

An Effective Solution for Regeneration Protection in Uninterruptible Power Supply

Lu, Jinghang; Guerrero, Josep M.; Savaghebi, Mehdi; Ghias, Amer M.Y.M.; Guan, Yajuan; Hou, Xiaochao; Vasquez, Juan C.

Published in:
IEEE Transactions on Industry Applications

DOI (link to publication from Publisher):
[10.1109/TIA.2019.2900601](https://doi.org/10.1109/TIA.2019.2900601)

Publication date:
2019

Document Version
Accepted author manuscript, peer reviewed version

[Link to publication from Aalborg University](#)

Citation for published version (APA):
Lu, J., Guerrero, J. M., Savaghebi, M., Ghias, A. M. Y. M., Guan, Y., Hou, X., & Vasquez, J. C. (2019). An Effective Solution for Regeneration Protection in Uninterruptible Power Supply. *IEEE Transactions on Industry Applications*, 55(3), 3055-3065. Article 8645693. <https://doi.org/10.1109/TIA.2019.2900601>

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal -

Take down policy

If you believe that this document breaches copyright please contact us at vbn@aub.aau.dk providing details, and we will remove access to the work immediately and investigate your claim.

An Effective Solution for Regeneration Protection in Uninterruptible Power Supply

Jinghang Lu, *Member, IEEE*, Josep M Guerrero, *Fellow, IEEE*, Mehdi Savaghebi, *Senior Member, IEEE*, Amer M.Y.M.Ghias, *Member IEEE*, Yajuan Guan, *Member, IEEE*, Xiaochao Hou, *Student Member, IEEE*, Juan C. Vasquez, *Senior Member, IEEE*

Abstract – In this paper, a regeneration protection solution is proposed to address the DC-link overvoltage issue and the unequal power sharing in the parallel Uninterruptible Power Supply (UPS) systems. First, a DC-link Voltage Protection (DCVP) control strategy is proposed to protect the inverter against the excessive DC-link voltage that may trigger the protection mechanism of the UPS system. In addition, an active power sharing control strategy by regulating the virtual resistance is proposed to solve the circulating current caused by UPS regeneration issue. Finally, the feasibility of the proposed regeneration protection solution is verified by experimental results from the parallel UPS system prototype.

Index Terms-- Active power sharing, DC-link voltage protection; Uninterruptible Power Supply (UPS); Virtual resistance.

I. INTRODUCTION

This widespread application of the Uninterruptible Power Supply (UPS) systems in critical sectors, such as data centers, financial institutions, cloud computing division, etc. [1], has continuously driven the UPS market to be growing in the past few years. Meanwhile, the reliable, secure and efficient requirement for uninterruptible power propels engineers and researchers into the UPS technology advancements [2].

According to IEC 62040-3 standard [3], UPS systems are classified into on-line, off-line and line-interactive topologies. In an on-line UPS system, the load is always powered by the inverter regardless of the grid condition. The only exception is when an overloading happens and the bypass switch connects the load to the grid [4]. In the off-line and line-interactive UPS systems, however, the load power is mainly supplied from the grid or a combination of the inverter and the grid. Due to its excellent characteristic in eliminating voltage irregularities, frequency variations, electromagnetic interference /radio-frequency interference line noise, and other grid issues, the on-line UPS systems have received more attention than other topologies and are increasingly installed in the data centers and financial institutions, etc.[5-8]

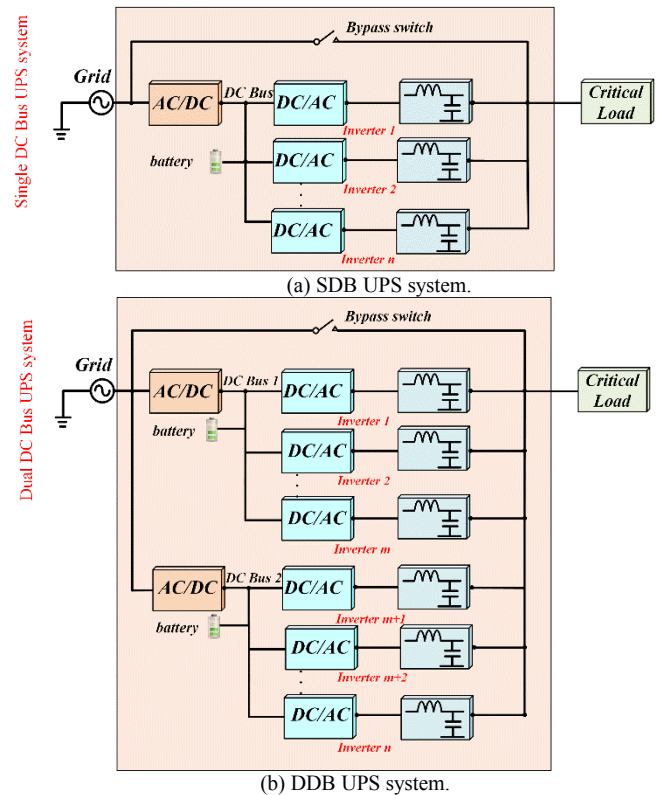


Fig. 1. Categories of parallel UPS system.

The on-line UPS system is comprised of an AC/DC rectifier, a DC/AC inverter, a battery and a static bypass switch [9]. Normally, a unidirectional power factor correction (PFC) circuit [10] is adopted as the AC/DC rectifier from the point of view of reducing the cost [3, 11]. Meanwhile, the two-level PWM converters are adopted for the DC/AC inverters. For the normal operation of the UPS system, the load is continuously supplied by the combination of AC/DC rectifier and DC/AC

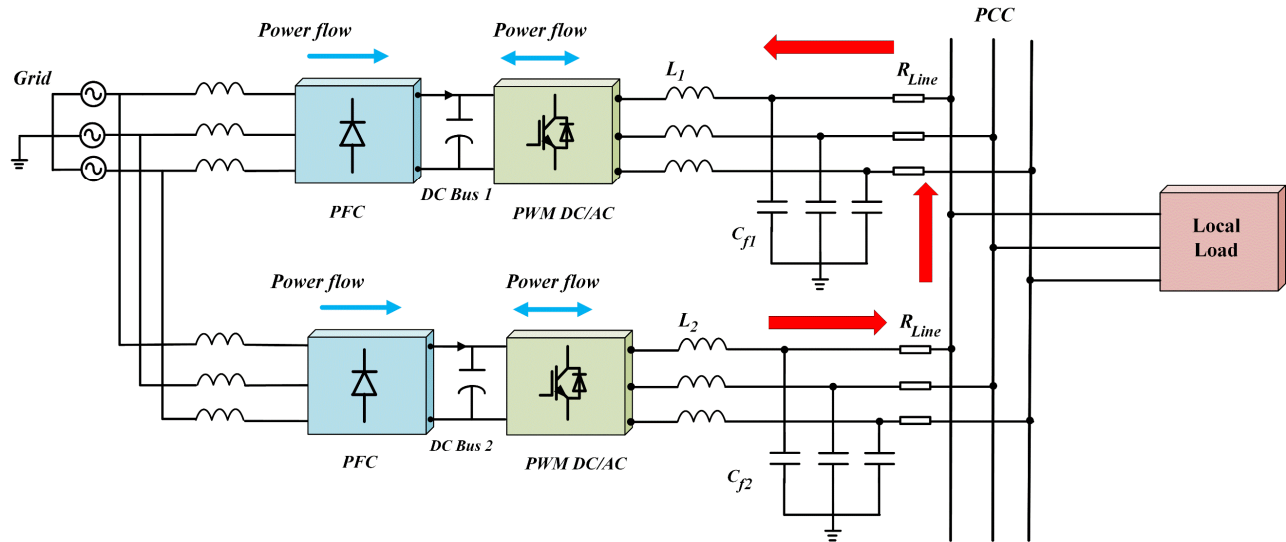


Fig. 2. Active power feeding in the DDB UPS system.

