Design of Controller for New EAST Fast Control Power Supply

HUANG Haihong (黄海宏), YIN Ming (殷明), WANG Haixin (王海欣)

School of Electrical Engineering and Automation, Hefei University of Technology, Hefei 230009, China

Abstract The effectiveness of the magnetic confinement of plasma can be improved by elongating the plasma cross-section in tokamak devices. But elongated plasma has vertical displacement instability, so a feedback control system is needed to restrain the plasma’s vertical displacement. A fast control power supply is needed to excite the active feedback coils, which produces a magnetic field to control the plasma’s displacement. With the development of EAST, the fast control power supply needs to keep on enhancing the fast response and output current. The structure of a new power supply is introduced in this paper. The method of multiple inverters paralleled with the current sharing reactor is presented to meet the need for large current and fast control. According to the design demands of the EAST fast control power supply, the adjuster of the current close loop is applied to the inverter, which can advance its ability to restrain the loop current in low frequency and DC output. The result of the experiment confirms the validity of the proposed scheme and control strategy.

Keywords: EAST, plasma, vertical stability, active feedback, fast control power supply, current close loop

PACS: 52.55.−s

DOI: 10.1088/1009-0630/16/11/13

(Some figures may appear in colour only in the online journal)

1 Introduction

The toroidal magnetic constraint tokamak device holds much promise for development into a commercial nuclear fusion power reactor. Elongating the plasma cross-section is a popular method to increase the ability of the magnetic field to constrain plasma [1], but elongated plasma has vertical displacement instability, so a feedback system is needed to restrain the plasma vertical displacement [2]. There are two methods of feedback control for plasma vertical displacement: passive feedback and active feedback. Passive feedback is a kind of fast response on the millisecond level. A conductor around the plasma (such as the metal wall of the vacuum vessel) will induce eddy current and produce a magnetic field if the plasma moves in a vertical direction, and the radial component of the magnetic field interacting with the plasma current produces a Lorentz force in the opposite direction to the plasma movement, which is the principle of passive feedback. But passive feedback will weaken after the conductor diffusion time because the eddy current is dissipated by conductor resistance. Therefore, active feedback is needed for slow disturbance beyond the diffusion time scale.

2 Active feedback control of plasma vertical displacement

The method of achieving active feedback is to sample the signal of the plasma’s vertical displacement and feed it back to a control power supply, upon which the current in the active feedback coils will be built up to produce a magnetic field to restrain the plasma’s vertical displacement.

Because the vacuum vessel causes a 24 ms and 11.5 ms shielding delay for the vertical component and radial component of the magnetic field caused by poloidal magnetic field coils, respectively, active feedback coils are installed in the EAST vacuum vessel as shown in Fig. 1. IC1 and IC2 are a pair of symmetrical active feedback coils positioned as a saddle shaped connection across the vertical conductor.

The active feedback coils in the vacuum vessel are shown in Fig. 2. There are two turns of each coil, and these are not connected. The coils are passed out of the vacuum vessel through the leading-out end. The connection method of the leading-out end depends on the requirements of the experiments.

The water cooling structure was adapted to the coils,
and the conductor was circular hollow copper wire. Coil turns: \( N = 4 \); Length of each turn: 15.5 m; Distance between upper and lower coil: 1.205 m; Net section of cooling hole: 1.327 cm\(^2\); Net section of conductor: 5.278 cm\(^2\); Max current: 20 kA.

There are two connection methods for active feedback coils: horizontal field connection (the series upper coils are connected to the series lower coils in series opposing configuration) and vertical field connection (the series upper coils are connected to the series lower coils in series configuration). The inductance of the active feedback coil is approximately 66 \( \mu \)H for the horizontal field connection method, and 72 \( \mu \)H for the vertical field connection method.

The working principle of EAST’s active feedback system to restrain the plasma’s vertical displacement is shown in Fig. 3 [3]. The plasma control system (PCS for short) detects plasma vertical displacement, and calculates a given signal for the fast control power supply. The given signal is linearly amplified and tracked in real time by the power supply. Then the power supply excites the feedback coil in the vacuum vessel to produce a magnetic field, which realizes the vertical balance and locates the plasma.

\[ \text{Fig. 3} \quad \text{Principle of EAST active feedback to plasma’s vertical displacement} \]

### 3 New power supply

The existing fast control power supply began to run in 2006, and its parameters are as follows [4]:

- Max output voltage \( (U_m) = \pm 800 \) V, Max output current \( (I_m) = \pm 5000 \) A.
- Current response time: \( t_r < 5 \) ms, from \(-5000\) A to \(5000\) A.

The factors affecting feedback control are current response time, ability to track current and max output current. With the development of EAST, the power supply needs to keep on enhancing its fast response and output current. Current response time and max output current mutually affect one another, and relatively the current response time is more important to the system. Because the primary part of the load is inductant, the most efficient measure to shorten response time is to heighten the output voltage.

The parameters of the new power system are as follows [5]:

- Max output voltage \( (U_m) = \pm 1600 \) V, Max output current \( (I_m) = \pm 9000 \) A.
- Voltage response time: \( t_{rv} < 1 \) ms, current response time: \( t_{ri} < 2 \) ms, from \(-9000\) A to \(9000\) A.

