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ORIGINAL RESEARCH

# On the Circulating Current Control of ITER Poloidal Field Converter

**Hongwen Yuan · Peng Fu · Ge Gao · Liansheng Huang**

**Abstract** The dynamic behavior of circulating current control of International Thermonuclear Experimental Reactor poloidal field converter is the subject of this investigation. Four quadrants operation with circulating current has proved to be a reasonable way to perform smooth transition at the zero crossover of load current. In this paper, a control method, specially for circulating current control, on the basis of equivalent circuit, is proposed. With simulations it is verified that the circulating current can be controlled in such a way that it never become zero, and load current can change polarity without any discontinuity and dead zone, even if in the case that the total reference voltage of converter changes rapidly.

**Keywords** Circulating current control · Four quadrant operation · Phase-controlled converter · ITER poloidal field

## Introduction

International Thermonuclear Experimental Reactor (ITER), which is currently under construction in the south of France, aims to demonstrate the feasibility of fusion energy [1–3]. The poloidal field (PF) converter system, as a component of ongoing ITER device, is of significant importance in plasma shape and position control in vertical and horizontal directions. In the first section of ITER construction, 14 sets of thyristor-based phase-controlled converter modules are designed, each of which performs four-quadrant operation [4–6]. According to the requirement of plasma operation [1], output current of PF converter modules should have the ability to change direction without any discontinuity in load current. To solve this problem, a circulating current mode is introduced into converter operations. Circulating current mode is used to maintain bridge conduction [5] during load current reverses polarity. In this paper, based on the equivalent model of circulating current circuitry, the behavior [6] of circulating current control is investigated; with the proposed circulating current control method, the impact of reference voltage with rapid rate of change on the circulating current control is analyzed to verify the dynamic response of circulating current control.

## Circuit Analysis

As is shown in Fig. 1, ITER PF converter module is constituted of four six-pulse bridges, respectively supplied by two converter transformers that are extendedly connected in such a way that 30° phase shift between secondary windings voltage is brought to perform 12-pulse operation. At the head of each six-pulse bridge, there is a dc reactor in series to make it possible for two bridges operating in parallel. In circulating current operation mode, CU1 and CU4 are decoupled by two dc reactors for the convenience of maintaining circulating current. Meanwhile, the other two bridges, CU2 and CU3, are blocked to avoid operation.

The schematic circulating current circuitry is shown in Fig. 2. Suppose the left-side bridge is forward, and the right-side bridge is reverse. Circulating current flows in clockwise direction whenever load current is positive or

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*Disclaimer*: The view and opinion expressed herein does not necessarily reflect those of the ITER organization.

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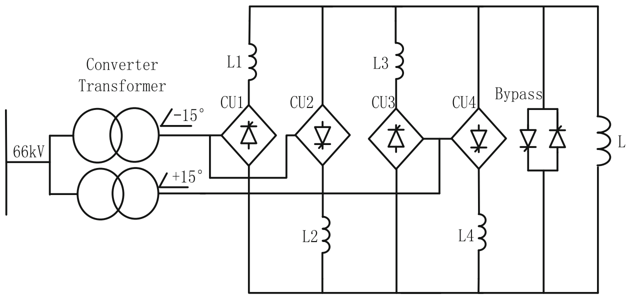


**Fig. 1** Topology of ITER PF converter module

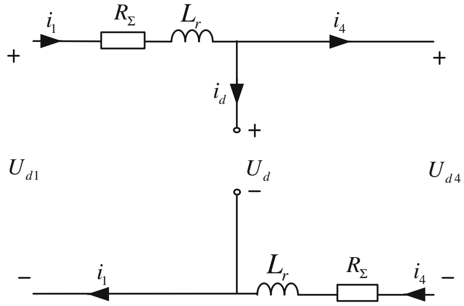


**Fig. 2** Schematic diagram of circulating current circuit

not. The average output voltage of six-pulse bridges can be expressed as

$$U_{d1} = 1.35U_2 \cos \alpha_1 \tag{1}$$

$$U_{d4} = 1.35U_2 \cos \alpha_4 \tag{2}$$

where, $U_2$ is the rms value of secondary phase to phase voltage of converter transformer; $\alpha_1$ and $\alpha_4$ are firing angles of CU1 and CU4; $R_\Sigma$ includes two parts: the equivalent resistance caused by the leakage inductance of converter transformer and the inner resistance of dc reactor. According to Kirchhoff's Current Law, the relations between load current and bridges current can be expressed as,

$$i_d = i_1 - i_4 \tag{3}$$

When load current is positive, not only does forward bridge carries load current, but it also carries circulating current; otherwise, reverse bridge carries both load current and circulating current when load current is negative.

