J Fusion Energ (2014) 33:456–462
DOI 10.1007/s10894-014-9695-4

ORIGINAL RESEARCH

Paralleling Inverters Study of EAST Vertical Stability Coil Power Supply

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Published online: 6 April 2014

Abstract Experimental advanced superconducting tokamak vertical stability (VS) coil power supply is a large capacity single phase inverter power supply. To meet the requirement of large current and fast response, multi-inverters in parallel is presented, which based on carrier phase-shifted modulation technology. In parallel inverter system, the disperse circuit parameters and phase-shift carriers between parallel inverter units will cause circulating current, which contains fundamental component and a large number of harmonic components. In this paper, the model of circulating current is analyzed when VS coil power supply is working in voltage given mode, and an instantaneous current sharing control strategy is proposed based on the combination of current sharing inductor and instantaneous circulating current feedback control. Parallel inverter units are connected together through current sharing inductors which can change the impedance characteristic of the circulating impedance and well restrain the high-frequency circulating current. Then, the real part of the circulating impedance will be increased and the ability to restrain the low-frequency circulating current will be advanced by introducing virtual resistance, which is realized in the instantaneous circulating current feedback routine. The designations of the current sharing inductor and the virtual resistance are provided. The results of simulation and experiment verify that this current-sharing strategy is available and efficient.

Keywords Vertical stability coil power supply · Inverter · Parallel · Current sharing inductor · Virtual resistance · Circulating impedance

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Introduction

Experimental advanced superconducting tokamak (EAST) is a kind of fusion experimental facility. The EAST vertical stability (VS) coil power supply is a large capacity single phase inverter power supply, which traces displacement signal of plasma, and excites four vertical stability coils in vacuum chamber to produce magnetic field that realizes plasma stabilization in large elongate model [1].

In order to output high voltage and large current, multi-inverters in series–parallel is adopted for VS coil power supply, which based on carrier phase-shifted modulation technology. In parallel inverter system, inconsistent circuit parameters (such as: different transformer ratios, scattered conduction voltage drops of switching devices, and so on) and phase-shift carriers between parallel inverter units will cause circulating current. The circulating current not only contains fundamental component but also contains a large number of low-order and high-order harmonic components.

The inverter impedance usually be regarded as a pure resistance and the resistance value is small. A smaller output voltage difference will cause a larger circulating current between parallel inverters. Therefore, the current-sharing strategy based on the combination of current sharing inductor and virtual resistance is proposed in this paper. Parallel inverter units are connected together through current sharing inductors which can effectively restrain the high-frequency circulating current. However, increasing the current sharing inductor cannot effectively improve the ability to restrain the low-frequency circulating current, and large current sharing inductor will reduce the dynamic response speed of the load current. Introducing the virtual resistance can increase the real part of the circulating impedance and advance the ability to restrain the low-frequency circulating current. The virtual resistance is realized in the instantaneous circulating current feedback routine and will not affect the output characteristic of the parallel system [2].

Working Mode and Circuit Structure of VS Coil Power Supply

The plasma control system (PCS) of EAST detects plasma vertical displacement and calculates given current or voltage signal for VS coil power supply. The given signal will be real-time traced and linear amplified by VS coil power supply. According to the principle of electromagnetic field, the excitation power supply can control the intensity of magnetic field, so whether the given signal is current signal or voltage signal, the ultimate goal of PCS is to control the magnetic field which is generated by vertical stability coils.

When the given signal is current signal, PCS will directly control the change of the magnetic field by controlling the output current of VS coil power supply. VS coil power supply can real-time trace and amplify the given current signal by using the load current close-loop feedback control strategy. The control loop of current given mode is shown in Fig. 1.

When the given signal is voltage signal, PCS will control the change rate of excitation current by controlling the output voltage of VS coil power supply, and then indirectly control the magnetic field. However, since the load of VS coil power supply is inductive coil, the load voltage is PWM wave of the power supply DC voltage, so VS coil power supply cannot realize load voltage close-loop control and only can work in voltage open-loop given mode, that is the given voltage signal is corresponding with the duty of output PWM wave. The control loop of voltage given mode is shown in Fig. 2.

