Long-pulse power-supply system for EAST neutral-beam injectors

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Abstract

The long-pulse power-supply system equipped for the 4 MW beam-power ion source is comprised of three units at ASIPP (Institute of Plasma Physics, Chinese Academy of Sciences): one for the neutral-beam test stand and two for the EAST neutral-beam injectors (NBI-1 and NBI-2, respectively). Each power supply system consists of two low voltage and high current DC power supplies for plasma generation of the ion source, and two high voltage and high current DC power supplies for the accelerator grid system. The operation range of the NB power supply is about 80 percent of the design value, which is the safe and stable operation range. At the neutral-beam test stand, a hydrogen ion beam with a beam pulse of 150 s, beam power of 1.5 MW and beam energy of 50 keV was achieved during the long-pulse testing experiments. The result shows that the power-supply system meets the requirements of the EAST-NBIs fully and lays a basis for achieving plasma heating.

Keywords: EAST, neutral-beam injector, power supply, long pulse

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

1. Introduction

In order to carry out the physical and engineering research on the state of high-density and high-temperature plasma, the EAST (Experimental Advanced Superconducting Tokamak) is equipped with two neutral-beam injectors (NBIs) as the auxiliary heating and current drive system [1–3]. At the first step, a neutral-beam test stand was constructed and operated in 2012, which has a similar structure to the EAST-NBIs, but without the injection unit [4]. The neutral-beam test stand was used for the conditioning and testing of the EAST-NBI ion source, and to demonstrate the feasibility and reliability of the other key components. The first neutral-beam injector (NBI-1) with two 4 MW ion sources was located in port A of EAST in order to be paralleled to the plasma current (co-direction), and the injector was operated in the EAST summer experiment in 2014. The second identical neutral-beam injector (NBI-2) was located in port F of EAST, and was anti-paralleled to the plasma current (counter-direction), which was operated in the EAST summer experiment in 2015.

Based on the EAST layout, involving both co-injection and counter-injection of neutral beams, it is feasible to research the physics issues of plasma rotation due to the momentum pinch [5]. A bird’s-eye view of two neutral-beam injecting lines on the EAST is illustrated in figure 1. The design values of EAST-NBI-1 and 2 are as follows: beam energy 50–80 keV, injection beam total power 2–4 MW, beam-pulse width 10–100 s. In order to achieve this aim, the power supply (PS) system should fulfill the requirement of long-pulse operation. In this paper, the topology and long-pulse operation experimental results of the PS system are introduced.

2. Long-pulse power-supply system

A long-pulse PS system in the EAST-NBI is made up of five sets of PSs: one is for the NBI test stand and the other four are for NBI-1 and NBI-2. Each set of PS systems consist of an arc PS, a filament PS, a beam-extraction PS and a bending-magnet PS. After 32 filaments are heated by a filament PS, the arc discharge is initiated by the arc PS, which supplies the arc voltage between the chamber wall and the negative plates of the 32 filaments. The negative output of the arc PS is
connected to the negative output of the filament PS. The beam-extraction PS provides a high-voltage and high-current PS for the plasma grid (PG). In addition, a voltage divider offers voltage to a gradient grid (GG) in the range of the PG voltage. The negative output of the suppressor grid (SG) PS is connected to the SG and its positive output is connected to the exit grid (EG). The bending-magnet PS is independently conducted to the magnet coil in the beam vacuum tank. As an important component in the PS system of the EAST-NBI, the snubber coil limits the beam energy deposited to the accelerator grid [6]. Figure 2 illustrates the schematic drawing of one 4 MW ion-source PS system. Along with the development of the NBI test stand, a PS system for the NBI test stand was designed and developed at the same time. Table 1 presents the specifications of the PS system for the NBI test stand and EAST beam lines.

2.1. Plasma-generator power supply

The plasma-generator PS includes the filament PS and arc PS. These PSs, which are located on the high-potential platform of the PG PS of the ion source, have a similar topology (see figure 2). Additionally, the cooling method for both of the PSs is air cooling instead of water cooling in this system. The filament PS, which is powered by an AC 380 V supply, can provide a maximum 20 V/5500 A constant-output voltage to 32 tungsten wires 1.5 mm diameter in parallel mode. The main circuit structure of the filament PS consists of a three-phase controlled converter, an isolating transformer, and output diode stacks and controllers. The function of the arc PS is to use thermal electrons generated by a filament to excite plasma. The arc PS is powered by an AC 380 V supply, and can supply a maximum 176 V/3000 A constant stable output [7, 8]. In order to match the rising edge of the high voltage, the arc PS also has a notch channel, which consists of a set of IGBT (insulated gate bipolar transistor) switches and resistors.