inverter [12]. In this way, the critical load is isolated from the grid and, therefore, it is immune from the power issues, such as temporary frequency variations and voltage irregularities in the grid. Bypass switch needs to be closed in case of overloading and circuit failure of the on-line UPS system [4]. By parallel connecting multiple inverters, the on-line UPS can provide more reliable power supply to the critical load. The parallel UPS systems can be further divided into Single DC Bus (SDB) and Dual DC Buses (DDB) UPS systems, as is shown in Fig. 1(a) and (b), respectively [3]. In the SDB UPS system, all the inverters are linked to the only DC link; whereas the DDB UPS system assigns the inverters into two DC links. By comparison of these two topologies, it is easily found that the DDB UPS system presents a higher redundancy, reliability, and flexibility compared with the SDB one, but at the expense of higher cost [13, 14].

Until now, most of the works in the literature have just focused on the normal operation of the DDB UPS system. Under light load, fault or temporary overvoltage situation in the DDB UPS system, the output voltage difference in the inverters inevitably leads to the active power feeding from a higher to lower output voltage of the UPS inverters [15]. Because the unidirectional power rectifier (unidirectional PFC circuit) is implemented for the AC/DC converter, the feeding active power cannot be delivered back into the grid. As a result, this feeding power causes the increase of the DC-link voltage, provokes the unequal active power sharing, and may even damage the DC-link capacitor. This issue can be eliminated with the regeneration protection solution, where a DC-link Voltage Protection (DCVP) method and a power-sharing strategy are implemented in DDB UPS system. Up to now, the research on the regeneration protection solution is quite limited. In order to protect the DC-link, a dissipating resistor may be connected at the DC link. However, the efficiency of the system is greatly reduced, which is not

beneficial for the on-line UPS system. In [15], a method based on rising the DC-link voltage in case of active power feeding is proposed. However, the dynamic response of this method is too slow, as the value of the DC-link capacitance is usually quite large to mitigate the ripples on the DC link. In other words, due to the large DC-link capacitance, it takes more time to increase the DC-link voltage. Therefore, this method may lead to the failure of the DC-link voltage protection and shut down for the UPS system. In addition, the work in [16] proposed a method to protect the DC-link from overvoltage by detecting the active power and shows good dynamic response. However, the reliability of this method is relatively low, as it depends on detecting the output active power instead of directly measuring the DC-link voltage. Moreover, the regeneration issue results in the unequal active power sharing in the UPS system, where the circulating current exists in the UPS system, leading to increased power losses. The circulating current issue has been investigated by many previous works [17-19]. The circulating current is usually caused by the difference of the parallel inverters, including filter parameter mismatch, dead-time of the PWM, and switching frequency difference. In addition, [20] points out that when the parallel inverters have the common DC and AC buses, the zero-sequence circulating currents appear in the system as well. Therefore, [20] proposed a droop plus virtual impedance-based method to deal with the zero sequence and cross-coupling circulating current, and it shows the good effect on mitigating the circulating current with complicated control strategy. Except the previous method, a transformer can be added at the output of the inverter to suppress the circulating current [21]. However, considering the bulky volume, it is preferable to achieve the circulating current suppression with control strategy. Therefore, the average current sharing control strategy with droop control and virtual impedance method has been proposed [22-26]. However, this method cannot fully

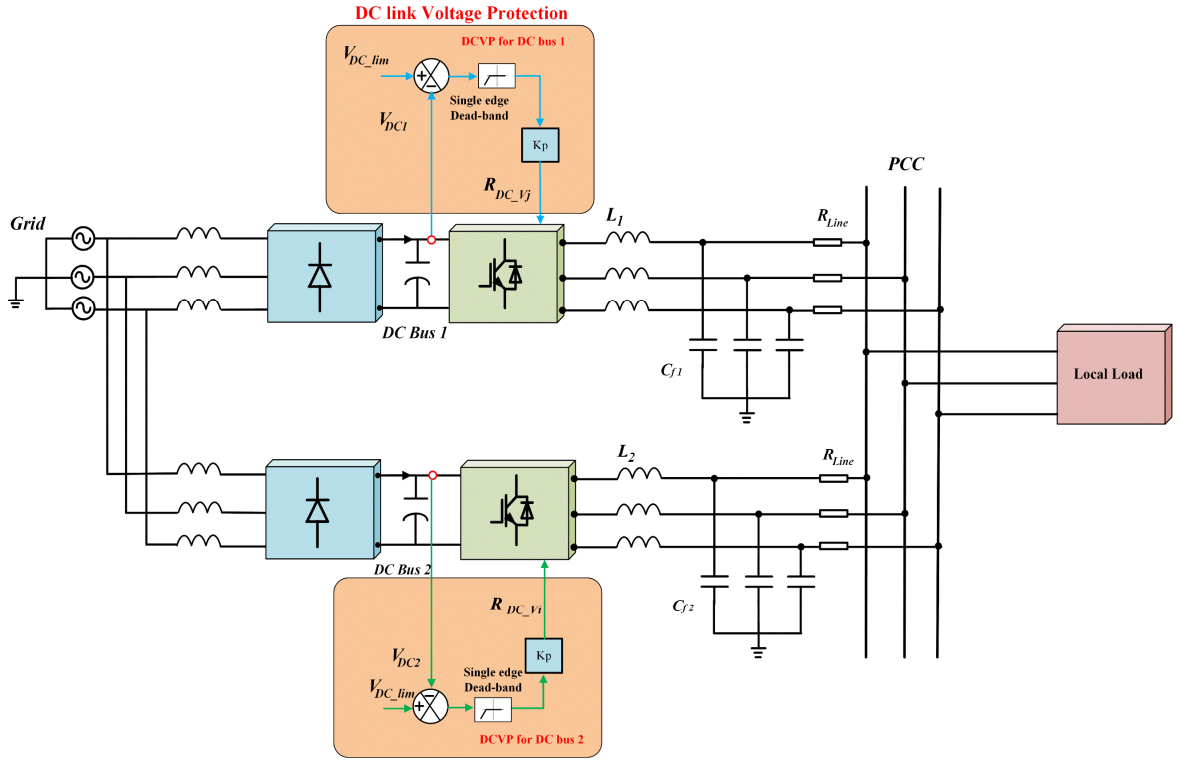


Fig. 3. DC link Voltage Protection Controller

suppress the circulating current in the system as the circuit parameters may drift due to temperature, humidity, line impedance mismatching, DSP clock drifting, the offset in the analog acquisition of the current and voltage and so on. As a result, with poor virtual impedance design, overall performance cannot be guaranteed with regard to the current sharing. In order to improve the performance of the droop with the virtual impedance control, the adaptive virtual impedance control has been proposed by several research works [26, 27]. Previous works, which mainly solved the circulating current caused by the common-mode output voltage, PWM switching, and the line impedance mismatching cannot deal with circulating current issue caused by power regeneration in the UPS system. Therefore, the simple and effective power-sharing control strategy needs to be explored.

