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Virtual Resistance-Based Control Strategy for DC link Regeneration Protection and Current Sharing in Uninterruptible Power Supply

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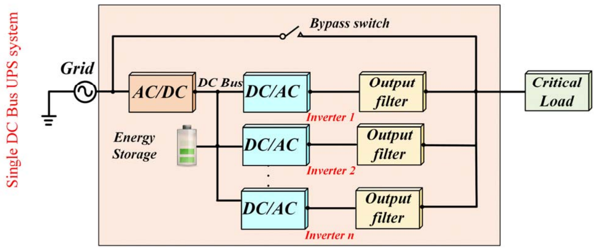
***Abstract*—To address the DC link voltage regeneration issue in parallel Uninterruptible Power Supply (UPS) system, a DC link voltage protection (DCVP) method through online virtual resistance regulation is proposed. The proposed control strategy is able to protect the DC link from overvoltage that may trigger the protection mechanism of the UPS system. Moreover, a current sharing control strategy by regulating the virtual resistance is proposed to address the circulating current caused by the active power feeding. Finally, the feasibility of the proposed method is verified by experimental results from a parallel UPS prototype.**

Keywords—Current sharing; DC-link voltage protection; Droop control; Microgrid; Virtual resistance; UPS;

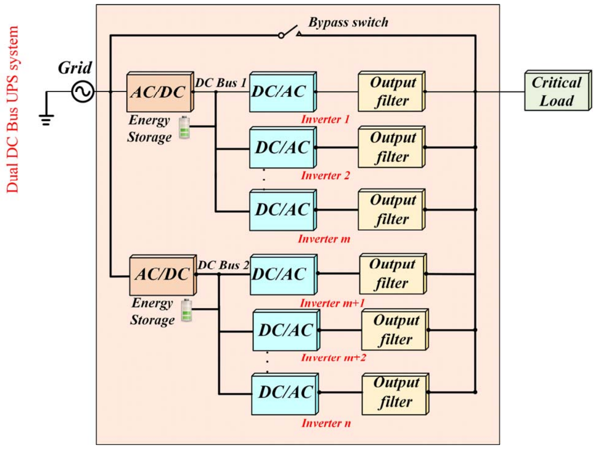
I. INTRODUCTION

With the widespread installation of Uninterruptible Power Supply (UPS) system in data centers, financial institutions, personal computers and healthcare facilities, UPS market has been continuously developing over the last few years to meet the requirement of clients who demand more reliable, secure and efficient uninterruptible power. Meanwhile, UPS technology advancements are drawing increasing attention from engineers and researchers of industry and academic area [2]

In accordance with IEC 62040-3 standard [3], UPS systems are categorized as on-line, off-line and line-interactive UPSs based on the power supply to the load mainly fed from the grid or from the inverter in the normal mode of operation. On-line UPS specifies that the load is always supplied by the inverter irrespective of the grid condition [4]. On the contrary, in off-line and line-interactive UPS systems, load power is mainly supplied from the grid or from the combination of inverter and the grid. Because of the excellent features in isolating voltage irregularities, frequency variation, EMI/RFI line noise and other power issues, on-line UPS system, which is able to provide the highest level of power protection for the critical loads, is increasingly installed in essential data centers and healthcare equipment [5, 6]



(a) Single DC Bus UPS system



(b) Dual DC Bus UPS system

Fig. 1. Categories of parallel UPS system

The on-line UPS system usually consists of AC/DC (rectifier), DC/AC(inverter), battery and a static bypass switch [7]. The AC/DC rectifier is responsible for energy conversion from incoming AC power to DC power and charging the battery. In normal operation, the load is continuously supplied by the combination of AC/DC rectifier and DC/AC inverter [8][9]. Bypass switch will be closed in case of overloading, fault current and outage of UPS units [4]. To achieve more reliable power supply to the critical load, two or more UPS modules are paralleled together to supply power to the load. For the parallel UPS system, it is divided into Single DC Bus (SDB) UPS and Dual DC Bus (DDB) UPS system, as is shown in Fig.1 [3]. In SDB UPS system, the DC/AC inverters are paralleled to supply

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power to the load and share one DC bus, whereas DDB UPS units present higher redundancy, reliability, and flexibility characteristic compared with SDB UPS system, such as a fault on one DC bus does not affect the other DC bus [3, 4].