$$\begin{array}{ll} i_{cir} = i_1 - i_d & (i_d > 0) \\ i_{cir} = i_4 - (-i_d) & (i_d < 0) \end{array} \tag{4}$$

From Eqs. (3) to (4), it is easy to deduce the circulating current equation, as follow,

$$i_{cir} = \frac{1}{2}(i_1 + i_4 - |i_d|) \tag{5}$$

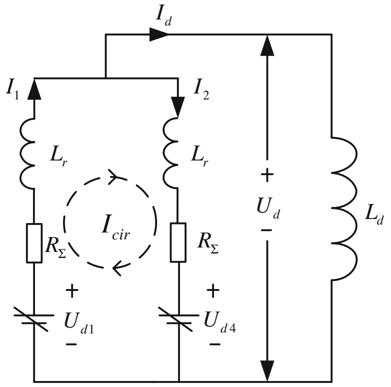


**Fig. 3** Equivalent circuit of circulating current mode

The equivalent circuit of circulating current mode is depicted in Fig. 3. Six-pulse bridges CU1 and CU4 separately are equivalent to two controlled dc voltage sources $U_{d1}$ and $U_{d4}$ with the same polarity. Voltage equations of circulating current loop after Laplace transformation are described,

$$U_{d1} = U_d + I_1(sL_r + R_\Sigma) \tag{6}$$

$$U_{d4} = U_d - I_4(sL_r + R_\Sigma) \tag{7}$$

By adding Eqs. (6)–(7), it is easy to derive the dc output voltage expression as follow,

$$U_d = \frac{U_{d1} + U_{d4}}{2} - (sL_r + R_\Sigma)\frac{I_d}{2} \tag{8}$$

The dc output voltage is determined by bridge voltage as well as load current. By Eqs. (5), (6) and (7), the circulating current can be expressed as,

$$I_{cir} = \frac{U_{d1} - U_{d4}}{2(sL_r + R_\Sigma)} - \frac{|I_d|}{2} \tag{9}$$

From Eq. (9), it is obvious that the behavior of circulating current is mainly decided by the voltage difference of bridge voltages. The absolute value of load current has an impact on the dynamic behavior of circulating current. In Eq. (8), the output voltage is mainly decided by the average value of $U_{d1}$ and $U_{d4}$, and the voltage difference has no impact on the output voltage of the converter. Moreover, the dynamic response of circulating current control has close relationship with the inductance of dc reactors.

## Circulating Current Control

### Dynamic Behavior

At the head of each bridge, there is a current sensor installed to obtain the bridge current. With Eq. (5) the circulating current can be calculated and used for feedback control. From Eq. (9), the circulating current is mainly determined by the voltage difference between CU1 and

CU4. Reactors L1 and L4 are of great significance in circulating control, because instantaneous voltage of two bridge voltage is different. If without dc reactors, the circulating current control would be impossible. Figure 4 illustrates the circulating current control block diagram. Due to the inherent characteristics of thyristor converter, it can be seen as a voltage amplifier with a time delay [5]. For the convenience of analysis, it can be further equivalent to a small first-order inertial element with time constant $\tau$. The transfer function of converter is expressed,

$$G_1(s) = \frac{K_s}{\tau s + 1} \tag{10}$$

where, $K_s$ is the amplification factor. In the circulating current circuitry, the voltage difference between CU1 and CU4 is put on the dc reactor and inner resistance of converter. The transfer function is

$$G_2(s) = \frac{1}{2(L_r s + R_\Sigma)} \tag{11}$$

where, $L_r$ and $R_\Sigma$ respectively represent the total inductance and resistance in the circulating current loop; In practical case, before the circulating current is used to compare with the reference, a low-pass filter with time constant $T_f$ is inserted into the feedback path, which transfer function is,

$$G_3(s) = \frac{1}{T_f s + 1} \tag{12}$$

If a *PI* controller is selected as the circulating current controller, the open loop transfer function of circulating current control system is,

$$G(s) = \left(K_p + \frac{K_i}{s}\right) \cdot \frac{K_s}{\tau s + 1} \cdot \frac{1}{L_r s + R_\Sigma} \cdot \frac{1}{T_f s + 1} \tag{13}$$

It is easy to observe the open loop frequency response of circulating current control from the bode diagram in Fig. 5. If without circulating current controller, the crossover frequency is 1,150 rad/s, the phase is lower than −200°, which indicates the control becomes unstable; if the controller is inserted into a *PID* correction, the crossover frequency becomes 247 rad/s, and the phase is −108°, which means that margin phase is 72°, which stands for a stable and rapid response to circulating current control.