The structure of VS coil power supply is shown in Fig. 3 [3]. There are a AC circuit breaker, a 380/380 V transformer, a three-phase rectifier, a filter, and an H-bridge inverter in each converter cabinet, as shown in Fig. 4. To output high voltage, three converter cabinets are cascaded

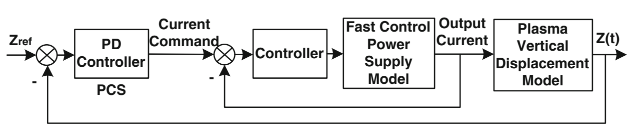

Fig. 1 The control loop of current given mode

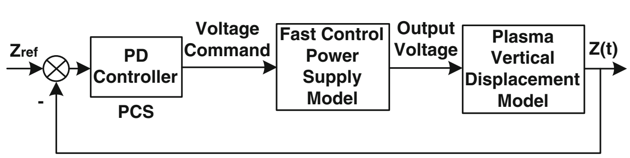

Fig. 2 The control loop of voltage given mode

to build a branch. To output large current, six branches are paralleled in the system. There is a sharing current inductor at each inverter branch output side to limit the circulating current from parallel connection. The technique of carrier wave Phase-shift PWM is applied in series–parallel system.

Analysis on Voltage Open Loop Given Mode

The Influence of Current Sharing Inductor on Circulating Impedance

If the delay and nonlinear components of PWM modulation are ignored, the inverter can be equivalent to a proportion part, which only linear amplifies the modulation wave. To simplify the analysis, the output impedance of parallel inverters are seen as consistent. Figure 5 shows the block diagram of parallel inverter system based on voltage open-loop control.where, u_{ref} is the given voltage signal. K_{pwm} is the ideal equivalent amplification gain of inverter, $K_{pwm} = u_d/u_c$, u_d is the voltage of DC bus and u_c is the amplitude of triangular carrier. u_s is the ideal output voltage of inverter. u_{o1}–u_{on} are the actual output voltage of inverters. u_{e1}–u_{en} are the bias voltage of inverters. L is current sharing inductor, ignoring its series equivalent resistance. R is inverter impedance. i_{o1}–i_{on} are the output current of inverters. i_o is the load current and u_o is the load voltage.

According to Fig. 5, Eq. (1) can be derived. Eq. (1) depicts the relationship between output voltage and given voltage signal, output current of each module.

$$\begin{cases} u_o(s) = K_{pwm}u_{ref}(s) + u_{e1}(s) - (Ls + R) \cdot i_{o1}(s) \\ \vdots \\ u_o(s) = K_{pwm}u_{ref}(s) + u_{ej}(s) - (Ls + R) \cdot i_{oj}(s) \\ \vdots \\ u_o(s) = K_{pwm}u_{ref}(s) + u_{en}(s) - (Ls + R) \cdot i_{on}(s) \end{cases} \quad (1)$$

In parallel system, the average value of all modules' bias voltage is defined as average-bias voltage $u_{eav}(s)$, depicted in Eq. (2). The average value of all modules' output current is defined as average-current $i_{av}(s)$, depicted in Eq. (3). The circulating current of j-th module $i_{Hj}(s)$ is the difference of its output current and the average-current, shown in Eq. (4) [4].