To avoid the problems caused by the regeneration issue (i.e., the DC-link overvoltage and the unequal power sharing) in the DDB UPS system, in this paper, a virtual resistance based control scheme for regeneration protection is proposed for the DDB UPS system. This work is an extended version of [28] with more details and discussion. Based on the proposed control scheme, the DC-link overvoltage caused by the regeneration issue is avoided. Moreover, unequal active power sharing issue is solved as well by the proposed power-sharing control strategy. The feasibility and effectiveness of the proposed scheme are validated by dSPACE 1006-based experimental prototype.

II. ACTIVE POWER BACK-FEEDING ANALYSIS

To analyze the regeneration issue, a DDB UPS system based on the PFC and the two-level PWM inverters is considered in this paper (see Fig.2). For the sake of simplicity and avoiding resonance caused by the LCL-type filter, the LC filter is employed in the UPS system. According to the IEC 62040-3:2011 [3], the battery is fully charged and operates in standby mode in normal operation for the on-line UPS system. Therefore, the battery system is not shown in Fig.2. The PFC delivers the active power unidirectionally from the grid to the DC link (one-way blue arrow); meanwhile, the inverters can operate bi-directionally to absorb or deliver the active power as is shown in Fig. 2 (two-way blue arrows). Under a light load condition, the difference between output voltages of the parallel inverters may cause a circulating current from the inverter with a higher voltage to that with a lower one. This circulating current may considerably increase the DC-link voltage in a short time and, consequently, trigger the DC-link protection or even damage its capacitance, if it is not equipped with a DCVP method. Therefore, it is imperative to explore an effective DCVP algorithm.

III. PROPOSED DC-LINK VOLTAGE PROTECTION AND POWER SHARING CONTROL STRATEGY

A. Proposed DC-Link Voltage Protection Strategy

According to the discussion in Section II, the DDB UPS system may suffer from the regeneration issue. So, in the proposed strategy, each DC link is equipped with a DCVP controller to monitor its DC-link voltage. If the measured DC-link voltage exceeds its predefined limitation, the DCVP controller is activated to counteract the injected active power by adjusting the virtual resistance. First, assume that the output voltage of UPS inverter 2 in Fig.2 drifts up. In this case, the excessive active power that is injected into UPS 1 leads to the DC-link voltage increase in the UPS 1. However, if the UPS 1 can deliver more active power and counteract the injected power by reducing its virtual resistance, its DC-link voltage should stop increasing and stabilize in a new steady-state point. The details of the proposed method are shown in Fig. 3. Each DCVP controller monitors its DC-link voltage in real time. If the DC-link voltage exceeds its pre-defined upper limit V_{DC_lim} , the DCVP controller will be automatically activated. The error of the DC-link voltage pre-defined upper limit and the measured DC-link voltage (V_{DC}) goes through a proportional controller to generate an adaptive virtual resistance R_{DC_V} . As a result, by reducing the adaptive virtual resistance of inverters, UPS inverters generate more active power to counteract the injecting power and stabilize the DC link voltage. The control strategy is expressed as:

$$R_{DC_V} = (V_{DC_lim} - V_{DC}) \cdot K_p \quad (1)$$

In Fig.3, R_{DC_Vi} and R_{DC_Vj} respectively represents the adaptive virtual resistance that is sent to the different inverters. K_p is the proportional controller. It is noted that the single-edge dead-band block is added in the DCVP controller considering that the controller should not take any action if the measured DC-link voltage is less than the DC-link pre-defined upper limit. Notice also that only proportional controller, instead of PI controller, is employed in the control strategy. The reason behind it is that the control purpose is to generate an adaptive virtual resistance with a fast response instead of reference tracking.

B. Proposed Power Sharing Strategy for UPS System

In this section, the principle of the power sharing for the UPS system will be first discussed based on a simplified UPS equivalent circuit. In addition, a power-sharing control strategy based on virtual resistance adjustment will be presented. In the UPS system shown in Fig. 2, consider the low voltage rating for the application of the UPS system, the line impedance shows the resistive characteristic. In order to achieve the active /reactive power sharing without communication, the droop control strategy is implemented in the UPS system. In addition, because the distance from the output filter of the UPS system to the load is usually short, the line resistance is quite small. Therefore, the virtual resistance

is usually added in the control strategy in order to enhance the stability in the droop control. Fig. 4 shows an equivalent circuit of two inverters connecting a load at the point of common coupling (PCC), in which each inverter is modeled as a controlled voltage source with the virtual resistance R_v . In addition, R_{line} denotes the resistive line impedance. It is noted that only resistive line impedance is considered since the line impedance shows a resistive nature in low voltage line.

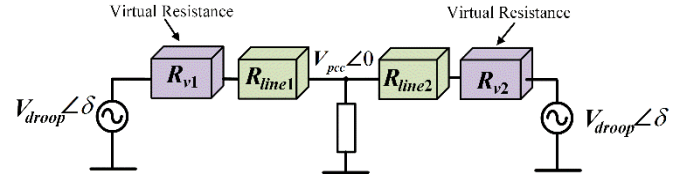


Fig. 4. The equivalent circuit of inverters.

Hence, the total equivalent resistance R_e is defined as the combination of virtual resistance and physical line resistance and expressed as follows:

$$R_e = R_v + R_{line} \quad (2)$$

The active and reactive power injected into the PCC can be expressed as [13]:

$$P \approx \frac{V_{pcc}}{R_e} (V_{droop} - V_{pcc}) \quad (3)$$

$$Q \approx -\frac{V_{droop} V_{pcc}}{R_e} \delta \quad (4)$$

where P and Q are respectively the active and reactive power injected into the PCC, V_{droop} is the voltage amplitude of the inverter, V_{pcc} is the voltage amplitude at PCC, δ is the phase angle difference between the V_{droop} and V_{pcc} .

Accordingly, from (3) and (4), it can be seen that the active power can be controlled by regulating output voltage amplitude V_{droop} , the reactive power can be controlled by regulating the phase angle δ . However, the initial phase angle of the inverter is difficult to obtain. Hence, the angular frequency ω , instead of the phase angle, is regulated to control the reactive power. So, the droop control strategy is given by:

$$\omega = \omega^* + D_q Q_{LPF} \quad (5)$$

$$E = E^* - D_p P_{LPF} \quad (6)$$

where ω^* and ω are the UPS nominal and reference angular frequency, E^* and E are the UPS nominal and reference voltage amplitude. P_{LPF} and Q_{LPF} are the output active and reactive power through a low pass filter with cut-off frequency ω_c , D_p and D_q are the droop coefficients for regulating the UPS active power and reactive power, respectively. In this paper, the design of the droop coefficient is based on the static deviation method, which ensures system is stable. D_q and D_p are defined as: $D_q = \Delta\omega / 2Q_{max}$ and $D_p = \Delta V / P_{max}$, $\Delta\omega$ and ΔV are the maximum frequency and voltage deviations, and P_{max} and Q_{max} are the maximum active and reactive power delivered by the inverter, respectively [29].

