Optimization Design for a High Voltage DC Power Supply Module Based on PSM Technology

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Abstract Pulse step modulator (PSM) topology is applied to the EAST auxiliary heating system, which consists of a neutral beam injection (NBI) and the related microwave heating system. This paper firstly analyzes the merits and demerits of the traditional PSM modules adopted by other international companies, and then optimizes the topology of the module using the analysis results. Finally, a new topology for the PSM module (a three-phase neutral-point diode-clamped rectifier) is proposed. This new module overcomes the problems of traditional modules and has better cost-effective performance. The experimental results verify that the new module is feasible for engineering applications.

Keywords: pulse step modulation, tokamak, HVPS, power supply module, NBI

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

1 Introduction

EAST is a tokamak facility built in ASIPP in 2006 \(^[1,2]\). A certain plasma current was achieved when it was operated for the first. In order to achieve much better physical parameters, EAST needs to be equipped with auxiliary heating systems such as NBI, LHCD, and so on. All of these systems need to be supplied by HVPS. Therefore, a kind of HVPS with PSM topology has been designed and successfully implemented, as shown in Fig. 1. A maximum steady output voltage of 100 kV were achieved and a maximum steady output current of 100 A in HVPS, respectively, in 2009 \(^[3-8]\). However, this HVPS still needs to be optimized to reduce the volume and cost. The best way is to optimize the module of the switching mode power supply (SMPS), since the volume and cost of the transformer are closely related to the capacity of HVPS; however, it is difficult to reduce them.

Fig.1 The HVPS on-site

2 Comparison between different SMPSs

2.1 SMPS requirement in EAST

The load of HVPS is ion sources, and it can hold very high voltages up to 100 kV with a current of 100 A. In order to prevent damage of the ion sources under the voltage breakdown condition, HVPS has to be switched off for several microseconds (\(\mu\)s) when a voltage breakdown occurs. In order to accomplish this requirement, IGBT must be applied in the SMPS. The detailed requirements of the SMPS are shown in Table 1.

Table 1. The requirements of each SMPS

<table>
<thead>
<tr>
<th>Items</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input voltage</td>
<td>AC 900 V</td>
</tr>
<tr>
<td>Output current</td>
<td>DC 100 A</td>
</tr>
<tr>
<td>Operation mode</td>
<td>Continuity</td>
</tr>
<tr>
<td>Turn-off time</td>
<td>&lt; 5 (\mu)s</td>
</tr>
<tr>
<td>Switching device</td>
<td>IGBT</td>
</tr>
</tbody>
</table>

2.2 Description of former EAST SMPS modules

Fig. 2 shows the three-phase full-wave rectifier module \(^[4]\). It is composed of a main circuit and a module controller. The main circuit comprises a contactor, a soft-starting circuit, a crowbar, IGBT, and so on. The module controller comprises an IGBT trigger, protection circuit, and the control board, which can communicate with the main control cabinet.
As with the EAST SMPS, the input voltage for each module is AC 900 V, but with 10% fluctuations from the grid, the output of each module can reach DC 1400 V. Thus, one IGBT at 1700 V is not enough; 3300 V IGBT has to be employed, but this is very expensive.

To reduce the cost with the previous topology, there are two methods available. One is to connect two IGBTs at 1700 V in series instead of one IGBT at 3300 V. But it is difficult for the two IGBTs to have a balanced dynamic voltage. The other is to decrease the input voltage from AC 900 V to AC 550 V, but more modules will be demanded. Meanwhile, the transformer will be more complicated because of further secondary windings. So, in order to optimize the HVPS, the SMPS topology has to be changed.

2.3 Description of SMPS modules for small current applications

Fig. 3 shows the three-phase half-wave rectifier module introduced by the THOMSON company for klystron [9,10]. When this type of SMPS is under operation, both IGBTs will share the DC voltage at the output terminal of the module. But it has a fatal issue: the ripple current flowing through the filter capacitor will reduce the service life of the capacitor when the output current of the module is above 100 A. If a thin capacitor is adopted, the volume is bigger than the electrolytic capacitor with the same capacitance. Meanwhile, the DC component of the secondary winding of the converter transformer is high, which may cause DC magnetization of the transformer when one half bridge is under operation. So, it can only be used for smaller current applications.