$$u_{eav}(s) = \frac{1}{n}\sum_{j=1}^{n} u_{ej}(s) \quad (2)$$

$$i_{av}(s) = \frac{1}{n}\sum_{j=1}^{n} i_{oj}(s) = \frac{1}{n} i_o(s) \quad (3)$$

$$i_{Hj}(s) = i_{av}(s) - i_{oj}(s) \quad (4)$$

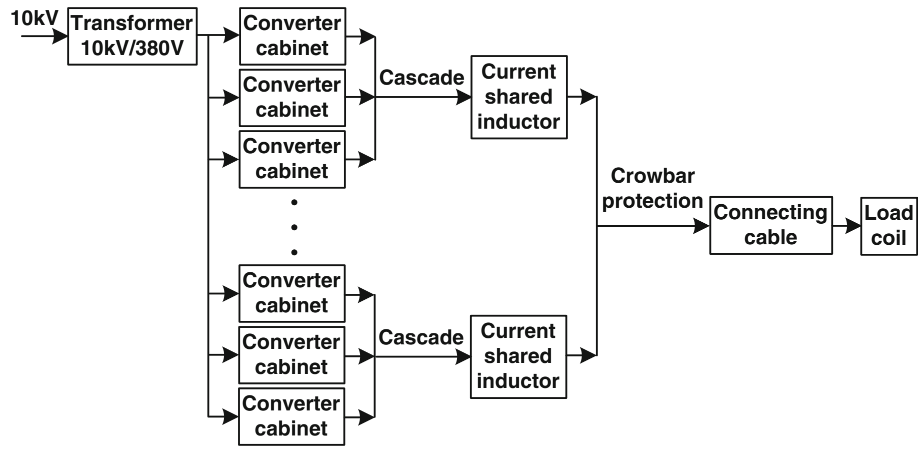

Fig. 3 Structure of VS coil power supply

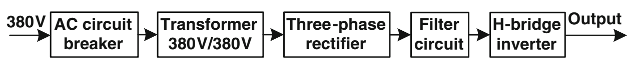

Fig. 4 Structure of converter cabinet

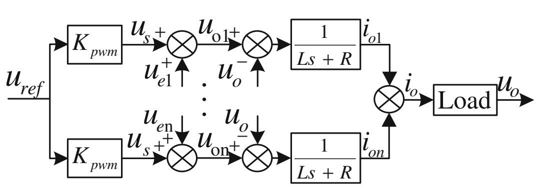

Fig. 5 Block diagram of voltage open-loop control

The output characteristic of parallel system is deduced from Eqs. (1) (2) and (3), shown in Eq. (5). Then Eq. (6) is derived from Eqs. (1), (4) and (5). It is indicated that the circulating-current of j-th module is decided by the difference of bias voltage of j-th module and average-bias voltage of parallel system. Equation (7) is derived from Eq. (6). The Eq. (7) is the mathematical model of circulating impedance. It indicates the relationship between the difference of bias voltage of j-th module and average-bias voltage of parallel system and the circulating current of j-th module [4]. It is because of the presence of circulating impedance, inverter parallel becomes possible.

$$u_o(s) = K_{pwm}u_{ref}(s) + u_{eav}(s) - (Ls + R) \cdot i_{av}(s) \tag{5}$$

$$i_{Hj}(s) = \frac{u_{eav}(s) - u_{ej}(s)}{Ls + R} \tag{6}$$

$$Z(s) = Ls + R = \frac{u_{eav}(s) - u_{ej}(s)}{i_{Hj}(s)} \tag{7}$$

As shown in Eq. (7), the circulating impedance is changed and its value at high frequencies is increased by current sharing inductor. The ability to restrain circulating current of parallel system is improved, especially the ability to inhibit the high-frequency circulating current is significantly enhanced.

Design of Current Sharing Inductor

For VS coil power supply, current sharing inductor is mainly used to restrain the high-frequency harmonics of circulating current, so the current sharing inductor can be designed according to the carrier phase-shift modulation [5].

