Study on the Current-Sharing Control System of the TF Power Supply for a Superconducting Tokamak

ZHU Zhe (朱哲)\(^1\), ZHU Yinfeng (朱银锋)\(^1,2\), HUANG Ronglin (黄荣林)\(^1\), FU Peng (傅鹏)\(^1\), DING Yixiao (丁选骁)\(^3\)

\(^1\)Institute of Plasma Physics, Chinese Academy of Sciences, Hefei 230031, China
\(^2\)School of Mechanical and Electrical Engineering, Anhui University of Architecture, Hefei 230601, China
\(^3\)College of Electrical and Information Engineering, Hunan University, Changsha 410082, China

Abstract The superconducting toroidal field (TF) plays an important role in a superconducting tokamak, whose power supply was developed based on the feedback control principle. In this paper, superconducting tokamaks in different countries are described, and the TF power supply of the International Thermonuclear Experimental Reactor (ITER) is taken as an example to study the current-sharing characteristics in the current-stabilized stage. Firstly, the mathematical model of the TF power supply is established, and then the 3-loop control method is put forward for achieving the stability and reliability of current-stabilization and current-sharing. Furthermore, further studies indicate that the current-sharing controller has no influence on the current-stabilizing control, and current-stabilizing and current-sharing can be realized at the same time. All the work done provides valuable references for the current-sharing design of the TF power supply for a superconducting tokamak, and all these studies lay a solid foundation for developing superconducting tokamaks.

Keywords: superconducting tokamak, TF power supply, current-sharing control system

PACS: 74.25.Ha

DOI: 10.1088/1009-0630/14/10/16

1 Introduction

At present, magnetically confined complex superconducting tokamak devices are used to realize controlled nuclear fusion, which can simulate multi-extreme environments at the same time. Therefore, it is selected to explore the scientific and technical feasibility for the peaceful use of commercial fusion energy. Table 1 is an introduction to the superconducting tokamaks of different countries. In structure, a superconducting tokamak consists mainly of the ground support, cryostat, internal and external thermal shields, superconducting toroidal field (TF), superconducting poloidal field (PF), superconducting central solenoid (CS), vacuum vessel, and other in-vessel components. In addition, superconducting correction field coils (CC) are used in large-scale superconducting tokamaks, in which a TF is used to confine the high temperature plasma, so it is crucial to the success of superconducting tokamak. However, the power supply is the basis of stability and reliability of the superconducting TF under operation; therefore, it is very necessary to study TF power supply control systems. For this reason, as an example, the current-sharing control system of the TF power supply for ITER was studied\(^{[1\sim3]}\). Figs. 1 and 2 are the 3-D model of the ITER magnets and their power supply system.

Table 1. Superconducting tokamaks of different countries

<table>
<thead>
<tr>
<th>Device name</th>
<th>EAST</th>
<th>KSTAR</th>
<th>SST-1</th>
<th>JT-60SA</th>
<th>ITER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Country</td>
<td>China</td>
<td>Korea</td>
<td>India</td>
<td>Japan</td>
<td>Europe, China, America, Russia, Japan, Korea, India</td>
</tr>
<tr>
<td>Large radius of plasma (m)</td>
<td>1.7</td>
<td>1.8</td>
<td>1.16</td>
<td>3.16</td>
<td>7.75</td>
</tr>
<tr>
<td>Small radius of plasma (m)</td>
<td>0.4/0.8</td>
<td>0.5~1.0</td>
<td>0.29/0.46</td>
<td>1.02</td>
<td>2.8/4.5</td>
</tr>
<tr>
<td>Aspect ratio R/a</td>
<td>4.25</td>
<td>3.6</td>
<td>4.0</td>
<td>3.1</td>
<td>2.77</td>
</tr>
<tr>
<td>TF B(_T) (T)</td>
<td>3.5~4.0</td>
<td>3.5</td>
<td>2.9</td>
<td>2.7</td>
<td>6.0</td>
</tr>
<tr>
<td>Plasma current IP (MA)</td>
<td>1</td>
<td>2</td>
<td>0.22</td>
<td>5.5</td>
<td>15</td>
</tr>
<tr>
<td>Pulse length t(_p) (s)</td>
<td>60~1000</td>
<td>20~300</td>
<td>300~1000</td>
<td>100</td>
<td>1000</td>
</tr>
<tr>
<td>Cross section shape</td>
<td>D shape</td>
<td>D shape</td>
<td>D shape</td>
<td>D shape</td>
<td>D shape</td>
</tr>
<tr>
<td>Time for completion</td>
<td>2006</td>
<td>2007</td>
<td>–</td>
<td>2014</td>
<td>2018</td>
</tr>
</tbody>
</table>