For the normal performance of the parallel UPS system, master-slave control [9], average load sharing control [10], circular chain control have been proposed with intercommunication system, which inevitably increases the system complexity. On the contrary, the droop control has been proposed without intercommunication where only local information of inverter is implemented to regulate the frequency and amplitude in order to achieve the power sharing [11]. Therefore, the droop control strategy is quite suitable for the normal mode of operation in parallel UPS systems.

However, most of the previous works have focused on the normal operation of DDB parallel UPS system. Under light load, fault or temporarily overvoltage situation that occur at the output of one of the inverters, the voltage difference between parallel UPS system inevitably leads to the active power feeding from higher to lower output voltage of UPS modules [13]. As a result, the feeding power will lead to the excessively high voltage of the DC-link voltage and influence the stable operation of UPS system. Therefore, a DC-link voltage protection (DCVP) method needs to be investigated to solve this issue in DDB parallel UPS system. Moreover, circulating current caused by active power feeding affects the normal operation of UPS system. Therefore, the simple and effective current sharing control strategy needs to be explored.

In this paper, the virtual resistance based control strategy for DCVP and current sharing is proposed for the DDB UPS system. Based on the proposed method, the DC-link overvoltage caused by the active power feeding is avoided. Moreover, the circulating current is solved by the proposed current sharing control strategy. The feasibility and effectiveness of the proposed control strategy are validated by the experimental prototype.

II. UPS SYSTEM STRUCTURE AND ACTIVE POWER FEEDING ANALYSIS

A. *UPS Structure*

Fig.1(b) shows the schematic diagram of a DDB parallel UPS system, which consists of two rectifiers, multiple inverters, two energy storage systems and a bypass switch. Usually, the SCR rectifier or PWM rectifier with a diode in the DC link is widely used in high power or low power UPS system to prevent the power back-feeding from the DC link to the grid. The AC/DC rectifier is in charge of power transfer from the grid to the DC link and supply the power to the battery. The inverters are cooperatively operated with droop control and work in Voltage Controlled Mode (VCM) by regulating outer-loop capacitor's voltage and inner-loop inverter side inductor's current. The bypass switch shall be closed in case of overloading or UPS outage.

B. *Power Flow Analysis of the UPS System*

A two-inverter DDB UPS system is adopted to analyze the power feeding issue, as shown in Fig.2. In compliance with the IEC 62040-3:2011 standard [3], for off-line, line-interactive and on-line UPS system, the battery is usually fully charged and operate in standby mode in normal operation. The AC/DC converter(rectifier) delivers the power unidirectionally from grid side to the DC link. Meanwhile, the DC/AC inverter can work in bi-directional operation to absorb or deliver power as shown in Fig.2 (blue arrows). Under light load condition and because of the tolerance between the output voltages of paralleled inverters or due to inverter's output voltage fault, the UPS module with higher output voltage may feed effective active power into the other UPS module (red arrows in Fig.2), leading to the rise of DC link voltage in a very short time. The DC-link voltage may exceed its upper limitation to shut down the converter without DCVP. Therefore, it is imperative to explore a DC link back-feed protection control algorithm.