According Fig. 5 and Eqs. (6) and (8) can be derived as follows

$$i_{Hj}(s) = \frac{\frac{1}{n}\sum_{j=1}^{n} u_{oj}(s) - u_{oj}(s)}{Ls + R} \tag{8}$$

The Interval time between the parallel inverters is τ, $\tau = T_c/n$, T_c is carrier period, which is caused by the carrier phase-shift modulation. If the carrier phase angle is based on the carrier of 1-th inverter unit, then the carrier phase angle of j-th inverter unit is $(j-1)\tau$. The output voltage $u_{oj}(t)$ and $u_{oj}(s)$ of j-th inverter unit can be expressed as Eqs. (9) and (10), respectively.

$$u_{oj}(t) = u_{o1}[t - (j-1)\tau] \tag{9}$$

$$u_{oj}(s) = u_{o1}(s)e^{-(j-1)\tau s} \tag{10}$$

where, $u_{oj}(s)$ is the Laplace transform of $u_{oj}(t)$.

Equation (11) is derived from Eq. (10). According to Euler's formula, the index term of Eq. (11) can be expressed as Eq. (12). Since $\omega L \gg R$, the influence of R can be ignored. Therefore, the circulating current of j-th inverter unit can be simplified as Eq. (13).

$$\frac{1}{n}\sum_{j=1}^{n} u_{oj}(s) = \frac{u_{o1}(s)}{n}\left(1 + e^{-\tau s} + \cdots + e^{-(n-1)\tau s}\right) \tag{11}$$

$$1 + e^{-\tau s} + \cdots + e^{-(n-1)\tau s} = 0 \tag{12}$$

$$i_{Hj}(t) = \frac{u_{oj}(t)T_c}{nL} \tag{13}$$

To simplify the design of current sharing inductor, output voltage $u_{oj}(t)$ can be regarded as square-wave voltage with

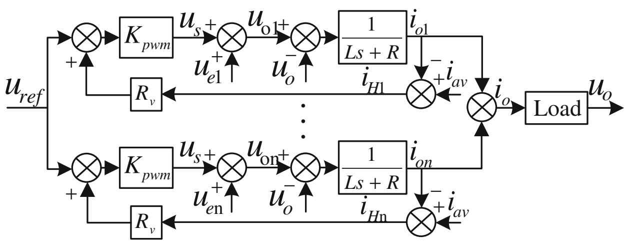

Fig. 6 Block diagram of instantaneous circulating current feedback control

50 % duty cycle, and its amplitude is equal to the voltage of DC bus and period is T_c. If the maximum circulating current of parallel system is i_H^*, then the circulating current of j-th inverter unit can be expressed as Eq. (14). Equation (15) is derived from Eq. (14). Equation (15) depicts the relationship between current sharing inductor and the voltage of DC bus, carrier period, the number of parallel inverters, the maximum circulating current of parallel system. The fewer number of parallel inverters or the lower carrier frequency will need the larger current sharing inductor.

$$i_{Hj} = \frac{U_d T_c}{nL} \le i_H^* \tag{14}$$

$$L \ge \frac{U_d T_c}{n i_H^*} \tag{15}$$

Instantaneous Circulating Current Feedback Control

The Influence of Virtual Resistance on Circulating Impedance

Figure 6 shows the block diagram of instantaneous circulating current feedback control of parallel inverter system. The output currents of all the inverter units are collected and averaged by the average current unit to generate the instantaneous circulating current for each inverter unit. The circulating current is multiplied by the virtual resistance and added to the given voltage signal for PWM modulation. The current-sharing can be realized by making the output currents of inverter units consistent with the average current of parallel system.where, R_v is the virtual resistance, which can be realized in the DSP program.

According to Fig. 6, the output voltage of each inverter unit with instantaneous circulating current feedback control can be expressed as follows:

$$\begin{cases} u_o(s) = K_{pwm}[u_{ref}(s) + R_v i_{H1}(s)] + u_{e1}(s) - (Ls+R)\cdot i_{o1}(s) \\ \vdots \\ u_o(s) = K_{pwm}[u_{ref}(s) + R_v i_{Hj}(s)] + u_{ej}(s) - (Ls+R)\cdot i_{oj}(s) \\ \vdots \\ u_o(s) = K_{pwm}[u_{ref}(s) + R_v i_{Hn}(s)] + u_{en}(s) - (Ls+R)\cdot i_{on}(s) \end{cases} \tag{16}$$