For the power flow through the feeder that consists of inductance and resistance, the voltage drop on the impedance

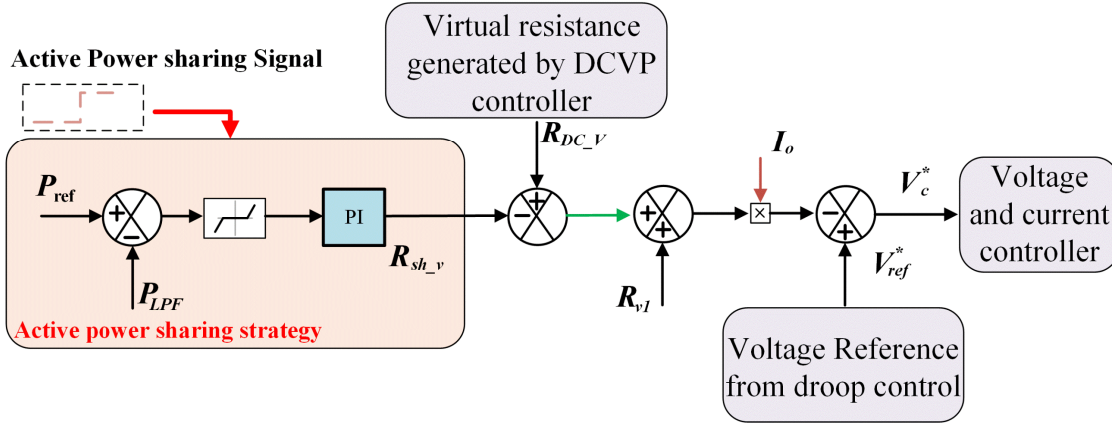


Fig. 5. Active power sharing control strategy.

leads to the expression [30]:

$$\Delta V = \frac{X \cdot Q + R \cdot P}{E^*} \quad (7)$$

where ΔV is the voltage drop on the impedance, P and Q are the active and reactive power respectively, R and X are the resistance and inductance of the line feeder, respectively. In the UPS system, by neglecting the inductance, the voltage drop on the resistance is expressed as:

$$\Delta V = \frac{R \cdot P}{E^*} \quad (8)$$

From (8), the voltage drop on the resistance of UPS system is derived as:

$$\Delta V_1 = V_{droop1} - V_{pcc} = \frac{R_{e1} \cdot P_1}{E^*} \quad (9)$$

$$\Delta V_2 = V_{droop2} - V_{pcc} = \frac{R_{e2} \cdot P_2}{E^*} \quad (10)$$

where R_{e1} and R_{e2} are the equivalent total resistance of each inverter. It is noted that as the frequency is a global state, the reactive power sharing with the droop control strategy should always be accurate in the steady state in UPS system. By subtracting (9) from (10), the active power error is expressed as:

$$P_2 - P_1 = \frac{(V_{droop2} - V_{pcc})E^*}{R_{e2}} - \frac{(V_{droop1} - V_{pcc})E^*}{R_{e1}} \quad (11)$$

It is observed from (11) that the active power sharing error is related to two factors, i.e., the total resistance difference (R_{e1} and R_{e2}) and the voltage magnitude difference (V_{droop1} and V_{droop2}). If the circulating current (active power difference) is caused by the difference between V_{droop1} and V_{droop2} due to active power feeding, it is possible to mitigate the active power sharing difference by adjusting each inverter's virtual resistance (R_{v1} and R_{v2}). Therefore, the adjustable virtual resistance R_{sh_v} for the active power sharing is expressed as:

$$R_{sh_v} = (P_{ref} - P_{LPF}) \cdot (k_p + \frac{k_i}{s}) \quad (12)$$

where P_{ref} is the average active power and expressed as: $P_{ref} = \frac{1}{N} \sum_{i=1}^N P_{LPF,i}$, $P_{LPF,i}$ is each UPS inverter's output active power through a low-pass filter. It is noted that the P_{ref}

can be obtained by the central or distributed communication system [29, 31, 32], where each inverter updates its active power $P_{LPF,i}$ to the central controller/distributed controller. After generating P_{ref} by the central or the distributed controller, it will be sent to each inverter again as the reference signal of the active power sharing strategy.

The active power sharing control strategy is shown in Fig. 5. First, assume that the DCVP method has been activated due to the regeneration issue occurring in the DDB UPS system. At this moment, the circulating current, due to the active power sharing difference, exists in the DDB UPS system. When the active power sharing signal flag changes from zero to one and is sent to each inverter modules through a communication line, it initializes the active power sharing strategy. In this condition, the output active power (P_{LPF}) of each inverter is compared with the reference value (P_{ref}), and the error goes through a PI controller to generate additional virtual resistance until the output active power of all inverters are equalized.

Compared to power sharing strategy of [33], the proposed sharing strategy does not need to disturb the frequency during the transient process, which is beneficial for the critical load that is sensitive to the frequency fluctuation.

The complete control diagram of each UPS module is shown in Fig. 6, where the outer loop voltage controller is employed for regulating the output filter's capacitor voltage, and inner loop current control strategy is nested inside the voltage regulation loop to directly control the inductor's current for limiting the current during the transient as a protection method [34].

The controllers for voltage and current regulation are expressed as:

$$G_v(s) = k_{pv} + \frac{k_{rv}s}{s^2 + (\omega_o)^2} \quad (13)$$

$$G_i(s) = k_{pi} + \frac{k_{ri}s}{s^2 + (\omega_o)^2} \quad (14)$$

where k_{pv} and k_{pi} are the proportional terms, k_{rv} and k_{ri} are the resonant term coefficient at $\omega_o = 314 \text{ rad/s}$. The inner current loop is designed to provide sufficient damping and protect the inductor's current from overcurrent.