An IPM (Intelligent Power Module) with 1200 V/2400 A is used as the power device in the new power supply. The structure of the new power supply is shown in Fig. 4.
To output 1600 V voltage, three H-bridges are cascaded to build a branch. To output 9000 A, six branches are paralleled in the system. There is a sharing current reactor at each inverter branch output side to limit the loop current from the parallel connection.

The controller consists of three parts: a unit controller, a branch controller and a master controller. Each H-bridge inverter unit is equipped with one unit controller. The unit controller can collect the rectifier voltage and current of every power unit, achieve soft-start of the AC input and has a protective function. A branch controller is used to manage one inverter branch which consists of three converter units. The given signal and the current signal of the inverter branch output are collected by the branch controller. The branch controller controls the PWM signals of the IPM by fibre, which can control the switch state of the IGBT. The other function is system protection which can be achieved by collecting the fault output signals of the IPM. The master controller detects signals from the PCS, unit controller information and the total voltage and current signals of the power supply. The signals from the PCS are isolated and allocated to all of the branch controllers. The information is integrated by the master controller and is used to control the PWM control signals which are sent by branch controller. The controllers' relationships are shown in Fig. 5.

To decrease switching loss, since large power devices can't switch very fast, the switching frequency of the IPM is 5 kHz. However, the PWM control of low switching frequency results in plentiful low frequency harmonics in the output wave, which will reduce control precision. So the technique of carrier phase-shift PWM was adopted in the new power supply to raise equivalent switching frequency, reduce low frequency harmonics and improve output wave.

The electrical structure of the branch controller is shown in Fig. 6. The high-performance DSP (TMS320F2812) from TI Company is used as the main control chip for the branch controller. The high-accuracy AD sampling chip is used to detect the given signal of the PCS and the output current of the inverter branch in real time, which are used by DSP to calculate the PWM control signal. The H-bridge structure with three levels is adopted in the power circuit to improve system equivalent switching frequency. The controller generates two 180° complementary carriers to modulate the left and the right arms of the H-bridge, which could achieve 10 kHz equivalent switching frequency for a single H-bridge PWM output. Using CPLD (Complex Programmable Logic Device), DSP output 4-way PWM waves are phase shifted 60° and 120° respectively to control the second and the third IPM of the cascaded H-bridges. Through the carrier phase shift between H-bridges, the equivalent switching frequency of each inverter branch reaches 30 kHz, which could effectively improve the quality of the output current waveform.

![Fig.6 Structure of branch controller](image)

![Fig.5 Structure of controller](image)
4 Design of control strategy

A universal sine-wave inverter with large capacity is made up with several parallel invert units, which has problems concerning current unbalance and circulating current. The overlarge circulating current may increase the burden of the inverter, and the dispersed circulating current may even break down the system. Considering that the function of EAST fast control power supply of vertical stability is to produce fast changing magnetic field by output excitation current to control plasma vertical displacement, its load is an inductance load with small resistance, so the output voltage of power supply mainly influences the current rising rate instead of the current value. To overcome the current unbalance problem in a paralleled invert system, the current closed-loop proportion controller is used in the inverter unit, and the input current signal is tracked in real time and linearly amplified. Its feedback signal comes from the current of sharing a current reactor. If the nonlinear loop, while the real part is increased by

\[ G(s) = \frac{K_0 e^{-\tau s}}{\beta K_0 + (R + L_\text{s})} \]  

Due to \( \tau s << 1 \), thus \( e^{-\tau s} \approx 1 - \tau s \), Eq. (2) can be simplified as:

\[ G(s) = \frac{K_0(1 - \tau s)}{\beta K_0 + R + (L - \beta K_0 \beta \tau)s}. \]  

The system’s stability range reduces because a zero point and a pole point are added to the system. To increase the stability of the system, or to increase the phase margin, when a pole point is added to the feedback loop, a zero point must be added as well. So the transfer function of the feedback branch’s low pass filter is \((1 + \tau_2 s)/(1 + \tau_1 s)\), and \(\tau_2 << \tau_1\). Then the high harmonic can be weakened above the frequency determined by the pole point, while the phase shift decreases above the frequency determined by the zero point. Suppose \( K_1 = K_0 e^{-\tau_2 s}/(R + L_\text{s}) \), then:

\[ G(s) = \frac{K_1}{1 + \beta_1(1 + \tau_1 s)} \]

Suppose \( \tau \) is the delay time in modulating the course, then the amplification gain of the PWM modulating amplifier is \( K_0 e^{-\tau s} \), Eq. (1) is changed as follows:

\[ G(s) = \frac{K_0 e^{-\tau s}}{\beta K_0 + R + L_\text{s}} \]  

The stability condition of the system is \( L - \beta K_0 \beta \tau > 0 \), and the maximum delay time in the modulation process is a period of carrier wave \( T \), so \( L > \beta K_0 \beta T \). Supposing \( f_k \) is the carrier frequency, the stability condition can be shown as follows:

\[ L f_k > \beta K_0 \]  

In conclusion, \( \beta K_0 \) should make a reasonable choice of open-loop gain according to the values of the equalizing reactor and carrier frequency. When a higher value of equalizing reactor is chosen, the system can allow a higher value of \( \beta K_0 \), which can improve the ability of paralleled inverters to current share. But the load of this power system is coil, and it is mainly inductive. Increasing the value of the equalizing reactor will influence the value of the load voltage and change the rate of the load current, which will decrease the effectiveness of the power current response. Thus the value of the equalizing reactor should be limited to a reasonable range. Increasing the carrier frequency is also beneficial to system stability, but the choice of carrier frequency should be limited by the allowable switching frequency value of the IPM.