\(\ast\)supported by the National Basic Research Program of China (973 Program) (No. 2007ID200), the Special Fund of Talent Development of Anhui Province (No. 2009Z056), the Research Fund for the Doctoral Program of Anhui University of Architecture (No.K02425)
3 Mathematical model of the TF power supply for ITER at the current-stabilized stage \[7\]

The TF consists of 18 superconducting coils in series, whose total inductance is \(L\), and loop resistance is \(R\), so the equivalent circuit is shown in Fig. 3, and Eq. (1) can be obtained according to Fig. 3.

\[
\begin{aligned}
U_{d1} - R_1I_1 &= U_d, \\
U_{d2} - R_2I_2 &= U_d, \\
U_d &= L\frac{dI_M}{dt} + RI_M, \\
I_M &= I_1 + I_2.
\end{aligned}
\]

A Laplace transform is performed on Eq. (1), then Eq. (2) is obtained:

\[
\begin{aligned}
U_{d1}(s) - R_1I_1(s) &= U_d(s), \\
U_{d2}(s) - R_2I_2(s) &= U_d(s), \\
U_d(s) &= (Ls + R)I_M(s), \\
I_M(s) &= I_1(s) + I_2(s).
\end{aligned}
\]

The relationship between the controlling voltage \((U_{k1}(s))\) and \((U_{k2}(s))\) and the output voltage of the rectifier is as shown in Eq. (3):

\[
\begin{aligned}
U_{d1}(s) &= \frac{K_{s1}}{T_{s1}s + 1}U_{k1}(s), \\
U_{d2}(s) &= \frac{K_{s2}}{T_{s2}s + 1}U_{k2}(s).
\end{aligned}
\]

On the basis of Eqs. (2) and (3), Eq. (4) is obtained:

\[
\begin{aligned}
\frac{K_{s1}}{T_{s1}s + 1}U_{k1}(s) - R_1I_1(s) &= U_d(s), \\
\frac{K_{s2}}{T_{s2}s + 1}U_{k2}(s) - R_2I_2(s) &= U_d(s), \\
U_d(s) &= \frac{1}{G_I(s)}I_M(s), \\
I_M(s) &= I_1(s) + I_2(s).
\end{aligned}
\]

\(U_d\) — the voltage of load; 
\(U_{d1}\) — the open circuit voltage of the #1 power supply.
4 Design of the feedback control system at the current-stabilized stage

4.1 Design of current-sharing control system

When the TF power supply is operating, the load current is distributed to each power supply according to their own external characteristic, as shown in Fig. 5. The difference of the external characteristic is the reason for the different current-sharing. If the output voltage of one power supply is higher, but the internal resistance is lower, most of the load current will be provided by this power supply, which will lead to full load or over load, and the normal operation of the parallel connection system will be affected.