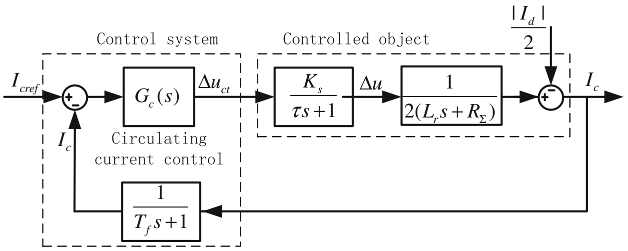


**Fig. 4** Circulating current control block diagram

As for PID regulator, $K_p$ plays an important role in the regulation, which has an impact on the crossover frequency. As is shown in Fig. 6, if $K_i$ and $K_d$ are certain, when $K_p$ is increasing, the open loop crossover frequency of circulating current control system varies from 148 to 368 rad/s, and the related phase margin decreases from 63° to 47°. According to the log magnitude-frequency characteristics and log phase-frequency characteristics, it signifies that lower $K_p$ brings relatively more phase margin and stability. However, crossover frequency will be sacrificed to some extent. In a control system, crossover frequency is as important as phase margin to the behavior of dynamics. From Fig. 7, it is obvious that lower $K_p$ brings slow step response, but too much $K_p$ subsequently results in overshoot in step response and performs low stability.