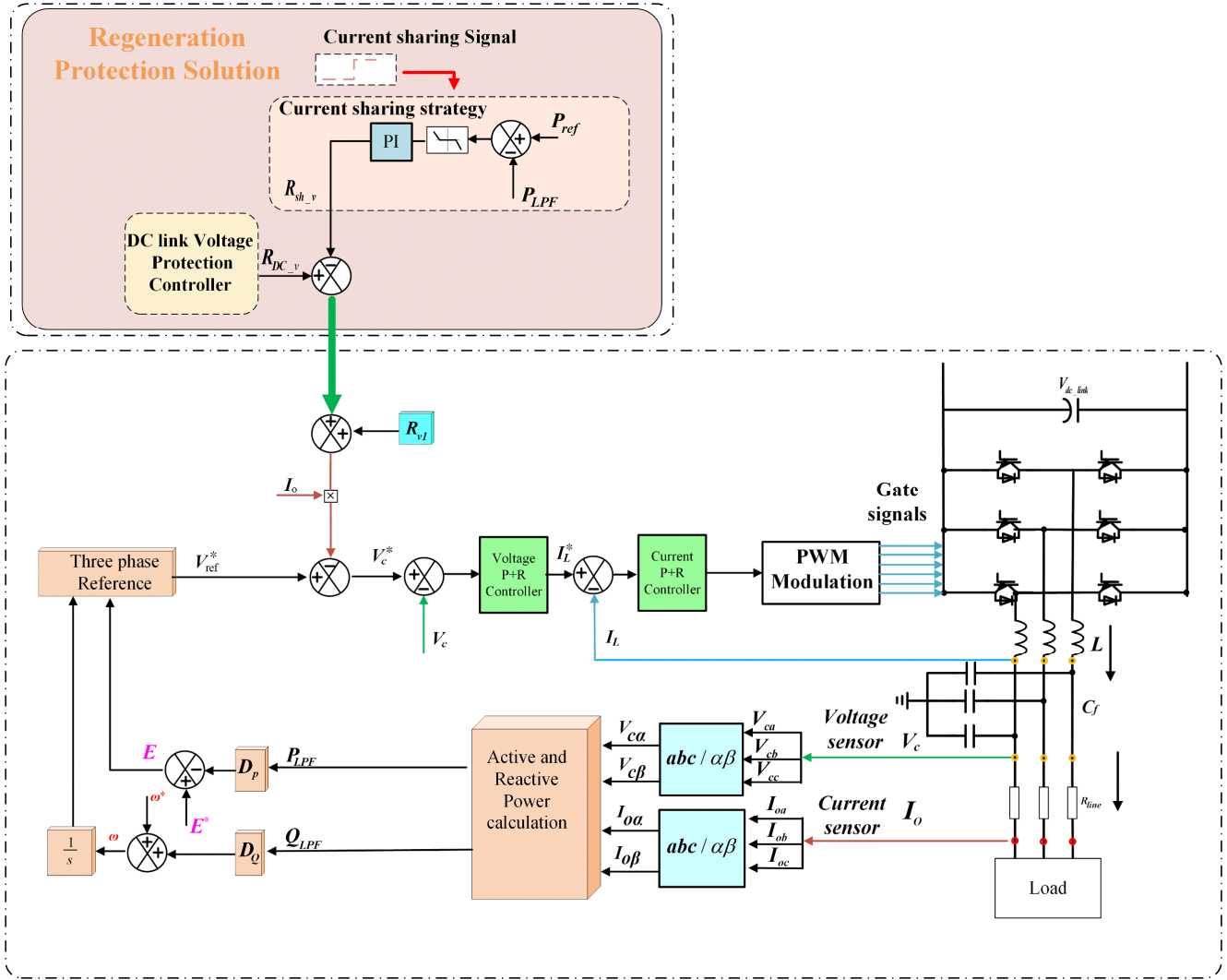


Fig. 6. Complete diagram of the UPS module with the proposed control method.

The DCVP and active power sharing control strategy are employed as the regeneration protection solution. R_v is the fixed virtual resistance to make sure that the system is stably operated even by subtracting the adjustable virtual resistance.

C. Small signal Modeling and Analysis of the virtual resistance

From the previous section's discussion, it is found that the regeneration protection and active power sharing can be achieved by adjusting the virtual resistance of the system. Therefore, in this section, the influence of the virtual resistance on the system's dynamic response is analyzed by small-signal modeling.

First, the power flow of the UPS system through a general line impedance is expressed as [13]:

$$P = \left(\frac{EV}{Z} \cos(\varphi) - \frac{V^2}{Z} \right) \cdot \cos(\theta) + \frac{EV}{Z} \sin(\varphi) \sin(\theta) \quad (15)$$

$$Q = \left(\frac{EV}{Z} \cos(\varphi) - \frac{V^2}{Z} \right) \cdot \sin(\theta) - \frac{EV}{Z} \sin(\varphi) \cos(\theta) \quad (16)$$

where P and Q are the instantaneous active and reactive power of the UPS system that flows out of the general line impedance. E and V are the amplitudes of the inverter output voltage and the common bus voltage, respectively, and φ is the power angle. Z and θ are the magnitude and phase of the output impedance.

Considering that in the UPS system, the virtual resistance is added in the control system, and the distance from the load to the UPS system is normally quite short, the line resistance can be omitted. Therefore, the power flow in the UPS system is expressed as:

$$P = \frac{V}{R_e} (E \cos(\varphi) - V) \cong \frac{V}{R_e} (E - V) \quad (17)$$

$$Q = -\frac{EV}{R_e} \sin(\varphi) \cong -\frac{EV}{R_e} \varphi \quad (18)$$

Hence, the active power and reactive power under the small signal disturbance of voltage amplitude and the phase angle are expressed as:

$$\Delta P = \left(\frac{\partial P}{\partial E} \right) \Delta E + \left(\frac{\partial P}{\partial \varphi} \right) \Delta \varphi = k_{PE} \Delta E + k_{P\varphi} \Delta \varphi \quad (19)$$

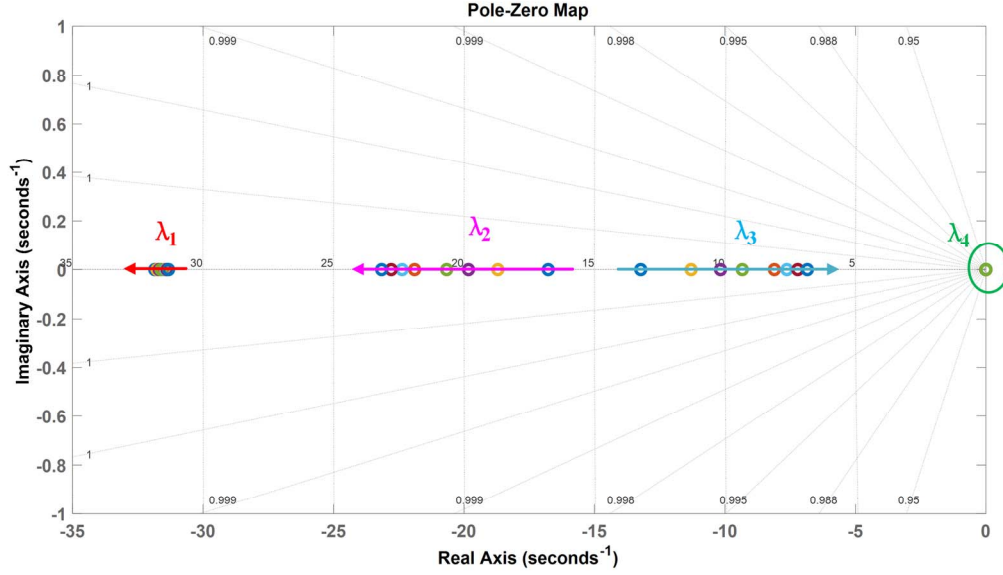


Fig. 7. Root locus when the virtual resistance changes from 0.3 to 0.8 Ω

$$\Delta Q = \left(\frac{\partial Q}{\partial E}\right) \Delta E + \left(\frac{\partial Q}{\partial \varphi}\right) \Delta \varphi = k_{QE} \Delta E + k_{Q\varphi} \Delta \varphi \quad (20)$$

where the operator Δ is the small-signal perturbation around the UPS's operating equilibrium point.

When there are some power fluctuation during the protection or active power sharing process, the small signal response of (5)-(6) are expressed as:

$$\Delta E = -D_P \Delta P_{LPF} \quad (21)$$

$$\Delta \omega = D_Q \Delta Q_{LPF} \quad (22)$$

$$\Delta P_{LPF} = \frac{1}{\tau s + 1} \Delta P \quad (23)$$

$$\Delta Q_{LPF} = \frac{1}{\tau s + 1} \Delta Q \quad (24)$$

where τ is the time constant of the low-pass filter in the active and reactive power calculation.