The load voltage can be obtained from Fig. 5:

\[
\begin{align*}
U_a &= U_{a1} - I_1 R_1, \\
U_d &= U_{a2} - I_2 R_2, \\
I_M &= I_1 + I_2, \\
U_d &= I_M R_l, \\
U_a &= \frac{R_2 R_l U_{a1} + R_1 R_l U_{a2}}{R_1 R_2 + R_1 R_l + R_2 R_l}.
\end{align*}
\]

The load current can be obtained from Fig. 5:

\[
I_1 = (U_{a1} - U_d)/R_1.
\]

Absolute value of the loop current:

\[
|I_p| = |I_1 - \frac{I_M}{2}| = |I_2 - \frac{I_M}{2}| = \left|\frac{I_1 - I_2}{2}\right|,
\]

\[
|I_p| = \frac{1}{2} \left|\frac{U_{a1} - U_d}{R_1} - \frac{U_{a2} - U_d}{R_2}\right|.
\]

From Eq. (10), we know that output current imbalance is mainly caused by the output voltage and the internal resistance of each power supply. Essentially, the current-sharing controller adjusts the output voltage and the internal resistance of each power supply, so the output current is adjusted, and consequently, the current-sharing is realized.
If the difference of the equivalent internal resistance of the 2 groups of power supplies is 10%, which means \( R_2 = 1.1R_1 \), the output voltage is equal; if \( I_M = 68 \text{ kA} \), from Eq. (12) we can obtain the loop current as shown in Eq. (13):

\[
I_{p1} = \frac{R_2 - R_1}{2(R_1 + R_2)} I_M = 1619 \text{ A}. \tag{13}
\]

\[\text{Fig.6}\] Mathemtical model of the TF power supply by single-loop control during the current-stabilizing stage

To increase the working efficiency and to reduce the design capacity of the TF power supply, some measures should be taken to reduce the current difference between the 2 groups of power supplies; therefore, a current-sharing controller is used to ensure the equality of the output current of each power supply, so the best working conditions of each power supply can be obtained, and the stability, reliability and high efficiency of the TF power supply system can be achieved.

In addition, the relationship between the output voltage \( (U_{di}) \) and the phase voltage of each power supply is as shown in Eq. (14).

\[
U_{di} = 2.34U_{2i}\cos \alpha_i. \tag{14}
\]

In Eq. (14), \( U_{2i} \) — phase voltage of each power supply; \( \alpha_i \) — controlling angle of each power supply.

From Eq. (14), the difference of the phase voltage of each power supply and the controlling angle of each power supply will inevitably lead to a difference in their output voltage, which can cause the loop current to exceed the permitted values. Therefore, this method cannot satisfy the requirements, and the current-sharing controller method should be adopted.

The current-sharing method is based on the single control system and realized by adding the current-sharing loop. The TF power supply is formed by parallel connection of two 3-phase bridges, the output current of the 2 groups of power supplies is adjusted by the current-sharing loop, which reduces the output current influence by the difference in the circuit parameters. This current-sharing method can realize a steady current and current-sharing at the same time. With its structural drawing as shown in Fig. 7, it is referred to as a 3-loop controlling system [8~10].

In Fig. 7, \( K_0 \) — coefficient of the current sensor; \( U_{sc1}(s) \) and \( U_{sc2}(s) \) — the deviation voltage by the current-sharing loop of each power supply; \( U_c(s) \) — the output voltage of the external loop adjuster; \( G(s) \) — the current adjuster of the TF power supply; \( \alpha_1 \) and \( \alpha_2 \) — the deviation amplification factor of the current-sharing loop of each power supply.

From Fig. 7 we can obtain Eq. (15):

\[
\begin{cases}
U_{d1} = K_{s1}[U_c - K_1(I_{p1}^2 - I_1)], \\
U_{d2} = K_{s2}[U_c - K_2(I_{p1}^2 - I_2)].
\end{cases} \tag{15}
\]

In Eqs. (15) and (16), \( U_c \) — the output voltage of the regulator. Eq. (16) is the corresponding relationship between the loop current and circuit parameters and the controlling parameters in the 3-loop controlling system: obviously, under the current-sharing controlling, the loop current still includes two parts, caused by the difference in voltage and resistance.

