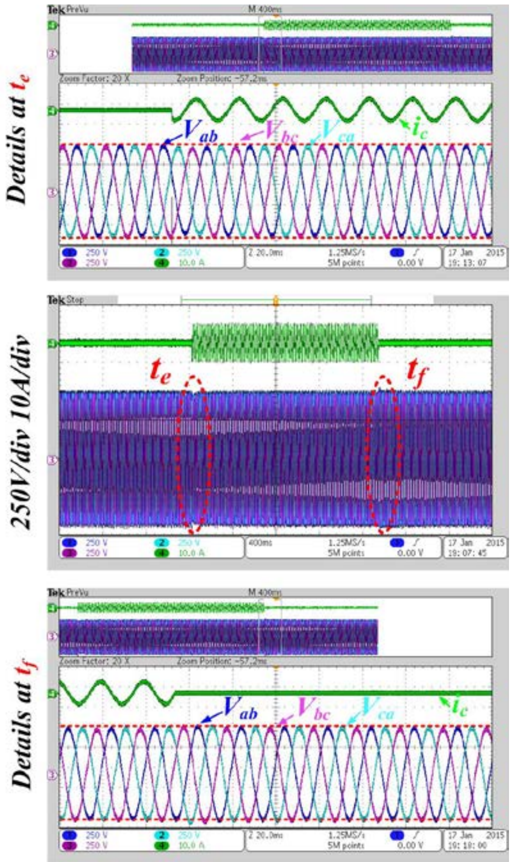

Fig. 16. UPS line to line voltage performance under load step test.

VI. Conclusion

In this paper, a control strategy intended for a modular online UPS system was developed with the capability of *plug'n'play*. With the inverter modules starting or stopping, the proposed recovery layer is able to control the AC bus tightly and make sure that the AC bus voltage is tightly synchronized with the utility. Both active and reactive power sharing performance is validated through experiments results in both steady and transient process. Two main load conditions, namely linear load and nonlinear load, were also tested. With the modules plugging in or out, the AC bus voltage is well controlled. And the transient time duration is also tightly controlled and it meets the standard IEC-64020-3. Experimental results are presented to support the proposed control approach performance.

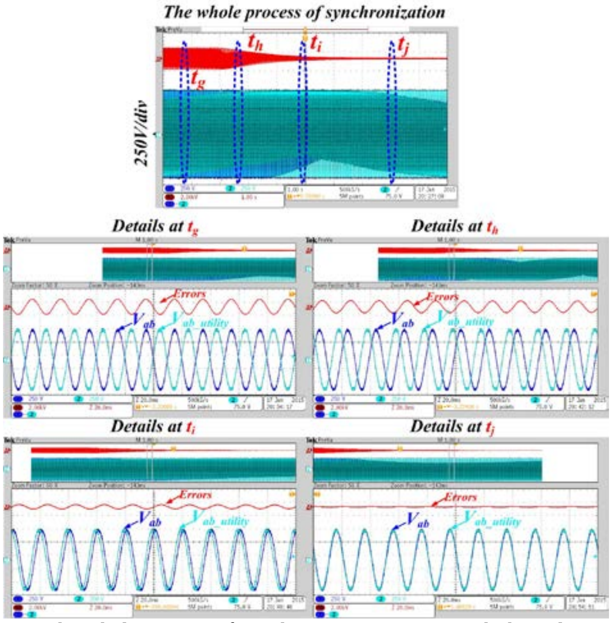

Fig. 17. The whole process of synchronization process with the utility under linear load condition.

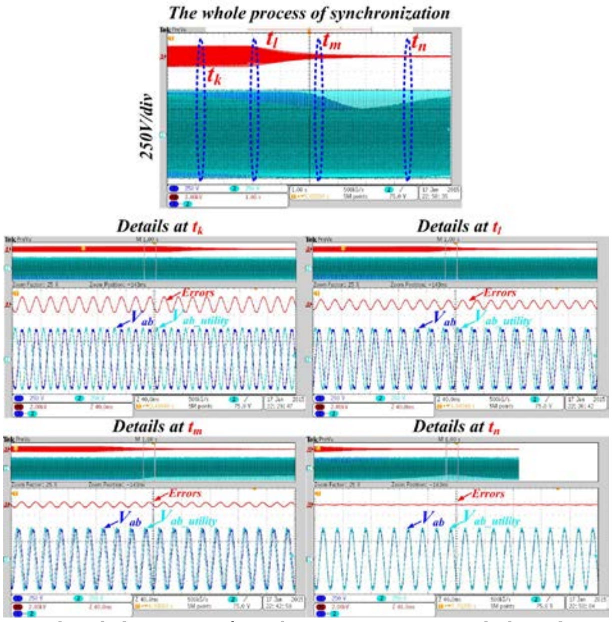

Fig. 18. The whole process of synchronization process with the utility under nonlinear load condition.

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