Considering that $\Delta \theta = \frac{1}{s} \Delta \omega$, and by the simple manipulation of (19)-(20), the dynamic performance of the UPS system yields the following expression:

$$(M_{2 \times 2} - N_{2 \times 2} \cdot L_{2 \times 2}) \cdot [\Delta E; \Delta \varphi]^T = 0 \quad (25)$$

where $M_{2 \times 2} = \begin{bmatrix} s(\tau s + 1) & 0 \\ 0 & s(\tau s + 1) \end{bmatrix}$, $N_{2 \times 2} =$

$$\begin{bmatrix} -D_P s & 0 \\ 0 & D_Q \end{bmatrix}, L_{2 \times 2} = \begin{bmatrix} k_{PE} & k_{P\varphi} \\ k_{QE} & k_{Q\varphi} \end{bmatrix}$$

Fig.7 shows the root locus of the UPS system with the different value of the virtual resistance. It can be seen that the system has three nonzero eigenvalues and one zero eigenvalue.. Meanwhile, only the nonzero eigenvalues are used for the dynamic response and stability study [35]. As can be seen from Fig.7 that system and dynamic performance is mainly determined by the dominant eigenvalue of λ_3 when the virtual resistance increases. But the system stability is still

guaranteed under large variation of the virtual resistance. As this eigenvalue is still far away from the imaginary axis.

IV. EXPERIMENTAL RESULTS

In order to validate the feasibility of the proposed control strategy, the configuration of the DDB UPS system in Fig. 2 is established in Fig. 8. The setup consists of two diode type rectifier and two inverters. Two DC links are formed by the DC-link capacitors. The control algorithm is tested in dSPACE 1006 platform for real-time control. The system parameters are summarized in Table I.

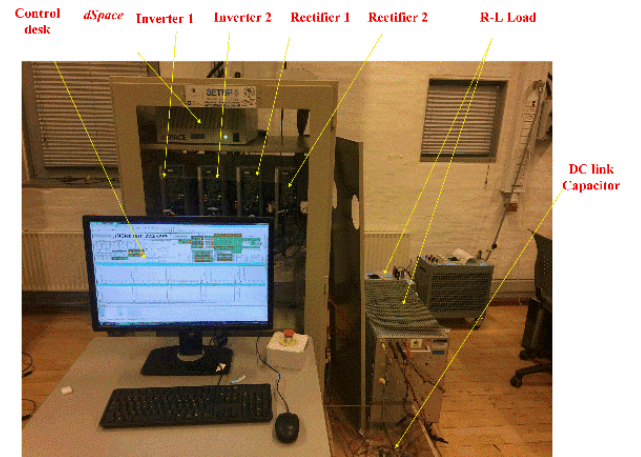


Fig. 8. Experimental setup.

TABLE I. SYSTEM PARAMETERS

| System Parameter | |
|----------------------------------|-------------|
| Filter Inductor L_f | 1.8mH |
| ESR of Inductor | 0.02ohm |
| Filter Capacitor C_f | 27uF |
| DC link Capacitor | 2200uF |
| Sampling frequency | 10kHz |
| Rated Line to Line RMS voltage | 120V |
| R-L load | 50Ω – 1.8mH |
| DC link Voltage Protection | |
| Proportional gain K_p | 0.2 |
| Current sharing Control strategy | |
| Proportional gain $K_{p,f}$ | 0.003 |
| Integral gain $K_{i,f}$ | 0.01 |
| Droop Coefficient | |
| Frequency droop D_q | 0.0001 |
| Voltage droop D_p | 0.00005 |
| Cut-off frequency ω_c | 30 rad/s |
| Virtual Resistance R_{v1} | 0.6Ω |
| Voltage Control Parameter | |
| Proportional gain K_{pv} | 0.2 |
| Resonant gain K_{rv} | 100 |
| Current controller Parameter | |
| Proportional K_{pi} | 5.6 |
| Resonant gain K_{ri} | 500 |

A. Parallel UPS Transient Response in Plug-and-Play Test

First, the power-sharing performance between the two inverters is evaluated in UPS system plug-and-play process as shown in Fig. 9, where it is observed that the active and reactive power are equally shared during the transient process.

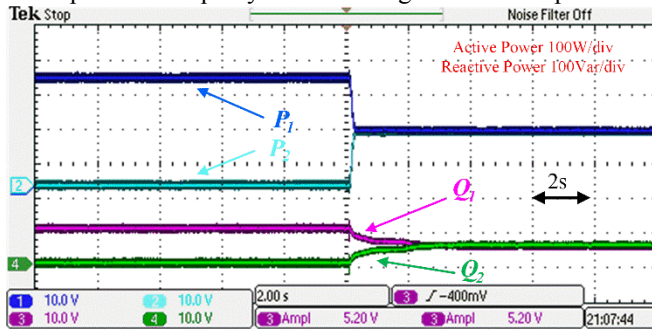


Fig. 9. UPS parallel power-sharing performance.

B. Active Power Back-Feeding Without DC-Link Voltage Protection Strategy

First, the DC-link voltage trip-protection is set to be 600V, which indicates the system will be tripped if the DC-link voltage exceeds 600V. At t_1 s, the output voltage in the inverter 2 drifts up from 100V to 103V, as a result, the active power regeneration leads V_{DC1} to increase (Fig. 10). As the DC link is not equipped with the DCVP controller, V_{DC1} finally reaches 600V after 1s (at t_2 s), triggering the trip-protection of the UPS system.

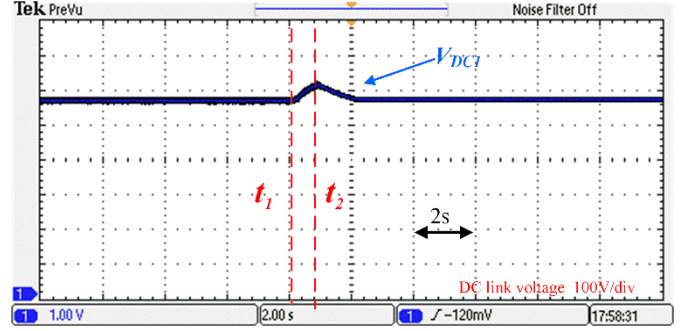


Fig. 10. The DC-link voltage 1 without a DCVP strategy.

C. Active Power Back-feeding With DC-Link Voltage Protection Strategy

In this section, the performance of the DCVP controller needs to be evaluated. First, the DC-link pre-defined upper limit (V_{DC_lim}) is set to be 570 V, so, the DCVP controller needs to be activated if the measured DC-link voltage is greater than 570V. As shown in Fig.11, at t_1 s, the output voltage in the inverter 2 drifts up from 100V to 103V, the output voltage difference results in the voltage increase of V_{DC1} (Fig. 11(a)). However, due to the installation of DCVP controller, V_{DC1} is stabilized at 585V at t_2 s. In addition, Fig. 12 shows that the output active power difference between P_1 and P_2 due to the active power regeneration and notice that this feeding active power leads to the large amounts of circulating current in the UPS system (see Fig.13) even the DC-link voltage is stabilized. This issue of circulating current will be addressed in the next section. It is noted that the circulating current in the system is generated due to the active power difference of the parallel UPS system. In the next section, the active power sharing strategy will be activated to equally share the active power and eliminate the circulating current in the system.