From Eq. (16), the loop current \( (I_{p1}) \) caused by resistance difference is as shown in Eq. (17):

\[
I_{p1} = \frac{R_3 - R_2}{2(K_1K_{s1} + K_2K_{s2} - R_1 + R_2)} I_M. \tag{17}
\]

Compared with Eq. (13), we obtain Eq. (18):

\[
I'_{p1} = \frac{R_3 + R_2}{R_1 + R_2 - (K_1K_{s1} + K_2K_{s2})} I_{p1}. \tag{18}
\]

When the controller is designed, the parameters of the current-sharing loop of the 2 groups of power supplies should be equal, \( K_1 = K_2 \). Obviously, the higher the \( K_1 = K_2 \), the lower the loop current; however, \( K_1 = K_2 \) is constrained by the controlling voltage \( U_{ki} \).

Once the parameters of the current-sharing loop are decided, the requirements of the current-sharing and its influence on the current accuracy should be considered at the same time.

If the parameters of the 2 groups of power supplies are considered equal, which are \( K_{s1} = K_{s2} = K_{si} \), \( I_{s1} = I_{s2} = T_{s1} \), \( R_1 = R_2 = R \), we can obtain Eq. (19) from Fig. 7.
The current-sharing is as follows:

\[
\begin{align*}
U_{d1} & = \frac{K_{s1}}{T_{s1} + 1}[U_c - K_1(I_M/2 - I_1)], \\
U_{d2} & = \frac{K_{s2}}{T_{s2} + 1}[U_c - K_2(I_M/2 - I_2)], \\
I_1 & = \frac{U_{d1} - U_a}{R}, \\
I_2 & = \frac{U_{d2} - U_a}{R}, \\
I_M & = I_1 + I_2, \\
U_a & = \frac{1}{G_1}I_M.
\end{align*}
\]

From Eq. (19) we can obtain Eq. (20):

\[
I_M = \frac{2K_s}{(T_s + 1)(R + 2G_1)}U_c.
\]

So the open-loop transfer function is shown in Eq. (21):

\[
G(s) = \frac{2K_sK_0K_{p2}G_1}{(T_s + 1)(RG_1 + 2)}.
\]

In Eqs. (20) and (21), \(K_s\) - the coefficient of amplification; \(K_0\) - the sampling coefficient; \(K_{p2}\) - the ratio amplification coefficient of the current regulator.

Obviously, the added current-sharing loop has no influence on the transfer function of the original system, so the added current-sharing loop has no influence on the accuracy of the steady current. With the 3-loop controlling system, which realizes current-sharing by the added current-sharing controller, current-stabilizing and current-sharing are realized by the different loops, the current-stabilizing is realized by the external loop adjuster, the current-sharing loop corrects the parameters of the power supply, and the current-sharing is realized by reducing the loop current between them. For each power supply, it does not set the current regulator alone, so there certainly is a loop current between the 2 groups of power supplies; therefore, the loop current between the 2 groups of power supplies must exist by 3-loop controlling, which can be expressed by Eq. (16). However, the loop current between the 2 groups of power supplies is constrained by the current-sharing loop. The feedback process is as follows:

If \(U_{d1}\) is rising, \(U_{d2}\) is unchangeable, so \(I_1 > I_2\), it is cleared that the loop current between the 2 groups of power supplies \(I_p = \frac{I_1 - I_2}{2}\) is rising, the process of current-sharing is as follows:

\[
I_1 \uparrow \Rightarrow I_p \uparrow \Rightarrow \begin{cases} U_{k1} \Rightarrow \alpha_1 \Rightarrow \cos \alpha_1 \Rightarrow U_{d1} \Rightarrow I_1 \uparrow \Rightarrow I_2 \downarrow \Rightarrow U_{k2} \Rightarrow \alpha_2 \Rightarrow \cos \alpha_2 \Rightarrow U_{d2} \Rightarrow I_2 \downarrow. \end{cases}
\]

Under the 3-loop controlling system, the current-sharing process has not only the loop current between the 2 groups of power supplies becoming lower, but also has the current-stabilizing process, where the current-sharing loop can restrain the alternating current effectively. Under the condition that the total current does not change, the loop current between the 2 groups of power supplies is limited to satisfy the requirements.