The output characteristic of parallel system can be deduced from Eq. (16), shown in Eq. (17). In addition, the sum of instantaneous circulating currents of inverter units is zero, depicted in Eq. (18).

$$u_o(s) = K_{pwm}u_{ref}(s) + \frac{R_v K_{pwm}}{n}\sum_{j=1}^{n} i_{Hj}(s) + u_{eav}(s) - (Ls+R)\cdot i_{av}(s) \tag{17}$$

$$i_{H1}(s) + \cdots + i_{Hj}(s) + \cdots + i_{Hn}(s) = 0 \tag{18}$$

According to Eqs. (17) and (18), the output characteristic of parallel system after using the virtual resistance can be rewritten as Eq. (19), which is the same as Eq. (5). Equation (19) means that the introduction of the virtual resistance will not affect the output voltage and impedance of parallel system though they modify the output characteristic of each inverter unit. This is the distinct advantage of introducing virtual resistance in the instantaneous circulating current feedback control strategy.

$$u_o(s) = K_{pwm}u_{ref}(s) + u_{eav}(s) - (Ls+R)\cdot i_{av}(s) \tag{19}$$

According to Eqs. (16) and (19), the circulating current of j-th inverter unit under instantaneous circulating current feedback control can be expressed as follows:

$$i_{Hj}(s) = \frac{u_{eav}(s) - u_{ej}(s)}{Z_v(s)} \tag{20}$$

where, $Z_v(s)$ is the circulating impedance after using virtual resistance and can be expressed as follows:

$$Z_v(s) = Ls + R + R_v K_{pwm} \tag{21}$$

As shown in Eq. (21), the real part of circulating impedance is increased by virtual resistance. If R_v K_{pwm} is much higher than R, the value of circulating impedance at low frequencies is greatly increased and the ability to restrain the low-frequency circulating current is significantly improved. But the ability to restrain the high-frequency circulating current of is still decided by the current sharing inductor.

Stability Analysis of Inverter Unit and Design of Virtual Resistance

According to Fig. 6, the block diagram of instantaneous circulating current feedback control of inverter unit is shown in Fig. 7.

Where, U_{ref} is considered as a disturbance. According to Fig. 7, the system characteristic equation can be derived as follows:

$$D(s) = Ls + R + R_v K_{pwm} \tag{22}$$

As shown in Eq. (22), the inverter unit is simplified to a single pole system, which is a stable system under closed-

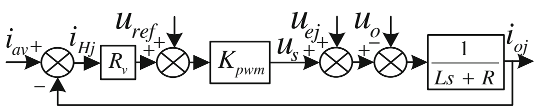

Fig. 7 Block diagram of an inverter with instantaneous circulating current feedback control

loop negative feedback control. However, sample delay and calculation delay certainly exist in the digital control system. In order to correctly implement the PWM control, a delay of one sample period is needed for control usually, which means that using the control value which is calculated in current sample period to change the duty of next sample period. Therefore, in order to analyze the stability of system, the delay which is generated in the PWM modulation process must be considered. If the delay time is τ, then the equivalent amplification gain of inverter is $K_{pwm}e^{-\tau s}$. In addition, because of $\tau s \ll 1$ and $e^{-\tau s} \approx 1 - \tau s$. Equation (22) should be rewritten as follows:

$$D(s) = \left(L - R_v K_{pwm}\tau\right)s + R + R_v K_{pwm} \quad (23)$$

Obviously, the condition for the stability of system is Eq. (24). Considering that the sample period is equal to switching period in PWM inverter generally, so maximum delay time is one switching period. If the switching frequency is f_c, the condition for the stability of system can be deduced from Eq. (24), shown in Eq. (25).

$$L - R_v K_{pwm}\tau > 0 \quad (24)$$

$$Lf_c > R_v K_{pwm} \quad (25)$$

As shown in Eq. (25), the value of virtual resistance is limited by the value of current sharing inductor and the switching frequency. Increasing current sharing inductor or improving the switching frequency can obtain larger virtual resistance which is helpful to improve the ability to restrain the circulating current. However, in order to ensure the dynamic response of load current, the value of current sharing inductor should not be too large. The switching frequency is also limited by the allowed range of power device. Therefore, the value of virtual resistance should be limited to a certain range.