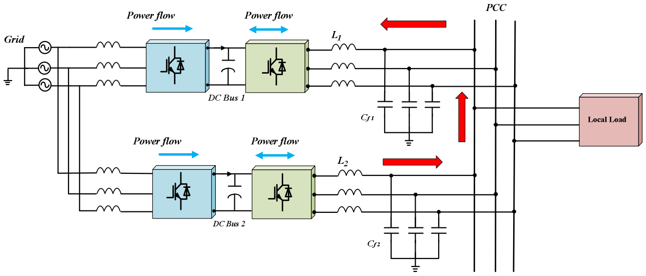


Fig. 2. Power flow in UPS system

III. PROPOSED DC LINK VOLTAGE PROTECTION METHOD AND CURRENT SHARING STRATEGY

A. *Proposed method for DC link voltage protection*

From the discussion in Section II, a proposed control strategy to prevent the DC-link regeneration in the DDB UPS system will be presented in this section. Each DC link is equipped with the DCVP controller to detect its own DC-link voltage, if the detected DC link voltage exceeds its predefined limitation, the DCVP controller needs to be activated. First, assume in Fig.2 that output voltage of UPS 2 drifts up and consequenctly the excessive power that is injected into UPS 1 will lead to the voltage increase of DC link in UPS 1. However, if more active power can be produced in the UPS module 1 to counteract the injected power by reducing its virtual resistance, the DC-link voltage of UPS 1 should stop increasing and operate in a new steady-state point. The details of the proposed method are shown in Fig.3. Each DCVP controller monitors its own DC-link voltage in real time, if the DC link voltage exceeds its upper limit setting value, the DC link voltage controller will be automatically activated. The error of DC link voltage setting upper limit and the measured DC-link voltage goes through a proportional controller to generate a dynamic virtual resistance, which will be sent to all the local controllers of UPS modules that link to the DC bus. As a result, by reducing the virtual resistance of the UPS modules, UPS modules will generate more active power to counteract the injecting power and stabilize the DC link voltage. The controller is expressed as:

$$R_{DC\_V} = (V_{DC\_lim} - V_{DC}) \cdot (-\mathrm{K}_P) \qquad (1)$$

where R_{DC_V} is the virtual resistance, V_{DC_lim} is the DC-link voltage upper limit, V_{DC} is the measured DC-link voltage, K_P is the proportional controller.

It is noted that the single edge dead band block is added in the controller to avoid control action when the DC link voltage is smaller than the DC link voltage upper limit.

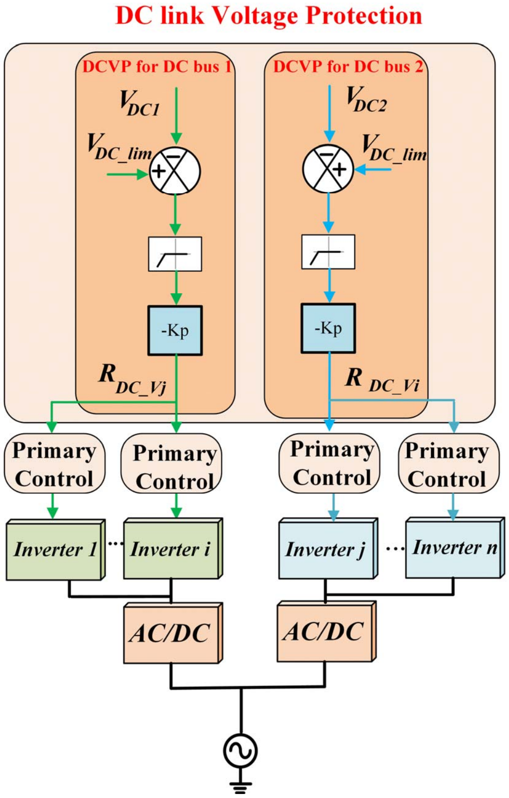


Fig.3. DC link voltage protection method

B. *Proposed method for current sharing of UPS system*

In this section, the power sharing principle for the UPS system needs to be first discussed and investigated according to a simplified UPS equivalent circuit. A current sharing control strategy will be proposed in secondary control level Fig.4 illustrates an equivalent circuit of the UPS modules, where it is found that the UPS module is modeled as the controlled voltage source with the virtual resistance, the physical resistive line impedance is modeled as well in Fig.4. Hence, the virtual resistance and physical line resistance form the total equivalent resistance:

$$R_e = R_v + R_{line} \tag{2}$$

The active and reactive power injected into the PCC can be expressed as [10]:

$$P \approx \frac{V_{pcc}}{R_e}(V_{droop} - V_{pcc})\cos\delta \tag{3}$$

$$Q \approx -\frac{V_{droop}V_{pcc}}{R_e}\sin\delta \tag{4}$$

where P and Q are respectively the active and reactive power delivering to 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}. By considering the small phase angle between the inverter and PCC, i.e., $\cos\delta \approx 1$, $\sin\delta \approx \delta$, the active and reactive power are given by:

$$P \approx \frac{V_{pcc}}{R_e}(V_{droop} - V_{pcc}) \tag{5}$$

$$Q \approx -\frac{V_{droop}V_{pcc}}{R_e}\delta \tag{6}$$

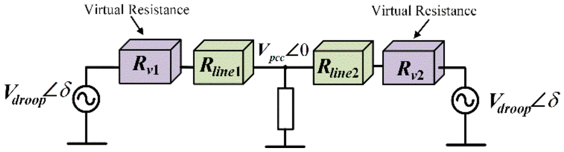


Fig. 4. Equivalent circuit of inverters.

From (5) and (6), it is observed that the active and reactive powers can be respectively controlled by regulating output voltage amplitude V_{droop} and phase angle δ. However, it is difficult to obtain the initial phase angle of the inverter. Hence, the angular frequency ω, instead of the phase angle, is employed to control the reactive power. So, the droop control strategy is given by:

$$\omega = \omega^* + D_q Q \tag{7}$$

$$E = E^* - D_p P \tag{8}$$

For the power flow through the feeder that consists of inductance and resistance, the voltage drop on the impedance leads to the expression [14]:

$$\Delta V = \frac{X \cdot Q + R \cdot P}{E_0} \tag{9}$$

where ΔV is the voltage drop on the impedance, P and Q are the active and reactive power, R and X are the resistance and inductance of the line feeder, E_0 is the nominal voltage. In the UPS system, by neglecting the inductance, the voltage drop on the resistance is expressed as:

$$\Delta V = \frac{R \cdot P}{E_0} \tag{10}$$

From (10), the voltage drop on the resistance of UPS system is derived as:

$$\Delta V_1 = V_{droop1} - V_{pcc} = \frac{R_{e1} \cdot P_1}{E_0} \tag{11}$$

$$\Delta V_2 = V_{droop2} - V_{pcc} = \frac{R_{e2}\cdot P_2}{E_0} \quad (12)$$

where R_{e1} and R_{e2} are the equivalent total resistance for 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 steady state in UPS system,. By subtracting (11) from (12), the active power error is expressed as:

$$P_2 - P_1 = \frac{(V_{droop2}-V_{pcc})E_0}{R_{e2}} - \frac{(V_{droop1}-V_{pcc})E_0}{R_{e1}} \quad (13)$$

It is seen from (13) that two factors have the influence on the active power sharing error, 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 (the active power difference) is caused by the difference between V_{droop1} and V_{droop2} due to active power feeding, the best way to mitigate the circulating current is to adjust each inverter's virtual resistance (R_{v1} and R_{v2}). Accordingly, the adjustable virtual resistance R_{sh_v} for the current sharing is expressed as:

$$R_{sh\_v} = (P_{ref} - P_{LPF})\cdot\left(k_p + \frac{k_i}{s}\right) \quad (14)$$

where P_{ref} is the average active power and expressed as: $P_{ref} = \frac{1}{N}\sum_{i=1}^{n} P_{ups\_i}$, P_{ups_i} is each UPS module's active power. P_{LPF} is the measured active power through a low-pass filter (LPF).

The current sharing control strategy is shown in Fig. 5. First, it is assumed that the DCVP control strategy has been activated due to the active power feeding. At this moment, the circulating current exists in the DDB UPS system. When the current sharing signal flag flips from 0 to 1, the current sharing strategy is activated, the difference of local output active power (P_{LPF}) and the reference active power (P_{ref}) goes through a PI controller to generate additional virtual resistance until the output currents of all inverters are equalized.