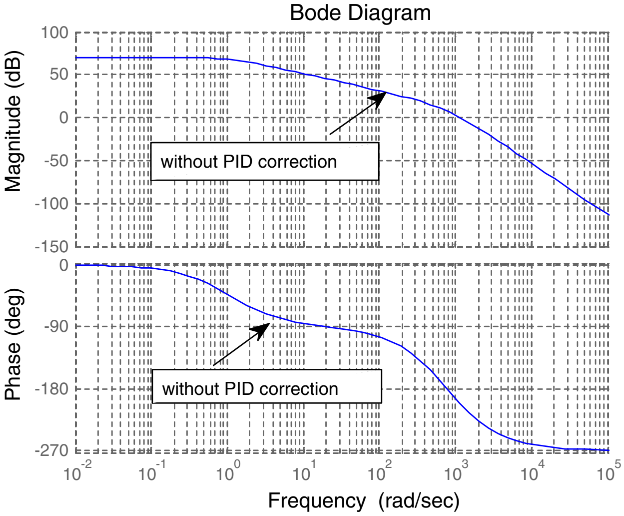


**Fig. 5** Open loop frequency characteristics without correction

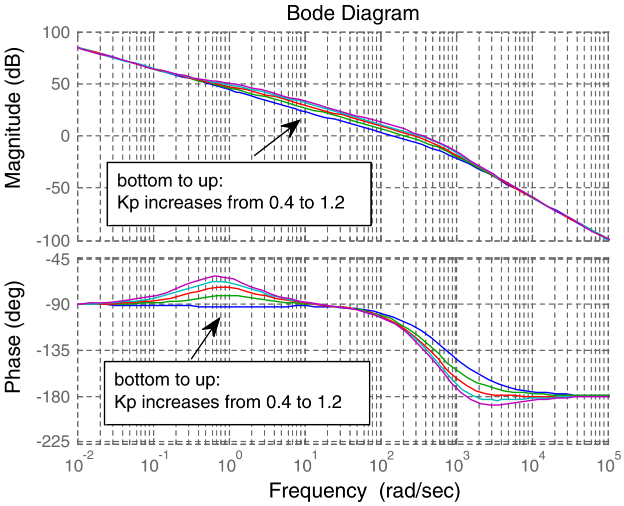


**Fig. 6** Open loop frequency characteristics with correction

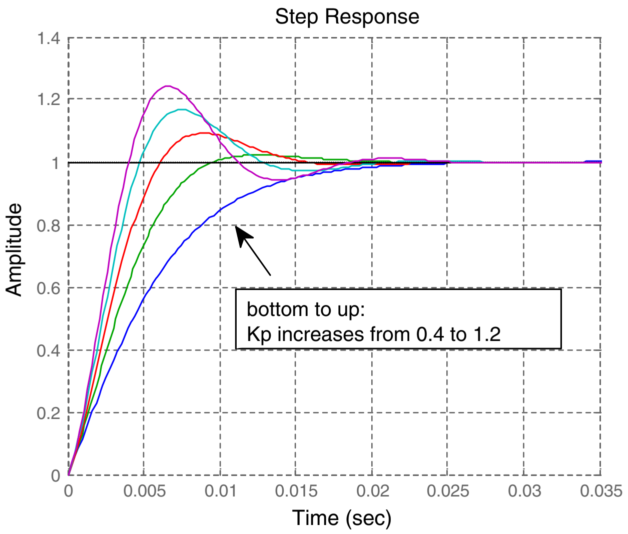


**Fig. 7** Step response of circulating current control with PID regulation

## Control Strategy

The circulating current control logic [7, 8] is shown in Fig. 8. To achieve circulating current control with excellent performance, the rather important thing is how to dispatch voltage difference between two bridges related to the circulating current mode. The voltage difference is obtained by calculating the error of circulating current to its reference value via *PID* controller. Circulating current, as the feedback variable, can be obtained from bridge current and load current with Eq. (5). In practical case, a filter with time constant 0.1 ms is inserted into the feedback path to remove the high-frequency interference of current sensors. The voltage difference of circulating current controller is subtracted from or added to the main voltage signal, sent by master controller, respectively as reference voltage signal of CU1 and CU4. Moreover, because CU1 and CU4 are anti-paralleled, the polarity needs to be reversed before it is ultimately used as reference voltage of CU4. According to the Eqs. (1) and (2), $u_1^*$ and $u_4^*$ can be converted into $\alpha_1$ and $\alpha_4$ for converter control.

**Table 1** System parameters of ITER PF converter

| | |
|---|---|
| *Converter transformer* | |
| Capacity | 2 × 41 MVA |
| Voltage ratio | 66 kV/1.05 kV |
| Short circuit impedance | 16 % |
| *DC reactor* | |
| Inductance | 250 μH |
| Resistance | 300 μΩ |

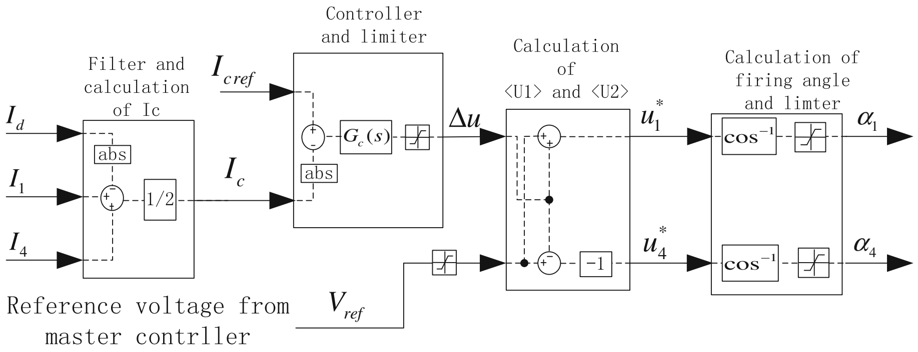
It is necessary to note that limiters are needed for the reference voltage of master controller and circulating current controller to suppress saturation in circulating current control. For example, when there is a step response in the load current, the master controller will output voltage as much as 1,350 V. If the range of firing angle in circulating current mode is (30°, 140°), the control voltage $\Delta u$ between two bridges will be overwhelmed by firing angle limiter and lose its ability in controlling circulating current.

## Simulation

With the proposed circulating current control strategy, simulations have been performed under different conditions to verify the performance of circulating current control. The system parameters of ITER PF converter system is shown in Table 1. Set 5 kA as the reference value, the range of firing angle in circulating current mode is limited as (35, 140). It can be seen that load current can smoothly crossover zero point without any discontinuity, as indicated in Fig. 9. The simulated circulating current is around 4.5–5.5 kA.

Due to the requirement of ITER plasma confinement that output voltage of converter may change rapidly from +1,050 to −1,050 V, or in reverse, without circulating current out of control, as is shown in Fig. 10. To suppress the uncontrolled circulating current, a rate limiter for firing