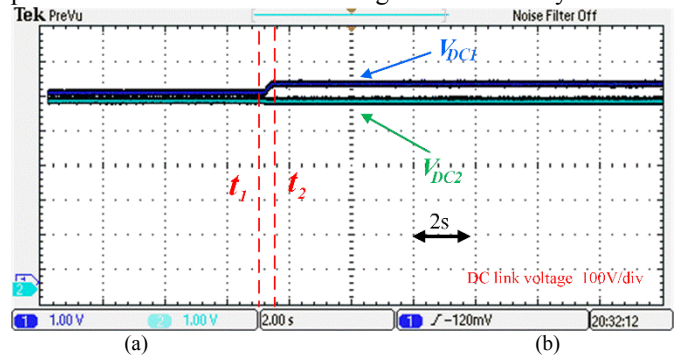


Fig. 11. DC-link voltage and active power during the activation transient time.

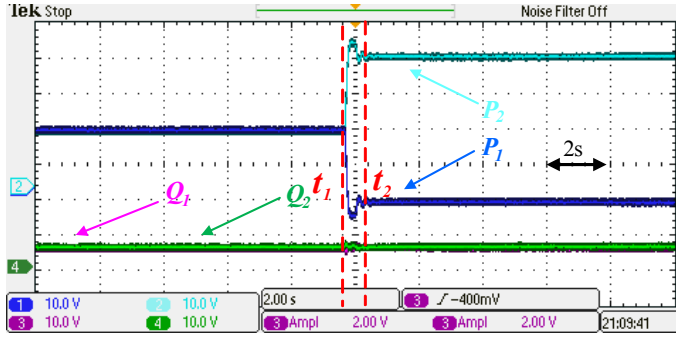


Fig. 12. active power during the activation transient time.

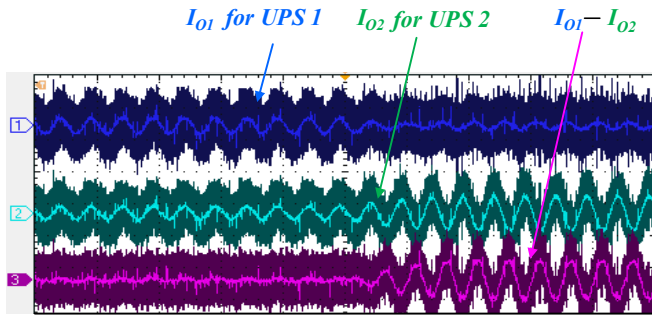


Fig. 13. Output current for inverter 1 (I_{o1}) and inverter 2 (I_{o2}) during the DCVP activation transient time. (Time Scale: 0.04s/div, Current Scale: 4A/div)

D. Active Power Sharing Control Strategy

The active power sharing process is shown in Fig. 14. As can be seen in Fig. 14, the power-sharing controller is activated at t_3 , so the active power in UPS 1 begins to increase and active power in UPS 2 begins to decrease. Meanwhile, it is shown that due to the Q - f droop control, the reactive power is almost immune to the active power sharing except at the beginning process.

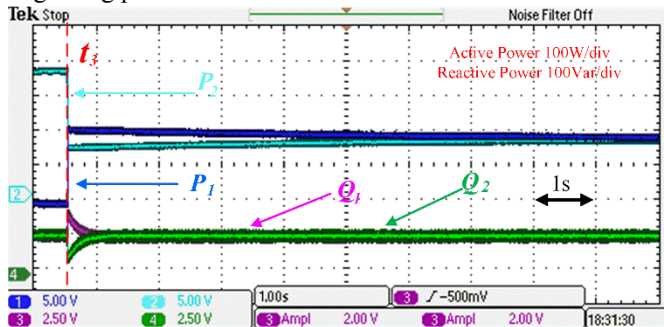


Fig. 14. Parallel UPS power sharing performance during the current sharing process.

Finally, in the steady state, the active and reactive power, output current of parallel UPS system are shown in Fig. 15, where it is observed that the current are equally shared and there is no circulating current due to the active power

difference.

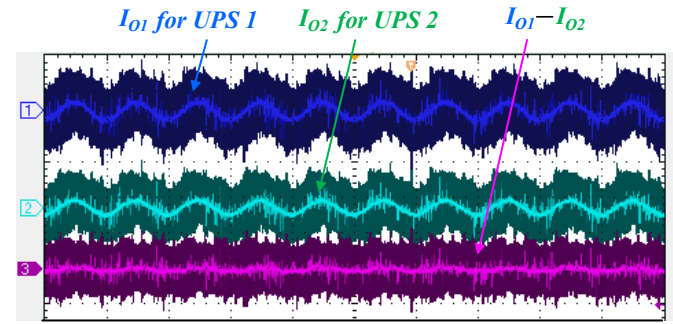


Fig. 15. UPS current and their errors at steady state after activation of current sharing control strategy. (Time Scale: 0.02s/div, Current Scale: 4A/div)

V. CONCLUSION

This paper proposed an effective regeneration protection solution in the DDB on-line UPS system. First, a virtual resistance-based power regeneration protection control strategy is proposed to prevent parallel UPS against the excessive DC-link voltage. Besides, a virtual resistance-based power sharing control strategy is proposed to mitigate the circulating current caused by the power back-feeding. The principle of the proposed control scheme has been discussed, and the dynamic response and stability of the proposed control strategy is analyzed with small signal modeling. Finally, experimental results show the effectiveness of the proposed control strategies.

ACKNOWLEDGEMENT:

This Research is supported by the MOE Academic Research Fund under the project number: M4012122.040.

REFERENCES

- [1] M. S. Racine, J. D. Parham, and M. H. Rashid, "An overview of uninterruptible power supplies," in *Proceedings of the 37th Annual North American Power Symposium, 2005.*, 2005, pp. 159-164.
- [2] G. N. Rajani, "Emerging trends in Uninterrupted Power Supplies: Patents view," in *2016 Biennial International Conference on Power and Energy Systems: Towards Sustainable Energy (PESTSE)*, 2016, pp. 1-5.
- [3] "IEC_62040-3-2011 Uninterruptible power systems (UPS) – Part 3: Method of specifying the performance and test requirements."
- [4] "EN 62040-3 Uninterruptible power systems (UPS) – Part 3: Method of specifying the performance and test requirements."
- [5] Y. Sun, X. Hou, J. Yang, H. Han, M. Su, and J. M. Guerrero, "New Perspectives on Droop Control in AC Microgrid," *IEEE Transactions on Industrial Electronics*, vol. 64, no. 7, pp. 5741-5745, 2017.
- [6] E. K. Sato, M. Kinoshita, Y. Yamamoto, and T. Amboh, "Redundant High-Density High-Efficiency Double-Conversion Uninterruptible Power System," *IEEE Transactions on Industry Applications*, vol. 46, no. 4, pp. 1525-1533, 2010.
- [7] Z. J. Zhou, X. Zhang, P. Xu, and W. X. Shen, "Single-Phase Uninterruptible Power Supply Based on Z-Source Inverter," *IEEE Transactions on Industrial Electronics*, vol. 55, no. 8, pp. 2997-3004, 2008.