Simulation

In VS coil power supply, the voltage of DC bus of converter branch is about 1,500 V, the current sharing inductor is 160 μH, the sum of current sharing inductor's series equivalent resistance and inverter impedance is 5 mΩ, the inductor and resistance of the load are 120 μH and 10 mΩ, respectively. If the value of virtual resistance is 3 mΩ, Fig. 8 shows the variation of circulating impedance of parallel system after introducing current sharing inductor and virtual resistance. Without current sharing inductor and virtual resistance, circulating impedance is a pure resistive and its value is very small. After using current sharing inductor, circulating impedance is resistive at low frequencies and is inductive at high frequencies, and the value of circulating impedance at high frequencies is significantly increased. After introducing virtual resistance, the value of circulating impedance at low frequencies is significantly increased, but the value of circulating impedance at high frequencies is not changed, which is still decided by current sharing inductor.

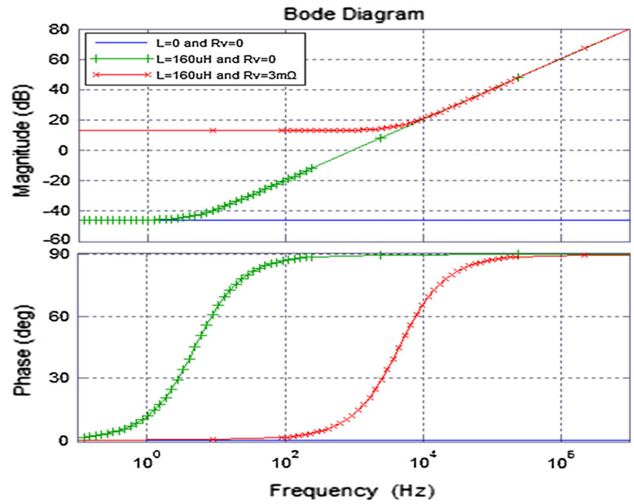

Fig. 8 The variation of circulating impedance

Considering the technique of carrier wave Phase-shift PWM is applied in VS coil power supply and the machining error of the current sharing inductor is ±5 %. Figure 9 shows the simulation waveforms of circulating current with and without virtual resistance. Without virtual resistance, the circulating current contains fundamental component and the amplitude is high. After introducing virtual resistance, the circulating current nearly does not contain fundamental component and mainly is high-frequency ripple.

Experimental Results

In order to verify the feasibility of the proposed strategy, four inverter units are developed for experiments. Figure 10 shows the main circuit of four parallel inverters. The system parameters are shown in Table 1 and the value of virtual resistance is. The technique of carrier wave phase-