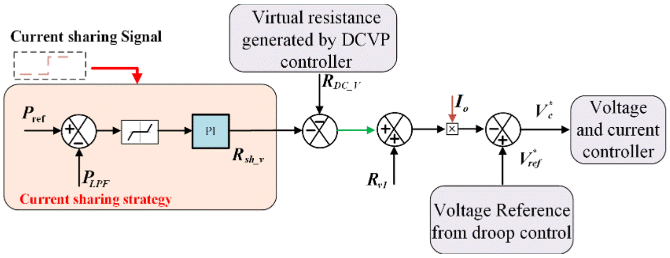


Fig.5. Current sharing strategy.

Compared to current sharing strategy of [15], the proposed current sharing strategy does not need to disturb the frequency during the transient process, which greatly increases the system stability and it 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

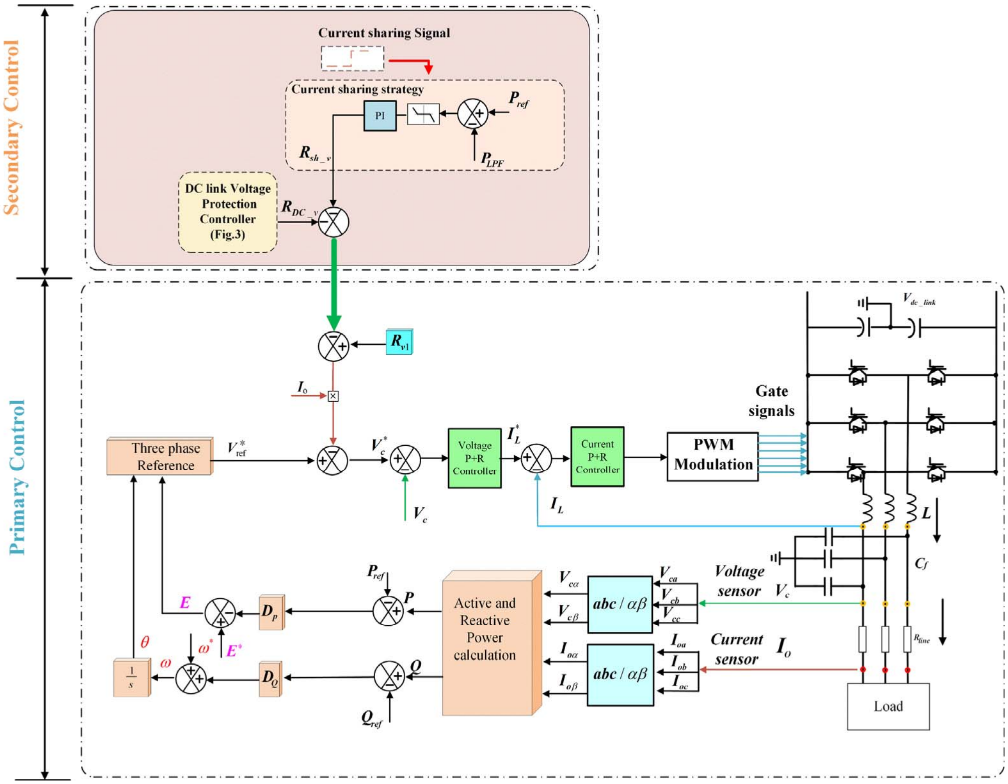


Fig.6. Complete diagram of the UPS module with the proposed control method.

loop to directly control the inductor's current for limiting the current during the transient as a protection method. The DCVP and current sharing control strategy are employed at the secondary control level. R_{v1} is the fixed virtual resistance to make sure that the system is stably operated even by subtracting the adjustable virtual resistance

Table I. System Parameters

System Parameter	
Filter Inductor L_f	$1.8mH$
Filter Capacitor C_f	$27uF$
DC link Capacitor	$2200uF$
DC link Voltage Protection	
Proportional gain	0.2
Current sharing Control strategy	
Proportional gain	$2e-4$
Integral gain	$1e-4$
Droop Coefficient	
Frequency droop	0.0001
Voltage droop	0.00005
Virtual resistance R_{v1}	0.7

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. 7. The setup consists of two rectifiers 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 shown in Table I.