Since output current contains lots of high harmonics, a one-order low pass filter is added for feedback current, so another pole will be brought in. Then the single pole feedback coefficient will be \( \beta_1 = \beta/(1 + \tau_1 s) \). The transfer function turns out to be:

\[ G(s) = \frac{K_0 e^{-\tau_2 s}}{1 + \tau_1 s} \]

Suppose \( K_1 = K_0 e^{-\tau s}/(R + L_\text{s}) \), then:

\[ G(s) = \frac{K_1}{1 + \beta_1(1 + \tau_1 s)} \]

\[ G(s) = \frac{K_1(1 + \tau_1 s)}{(1 + \beta_1)(1 + \tau_1 s + \frac{\tau_1 + \beta K_1 \tau_2 \tau_1}{1 + \beta K_1})}. \]
Compared with the former system, a pole point and a zero point are added. The zero point is equal to the pole point in the feedback branch. When \( \beta K_1 > 1 \), the added pole point is very similar to the zero point. To increase the stability of the system, a one-order low pass filter should be added to the input signal branch, which is before the feedback loop. This is a single zero pole system. If the zero point and pole point of the low pass filter are matched with those added in the closed loop transfer function, the low pass effect in the feedback branch will be eliminated. The transfer function is still \( K_1/(1+\beta K_1) \) for the input signal port, which is beneficial to the closed-loop system. The control block diagram is shown in Fig. 8.

\[
G(s) = \frac{K_0 T_2 s + K_0}{L T_1 s^2 + (R T_1 + L + K_0 \beta T_2) s + (R + K_0 \beta)}.
\]  

(7)

When the actual parameters of the system are substituted into Eq. (7), the Bode diagram of the inverter unit's current inner-loop is shown in Fig. 9. The phase margin of the inverter unit’s current inner-loop is approximately 92° and the cutoff frequency is approximately 60 kHz.

5 Result of experiment

The function of the fast control power supply of EAST is to track the reference signal in real time. To detect the power system’s current tracking ability and each inverter branch’s current sharing condition, a 100 Hz sine wave and square wave have been used as given signals in the experiment. The experimental waveforms are shown in Fig. 10. The input signal is shown in channel 1. The output currents of three branches are detected by current sensor (output relation is 1 V to 735 A) and shown separately in channels 2 to 4. In Fig. 10, the delay time of the output current to input signal is just about 0.6 ms, and every branch can output 1500 A, so the system can output 9000 A. In Fig. 10(b), the time from −9000 A to 9000 A is about 1.6 ms. The current waves of the three branches are basically in coincidence. Considering the peak-peak value, the current uneven degree is less than 1.7%.
In Fig. 11(a), the peak value of the output current is 1500 A, as shown in channel 3, and the equivalent switching frequency of a single H-bridge is 10 kHz. In Fig. 11(b), the peak value of the output current is 1050 A, as shown in channel 2, and the equivalent switching frequency of the inverter is 30 kHz. It is obvious that the quality of the output current wave is improved with an increase of equivalent switching frequency.

![Fig.11 Comparison of input signal with output current wave](image)

(a) Single H-bridge, (b) Three H-bridges in cascade

### 6 Conclusions

Research into nuclear fusion is an important step towards solving the energy problems of mankind. Tokamaks hold promise for development into fusion reactors. The method of elongating plasmas in tokamak devices can improve the ability of the magnetic field to constrain the plasma. However, the vertical displacement of the elongated plasma is not stable. As an important part in active feedback control systems, a fast control power supply adopting several H-bridges with cascaded and paralleled inverters is introduced.

The parallel inverter technique is an effective method to improve the reliability of the inverter system and to enlarge system capacity. The key to the successful operation of parallel voltage source inverters is to ensure the performance of the system and to achieve good current sharing between each inverter unit. Compared with the traditional sine wave inverter, it is difficult to share current between each inverter unit because the load of the EAST fast control power supply is an inductance coil with low resistance. In order to effectively restrain circulation, the closed-loop output current feedback mode was used in the power supply, which let the voltage source inverter present the current source inverter’s characteristics, and effectively solved the problem of current sharing between inverter units. It is confirmed by experiments that the new power supply system can supply large currents, has good tracing and sharing current abilities, and thus can meet the design requirements.

### References


(Manuscript received 20 March 2014)
(Manuscript accepted 30 April 2014)
E-mail address of HUANG Haihong: hhaihong741@126.com