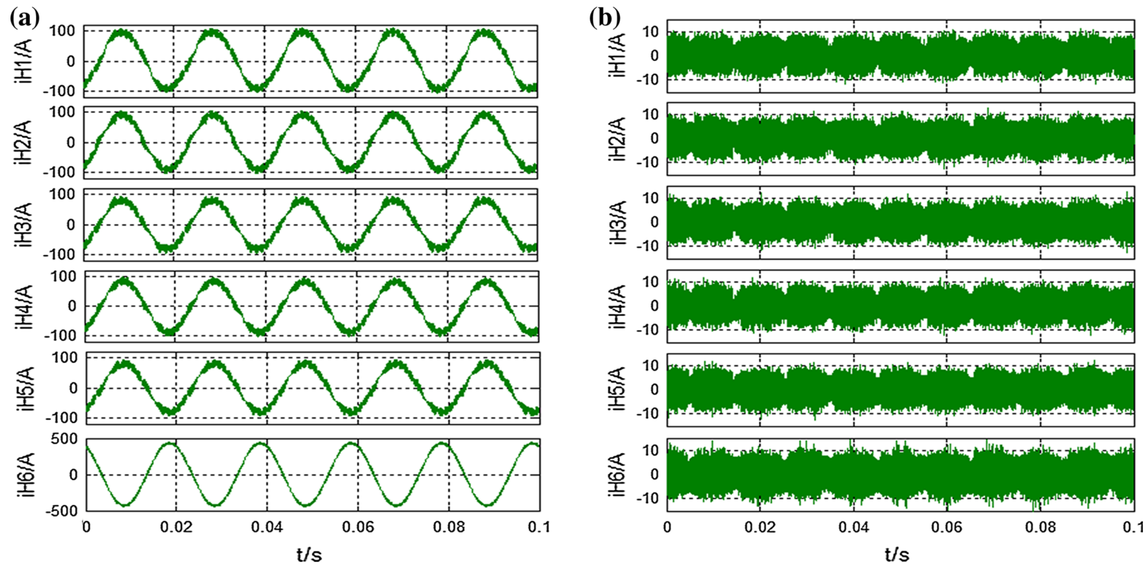

Fig. 9 Simulation waveforms of circulating current. **a** Without virtual resistance. **b** With virtual resistance

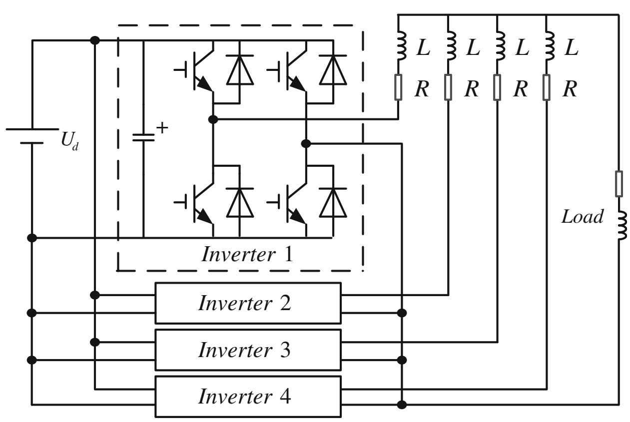

Fig. 10 Experimental circuit

shift PWM is applied in parallel system. The control strategy is implemented in the DSP(TMS320F28335).

With the same given voltage signal for four units, the waveforms (output currents of each unit i_{o1}–i_{o4}, and the maximum current difference between each unit Δi) of parallel system with current sharing inductor of 820 μH are shown in Fig. 11, and the waveforms of parallel system with current sharing inductor of 1,620 μH are shown in Fig. 12.

According to Figs. 11a and 12a, increasing the value of current sharing inductor is helpful to reduce the high-frequency harmonic components of circulating current and improve the ability to restrain the circulating current. According to Fig. 11a and b or Fig. 12a and b, introducing virtual resistance can greatly increased the ability to restrain the low-frequency circulating current. Experimental results

Table 1 Parameters of experimental circuit

	u_d (V)	L (μH)	R (mΩ)	Load
Case 1	30	820	5	3 mH 50 mΩ
Case 2	30	1,620	9	3 mH 50 mΩ

are shown as Table. 2. It demonstrates that the proposed strategy based on the combination of current sharing inductor and virtual resistance can well suppress the circulating current and ensure high current-sharing coefficient (k).

Summary

For the voltage open loop given mode of VS coil power supply, the current-sharing strategy based on the combination of current sharing inductor and virtual resistance is proposed in this paper. The value of circulating impedance at high frequencies can be increased and the ability to restrain the high-frequency circulating current can be improved by using current sharing inductor. The value of circulating impedance at low frequencies can be increased and the ability to restrain the low-frequency circulating current can be improved by introducing virtual resistance. The current sharing inductor and the virtual resistance are designed respectively, and the strategy is employed in simulation and experiment. The simulation and experimental results indicate this current-sharing control scheme has good load-sharing performance for parallel multi-inverter system, which can be applied to VS coil power supply.