- [8] J. K. Park, J. M. Kwon, E. H. Kim, and B. H. Kwon, "High-Performance Transformerless Online UPS," *IEEE Transactions on Industrial Electronics*, vol. 55, no. 8, pp. 2943-2953, 2008.
- [9] C. Zhang, J. M. Guerrero, J. C. Vasquez, and E. A. A. Coelho, "Control Architecture for Parallel-Connected Inverters in Uninterruptible Power Systems," *IEEE Transactions on Power Electronics*, vol. 31, no. 7, pp. 5176-5188, 2016.
- [10] J. W. Kolar and F. C. Zach, "A novel three-phase utility interface minimizing line current harmonics of high-power telecommunications rectifier modules," *IEEE Transactions on Industrial Electronics*, vol. 44, no. 4, pp. 456-467, 1997.
- [11] "White Paper: The different types of UPS system-APC."
- [12] A. Nasiri, Z. Nie, S. B. Bekiarov, and A. Emadi, "An On-Line UPS System With Power Factor Correction and Electric Isolation Using BIFRED Converter," *IEEE Transactions on Industrial Electronics*, vol. 55, no. 2, pp. 722-730, 2008.
- [13] J. M. Guerrero, L. Hang, and J. Uceda, "Control of Distributed Uninterruptible Power Supply Systems," *IEEE Transactions on Industrial Electronics*, vol. 55, no. 8, pp. 2845-2859, 2008.
- [14] T. Iwade, S. Komiya, Y. Tanimura, M. Yamanaka, M. Sakane, and K. Hirachi, "A novel small-scale UPS using a parallel redundant operation system," in *Telecommunications Energy Conference, 2003. INTELEC '03. The 25th International*, 2003, pp. 480-484.
- [15] H. P. Glauser, M. Keller, A. Pluss, M. Schwab, and R. Scherwey, "New inverter module with digital control for parallel operation," in *TELESCON 2000. Third International Telecommunications Energy Special Conference (IEEE Cat. No.00EX424)*, 2000, pp. 265-269.
- [16] J. Lu et al., "DC-Link Protection and Control in Modular Uninterruptible Power Supply," *IEEE Transactions on Industrial Electronics*, vol. PP, no. 99, pp. 1-1, 2017.
- [17] M. J. Tsai and P. T. Cheng, "Evaluation of PWM Methods for Suppressing Circulating Current Among Parallel-Connected Four-Pole Inverters," *IEEE Transactions on Industry Applications*, vol. 52, no. 6, pp. 4928-4934, 2016.
- [18] M. C. Cavalcanti, K. C. d. Oliveira, A. M. d. Farias, F. A. S. Neves, G. M. S. Azevedo, and F. C. Camboim, "Modulation Techniques to Eliminate Leakage Currents in Transformerless Three-Phase Photovoltaic Systems," *IEEE Transactions on Industrial Electronics*, vol. 57, no. 4, pp. 1360-1368, 2010.
- [19] Z. Xueguang, C. Jiaming, M. Yan, W. Yijie, and X. Dianguo, "Bandwidth Expansion Method for Circulating Current Control in Parallel Three-phase PWM Converter Connection System," *IEEE Transactions on Power Electronics*, vol. 29, no. 12, pp. 6847-6856, 2014.
- [20] B. Wei, J. M. Guerrero, J. C. Vásquez, and X. Guo, "A Circulating-Current Suppression Method for Parallel-Connected Voltage-Source Inverters With Common DC and AC Buses," *IEEE Transactions on Industry Applications*, vol. 53, no. 4, pp. 3758-3769, 2017.
- [21] T. P. Chen, "Zero-Sequence Circulating Current Reduction Method for Parallel HEPWM Inverters Between AC Bus and DC Bus," *IEEE Transactions on Industrial Electronics*, vol. 59, no. 1, pp. 290-300, 2012.
- [22] J. M. Guerrero, J. Matas, L. G. D. V. D. Vicuna, M. Castilla, and J. Miret, "Wireless-Control Strategy for Parallel Operation of Distributed-Generation Inverters," *IEEE Transactions on Industrial Electronics*, vol. 53, no. 5, pp. 1461-1470, 2006.
- [23] J. M. Guerrero, J. C. Vasquez, J. Matas, M. Castilla, and L. G. d. Vicuna, "Control Strategy for Flexible Microgrid Based on Parallel Line-Interactive UPS Systems," *IEEE Transactions on Industrial Electronics*, vol. 56, no. 3, pp. 726-736, 2009.
- [24] H. Zhang, S. Kim, Q. Sun, and J. Zhou, "Distributed Adaptive Virtual Impedance Control for Accurate Reactive Power Sharing Based on Consensus Control in Microgrids," *IEEE Transactions on Smart Grid*, vol. 8, no. 4, pp. 1749-1761, 2017.
- [25] C. A. Macana and H. R. Pota, "Adaptive synchronous reference frame virtual impedance controller for accurate power sharing in islanded ac-microgrids: A faster alternative to the conventional droop control," in *2017 IEEE Energy Conversion Congress and Exposition (ECCE)*, 2017, pp. 3728-3735.
- [26] H. Mahmood, D. Michaelson, and J. Jiang, "Accurate Reactive Power Sharing in an Islanded Microgrid Using Adaptive Virtual Impedances," *IEEE Transactions on Power Electronics*, vol. 30, no. 3, pp. 1605-1617, 2015.
- [27] M. Mao, Z. Dong, Y. Ding, and L. Chang, "A unified controller for a microgrid based on adaptive virtual impedance and conductance," in *2014 IEEE Energy Conversion Congress and Exposition (ECCE)*, 2014, pp. 695-701.
- [28] J. Lu, Y. Guan, M. Savaghebi, and J. Guerrero, "Virtual resistance-based control strategy for DC link regeneration protection and current sharing in uninterruptible power supply," in *2017 IEEE Energy Conversion Congress and Exposition (ECCE)*, 2017, pp. 4481-4487.
- [29] J. M. Guerrero et al., "Hierarchical Control of Droop-Controlled AC and DC Microgrids : A General Approach Toward Standardization," *Industrial Electronics, IEEE Transactions on*, vol. 58, no. 1, pp. 158-172, 2011.
- [30] J. D. G. a. M. S. Sarma, *Power System Analysis and Design, Fifth Edition*. Cengage Learning, 2011.
- [31] Q. Shafiee, J. M. Guerrero, and J. C. Vasquez, "Distributed Secondary Control for Islanded Microgrids-A Novel Approach," *Power Electronics, IEEE Transactions on*, vol. 29, no. 2, pp. 1018-1031, 2014.
- [32] D. He, D. Shi, and R. Sharma, "Consensus-based distributed cooperative control for microgrid voltage regulation and reactive power sharing," in *IEEE PES Innovative Smart Grid Technologies, Europe*, 2014, pp. 1-6.
- [33] H. Jinwei, L. Yun Wei, and F. Blaabjerg, "An Enhanced Islanding Microgrid Reactive Power, Imbalance Power, and Harmonic Power Sharing Scheme," *Power Electronics, IEEE Transactions on*, vol. 30, no. 6, pp. 3389-3401, 2015.
- [34] J. C. Vasquez, J. M. Guerrero, M. Savaghebi, J. Eloy-Garcia, and R. Teodorescu, "Modeling, Analysis, and Design of Stationary-Reference-Frame Droop-Controlled Parallel Three-Phase Voltage Source Inverters," *Industrial Electronics, IEEE Transactions on*, vol. 60, no. 4, pp. 1271-1280, 2013.
- [35] H. Jinwei and L. Yun Wei, "Analysis, Design, and Implementation of Virtual Impedance for Power Electronics Interfaced Distributed Generation," *Industry Applications, IEEE Transactions on*, vol. 47, no. 6, pp. 2525-2538, 2011.