### 4.2 Simulating circuit at the current-stabilized stage

According to the requirements of the 3-loop control system, the entire steps to design the circuit are as follows:

- **a.** Comparing the given excitation current \(I_{\text{ref}}\) and the total current \(I_M\) of the magnets, and obtaining \(U_c\) by interpolation calculation.

- **b.** Sampling the current of magnets, then the obtained values are decreased to \(\frac{I_M}{2}\).

- **c.** Sampling the output current \(I_1\) and \(I_2\) of double 3-phase bridges, then the currents are performed with low-pass filters.

- **d.** Comparing the current of double 3-phase bridges and half of the current \(\frac{I_M}{2}\) of magnets, respectively, then enlarging the difference and output \(U_{sc1}\) and \(U_{sc2}\).

- **e.** Comparing \(U_c\) with \(U_{sc1}\) and \(U_{sc2}\), respectively, then the results are performed with low-pass filters, and \(U_{k1}\) and \(U_{k2}\) are obtained.

- **f.** Constraining the \(U_{k1}\) and \(U_{k2}\) in the range of 0 ~ 10 V.

### 5 Simulation

To verify whether the 3-loop controlling system can meet the requirements, simulations of the 1-loop and 3-loop control system are performed based on the methods indicated in Fig. 6 and Fig. 7, and the two simulating diagrams are shown in Fig. 8 and Fig. 9. The calculated inductance \((L)\) of the TF magnets is 17.33 H, the resistance \((R)\) of the bus bar between the power supply and the TF magnets is 0.48 mΩ, the resistance of the power supply module is 0.26 mΩ, which includes the leakage magnetic flux of the transformer and the equivalent resistance of the thyristor. From the obtained results as shown in Fig. 10 and Fig. 11, we know when the given current is rated 68 kA, the stabilized current of the 1-loop control system is 67884.43 A, which is lower than the rated current, the difference is 115.57 A, the output current of No.1 power supply is 35560.27 A, the
output current of No.2 power supply is 32324.16 A, so the output current of No.1 power supply is bigger than that of No.2 power supply, and the difference is 3235.11 A. Obviously, the difference between the currents is bigger than the required peak value 680 A. However, the stabilized current of the 3-loop control is 67884.35 A, and compared to the given values, the difference is 115.65 A, the output current of No.1 supply is 34258.17 A, the output current of No.2 supply is 33626.18 A, so the output current of No.1 power supply is bigger than that of No.2 power supply, and the difference is 631.99 A. Clearly, the difference between the currents is lower than the required peak value 680 A. Consequently, the 3-loop controlling systems can satisfy the requirements.

6 Conclusion

a. The superconducting tokamak and the TF power supply for ITER are briefly introduced, and the necessity of current-sharing control is analyzed, which provides the aim for performing the study on the TF power supply for ITER.

b. The added current-sharing controller has no influence on the current-stabilized control of the TF power supply for ITER, and the current-stabilized and current-sharing can be realized at the same time.

c. Under the 3-loop controlling system, the loop current becomes lower with the current-sharing process, which is also the current-stabilized process of the 2 groups of power supplies, and the current-sharing loop can restrain the alternating current effectively.

d. The simulating results indicate that the 1-loop controlling system cannot satisfy the requirements, but the 3-loop controlling system can satisfy the requirements.

References

6 Chen Peng, Fu Peng, Song Zhiquan. 2011, Plasma Science and Technology, 13: 497

(Manuscript received 18 July 2011)
(Manuscript accepted 25 October 2011)
E-mail address of ZHU Zhe: zhuzh66@163.com