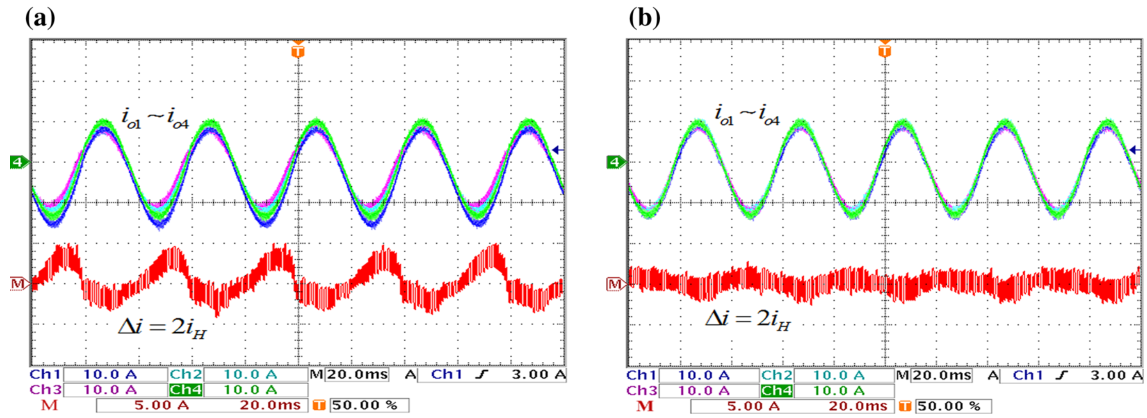

Fig. 11 Experimental waveforms of parallel system with current sharing inductor of. **a** Without virtual resistance. **b** With virtual resistance

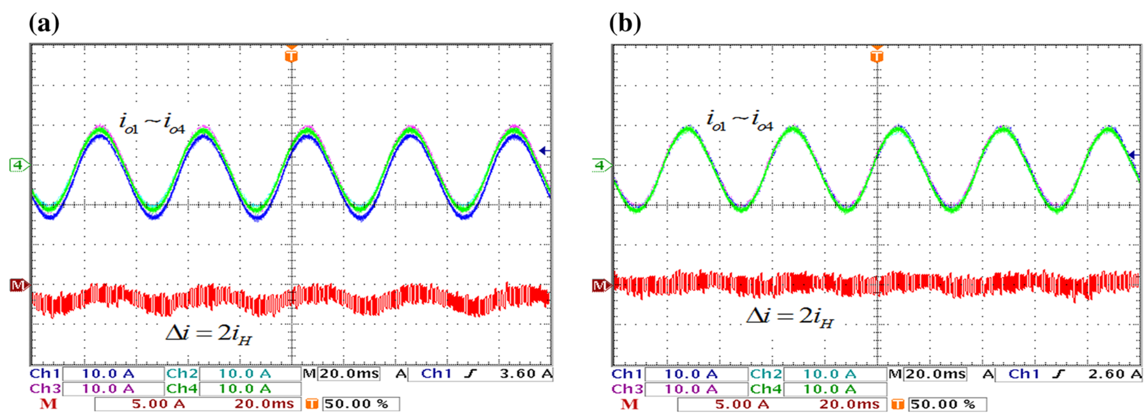

Fig. 12 Experimental waveforms of parallel system with current sharing inductor of 1,620 μH. **a** Without virtual resistance. **b** With virtual resistance

Table 2 Experimental results

	$R_v = 0$ (%)	$R_v = 50$ mΩ (%)
$L = 820$ μH	k = 79	k = 92
$L = 1{,}620$ μH	k = 82.82	k = 93.18

Acknowledgments This work is supported by National Magnetic Confinement Fusion Energy Special Program of China (No. 2011GB109002). The authors thank the members of the VS coil power supply team in the Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP) for their continuous encouragement and support.

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