2.2. High-voltage power supply

The high-voltage PS system for the ion-beam extraction is made up of a PG PS, a GG voltage divider, and an SG PS (see figure 2). The maximum output value of the PG PS to the plasma grid is 95 kV/70 A. The PG PS consists of a high-voltage isolating transformer and two high-voltage rectifier platforms, each of which can provide 50 kV DC. Each high-voltage rectifier platform consists of 72 pulse-step modulation (PSM) units in series [9], and every unit can output 750 V DC through the IGBT in less than 20 μs (see figure 2) [10]. When the PSM units are switched on, a high voltage is applied to the PG. Meanwhile, the voltage divider of the PG allocates the voltage to the GG based on a preset rate (75%–90% of the PG voltage), which allows a 1% adjustment rate, and then delivers it to the GG. The SG PS consists of a high-voltage rectifier: a set of series IGBT switches for ON/OFF output. It is able to deliver a maximum output of −5 kV/30 A for the SG.

2.3. Arc discharge mode for long-pulse beam extraction

In order to achieve stable long-pulse operation, the real-time feedback-control method was used on the arc PS of the EAST-NBI ion source. This method involves using a Langmuir probe to measure the plasma density, then controlling the arc voltage to achieve stable discharge and beam extraction [11]. The Langmuir probe was installed in front of the accelerator to measure the plasma density with negative bias voltage. Figure 3 gives the schematic of the probe feedback mode to control the arc PS.

2.4. Power-supply operation mode of long-pulse-modulating beam extraction

An essential method for part transport analysis of plasma is the modulation of the neutral-beam injection. In this mode, the ion source can worked alternately at 1–100 Hz frequency. Figure 4 illustrates the voltage/current waveforms of the gas power, the filament PS, the arc PS, the SG PS and the accelerating PG PS during modulation of the beam extraction in the NBI test stand.

3. Experiment results

In order to test the ability of long-pulse beam extraction, the waveform of the beam extraction of each PS was measured. Figure 5 gives the 150 s modulating beam extraction in the test stand. The neutral-beam lines of NBI-1 and NBI-2 installed on EAST have two positive ion sources, respectively, and every ion source is supplied by a set of the PS system. Figure 6 gives the waveform of NBI-1 electrical parameters in EAST 102 s long-pulse plasma. Here, the waveform of the electrical...
parameters of the right ion source (1R) and left ion source (1L) of NBI-1 with the plasma current ($I_p$) in EAST are shown.

Table 1. Specification of PSs of the NBI test stand and NBI lines of EAST.

<table>
<thead>
<tr>
<th>Item</th>
<th>NBI test stand</th>
<th>NBI-1 (2 sets)</th>
<th>NBI-2 (2 sets)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filament PS</td>
<td>20 V, 5.5 kA</td>
<td>20 V, 5.5 kA</td>
<td>20 V, 5.5 kA</td>
</tr>
<tr>
<td>Arc PS</td>
<td>200 V, 3 kA</td>
<td>176 V, 3 kA</td>
<td>176 V, 2 kA</td>
</tr>
<tr>
<td>PG PS</td>
<td>100 kV, 100 A</td>
<td>95 kV, 70 A</td>
<td>95 kV, 70 A</td>
</tr>
<tr>
<td>GG voltage divider</td>
<td>75%–90% of V(PG)</td>
<td>75%–90% of V(PG)</td>
<td>75%–90% of V(PG)</td>
</tr>
<tr>
<td>SG PS</td>
<td>−4 kV, 20 A</td>
<td>−5 kV, 30 A</td>
<td>−5 kV, 30 A</td>
</tr>
<tr>
<td>Beam-pulse length</td>
<td>10–100 s</td>
<td>10–100 s</td>
<td>10–100 s</td>
</tr>
<tr>
<td>Bending-magnet PS</td>
<td>80 V, 600 A</td>
<td>80 V, 600 A</td>
<td>80 V, 600 A</td>
</tr>
<tr>
<td>Snubber-coil PS</td>
<td>30 V, 100 A</td>
<td>50 V, 150 A</td>
<td>50 V, 150 A</td>
</tr>
</tbody>
</table>

Figure 2. Schematic drawing of a set power supply (PS) for one ion source.

Figure 3. Probe feedback mode to control the arc PS.
4. Conclusion

The PS of the NBIs is a complex system. For long-pulse beam extraction, it stakes a higher claim in terms of stability and reliability. The result obtained in the NBI test stand [12] and

EAST-NBI-1 and 2 [13, 14] show that the PS system can meet the requirements of long-pulse beam extraction and this provides the basis for neutral-beam plasma heating.

Acknowledgments

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