**Fig. 8** Block diagram of circulating current control strategy



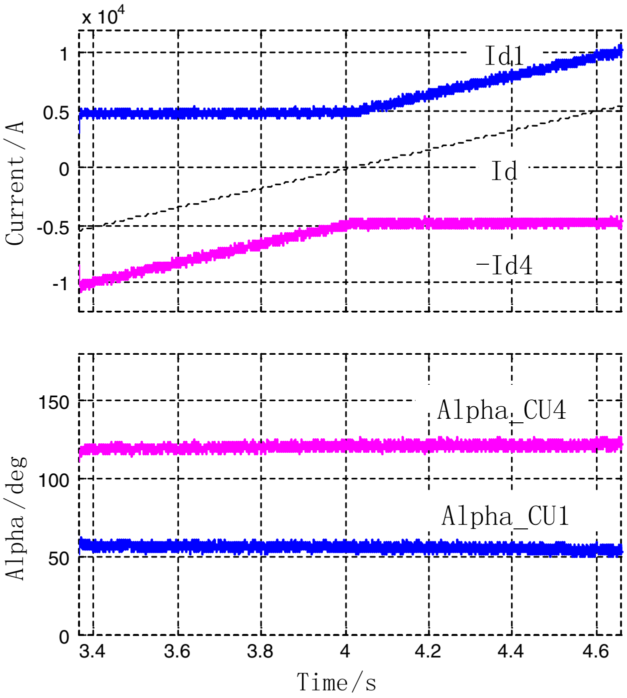


**Fig. 9** Normal circulating current waveform

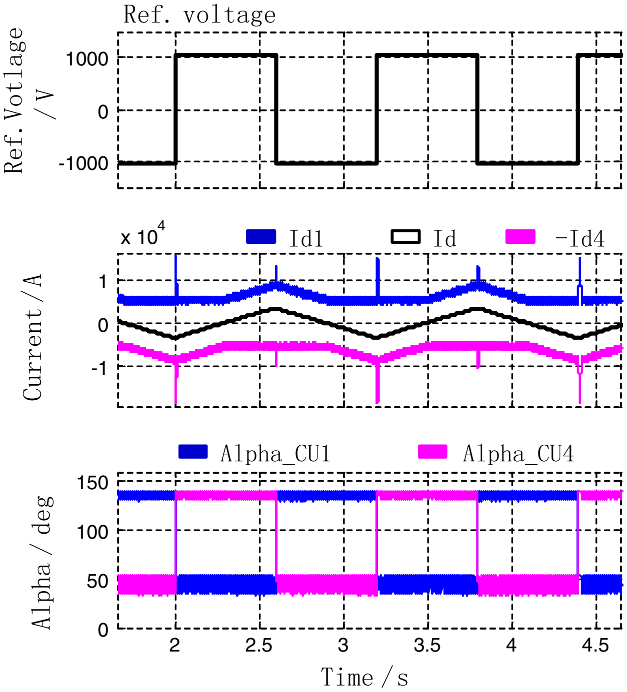


**Fig. 10** Circulating current control without rate limiter

angle is applied to circulating current control algorithm. The maximum rate of rate limiter is fixed as 18,000 °/s which means the maximum change rate of firing angle from 0° to 180° is limited in 10 ms. As is shown in Fig. 11, the rate limiter succeeds in suppressing uncontrolled circulating current.

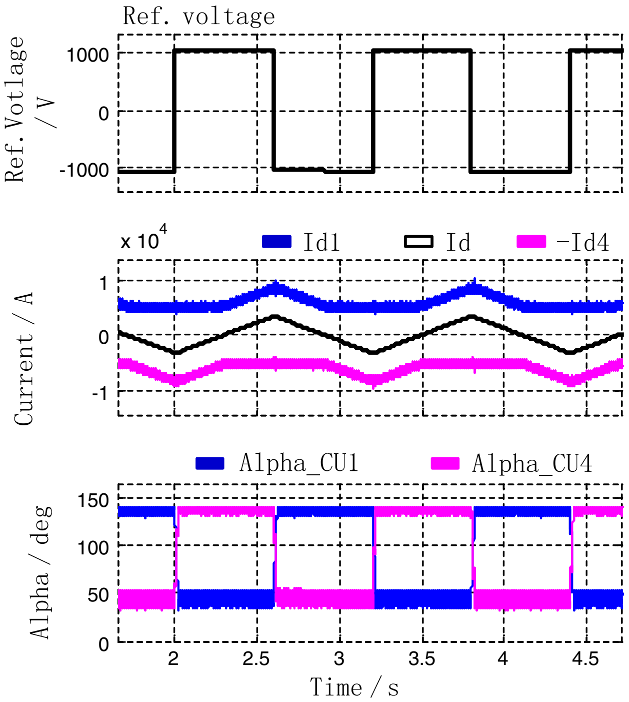


**Fig. 11** Circulating current control with rate limiter

## Conclusion

As the result of circulating current control, load current of ITER converter system achieves to change direction smoothly without any discontinuity and dead zone. To perform effective control of circulating current with high level dynamic behavior, parameter correction of PID controller needs deliberately considered, because it greatly impacts on the reliability and dynamic responses. Anyway, the emphasis of circulating current control is how to dispatch voltage difference between the two bridges related to circulating current mode in a reasonable way. Moreover, voltage limiters are indispensable for master controller as well as circulating current controller to avoid saturation in regulator. With effective circulating current control, the output voltage of ITER PF converter can be controlled independently of load current.

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