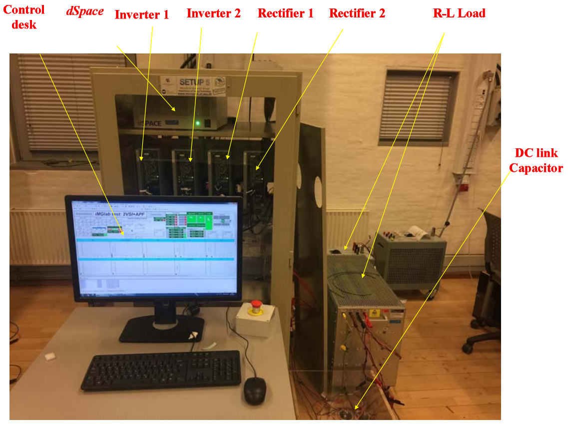
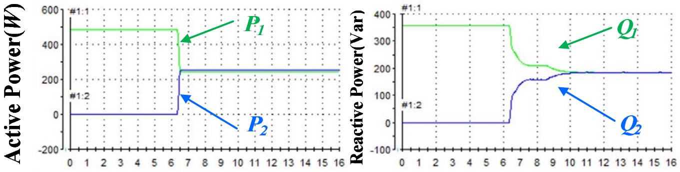


Fig.7. Experimental Setup.

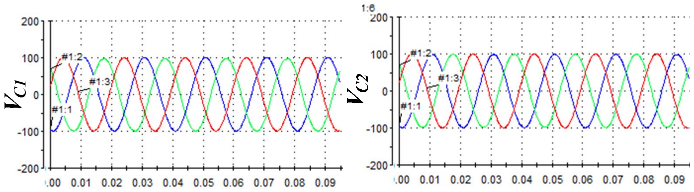
A. Parallel UPS Transient Response in Start-up Process

First, the power sharing performance between the two inverters is evaluated in UPS system start-up process as shown in Fig. 8, where it is observed that the active and reactive power are equally shared during the transient process. In the steady state, the output voltage of inverter 1 and inverter 2 are shown in Fig.9.



(a) (b)

Fig.8.UPS parallel power sharing performance.



(a) (b)

Fig.9.Output voltage for inverter 1 (V_{c1})and inverter 2(V_{c2}).

B. Active Power back-feeding without DC-link Voltage Protection Strategy

To emulate the DC link voltage drifts up and circulating current in the parallel UPS system, the DC link protection is set to be 600V. When the voltage exceeds the 600V, the inverter will stop operation. At 11.4s, the output voltage in UPS2 drifts up from 100V to 103V, as a result, V_{DC1} keeps increasing (Fig.11). Because there is no equipment of DCVP controller, V_{DC1} finally reach 600V, triggers the system protection mechanism and inverter 1 stopped operation because of the overvoltage protection of the DC link

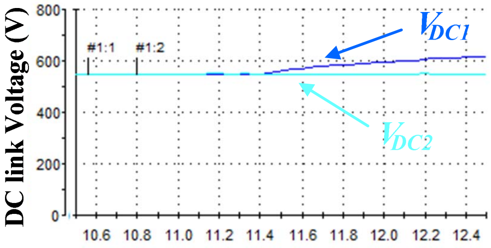
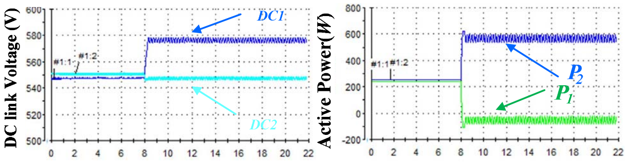


Fig.10. The DC-link voltage of inverter 1 and inverter 2 without a DCVP strategy.

C. Active Power back-feeding with DC-link Voltage Protection Strategy

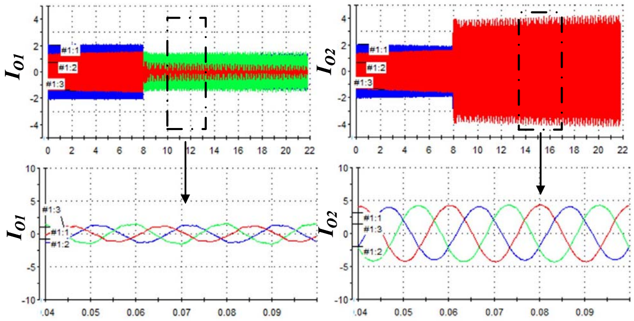
In this section, the DCVP control strategy is evaluated. First, the DC-link voltage limit V_{DC_lim} is set to be 570 V, which indicates that if the measured DC-link voltage is greater than 570V, the DCVP controller will be activated. At 8s, the output voltage of the UPS2 drifts up from 100V to 103V again, the output voltage difference leads to the voltage increase of V_{DC1}

(Fig. 11(a)). However, due to the installation of DCVP controller, V_{DC1} is stabilized at 578V at 8.2s, achieving a fast dynamic response. In addition, Fig. 11 (b) illustrates that the output active power of inverter 1 is reversed due to the active power feeding and this feeding active power leads to the large amounts of circulating current in the UPS system even the DC-link voltage is stabilized (Fig. 12(a) and (b)). This circulating current will be solved in the next section.



(a) (b)

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

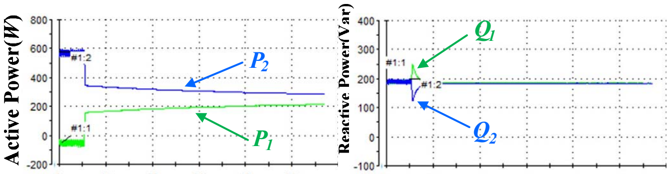


(a) (b)

Fig.12. Output current for inverter 1 (I_{o1})and inverter 2(I_{o2}) during the DCVP activation transient time.

D. Current Sharing Control Strategy

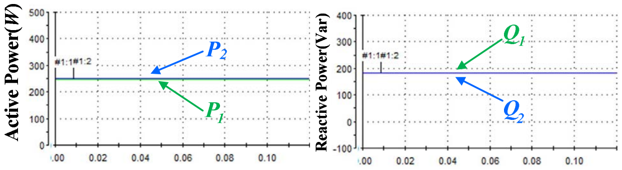
The current sharing process is presented in Fig. 13. As is shown in Fig. 13 (a), a current sharing flag is produced at 5s, which activates the current sharing process. Therefore, the active power in UPS 1 begins to decrease from 600W and active power in UPS 2 increase from -60W. Meanwhile, as it can be observed in Fig. 13(b), due to the Q-f droop control, the reactive power is almost immune to the variation of active power except at the beginning of process (at 5s).



(a) (b)

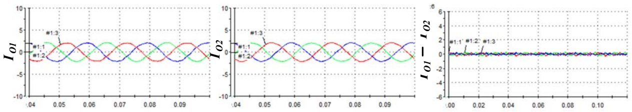
Fig.13. UPS parallel power sharing performance during the current sharing process.

Finally, the steady-state active and reactive power and output current of parallel UPS system are shown in Figs. 14 and 15, respectively where it is observed that the currents are equally shared and there is no power error.



(a) (b)

Fig.14. UPS parallel active and reactive power at steady state after current sharing.



(a) (b)

(c)

Fig.15. UPS current and their errors at steady state after activation of current sharing control strategy.

V. CONCLUSION

In this paper, a DC-link voltage protection and current sharing control strategy has been proposed for the DDB UPS system based on on-line adjustment of the virtual resistance. The proposed control strategy has been thoroughly discussed and experimentally evaluated to demonstrate the effectiveness on improving the performance of UPS system.

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