2.4 New topology for the EAST SMPS

The new topology adopts a three-phase full-wave rectifier module with the neutral point clamped as shown in Fig. 4. When the module begins to work, both IGBTs will share the DC voltage at the output terminal of the module, and the module can ensure that the ripple current flowing through the capacitor is less than the allowed value, which is one of the benefits of full-wave rectifier topology [11–13].

If the two IGBTs are under operation asynchronously, the delayed IGBT (such as IGBT2) will be damaged by the overvoltage. This is due to the fact that the filter capacitor (C2) will be charged and cannot be discharged, and vice versa. Some measures have to be taken to protect the SMPS module in this situation. However, the rate of voltage change for the filter capacitor is slow, and thus it is feasible for the control system to take necessary measures to protect the IGBT.
When the load is short circuited, the SMPS has to be switched off as soon as possible. In order to meet this requirement, it is better for the capacitor for the snubber of IGBT to be smaller, but this is worse for IGBT, and may bring overvoltage damage to IGBT since the energy stored in stray inductance will make the voltage of the capacitor for the snubber of IGBT increase. From this point of view, it is better for the capacitor to be larger. So, with both facts taken into account, if the stray inductance is taken as $2 \mu H$, the capacitor for the snubber of each IGBT is set to be $0.22 \mu F$, and the result will be satisfactory in both safety and reliability.

3 Simulation of the new topology

A three-phase full-wave rectifier module with the neutral point clamped has been simulated by Simplorer 7.0 based on the scheme in Fig. 4. During the simulation, the load is assumed as $R_{12} = 11 \Omega$ and the other simulation parameters are listed as follows.

a. The short-circuit impedance and loss of transformer are 6% and 1%, respectively;  
b. the input voltage is AC 900 V;  
c. the output current is 100 A;  
d. the soft-starting resistance is 1 kΩ;  
e. both filter capacitors are $C_1 = C_2 = 5 \text{ mF}$;  
f. both limit-current inductances are 50 $\mu H$.

3.1 Analysis of the simulation results

When both IGBTs begin to switch off at the same time, the main circuit and voltage current between the two ends of each IGBT in the short circuit condition are shown in Fig. 5. From the simulation results, because of the RCD snubber of IGBT, the voltage between two ends of each IGBT is less than 900 V, as shown in Fig. 5, and thus it is safe enough to adopt IGBT to work at 1700 V from a voltage point of view.

When both IGBTs are switched off asynchronously, the results of the simulation are shown in Figs. 6 and 7 (VM1 is the voltage of capacitor C1, and VM2 is the voltage of capacitor C2). The delay time is assumed to be 1 s between the two IGBTs during the simulation process.
From the simulation results, when IGBT1 is switched on 1 s earlier than IGBT2, it takes about 500 ms for the voltage of the filter capacitor to increase from about 600 V to 1300 V, and IGBT2 may be in danger. Fortunately, the rate of voltage change is very slow. Because the contactor can be switched off in 30 ms, the maximum voltage of IGBT2 is less than 1 kV, which is safe for IGBT at 1700 V.

4 New topology experiments

A prototype of the three-phase full-wave rectifier module with neutral point clamping has been designed, as shown in Fig. 8 (module after optimization). Because of the relatively large short-circuit impedance of the test transformer, the output voltage of the module is less than 900×1.414=1270 V when the output current is 100 A.

Fig. 9 shows the voltage between two ends of each IGBT (CH1: the green line is the voltage signal, CH2: the blue line is the trigger signal), when both IGBTs are switched on at the same time. From the experimental results, it takes about 1.4 µs to switch on IGBT. Figs. 10 and 11 show the voltage between two ends of each IGBT when both IGBTs are switched off. From these results, the IGBT has good performance in synchronization.

Fig. 12 shows the comparison between the voltages of both IGBTs in the short-circuit condition (CH1 and CH2 are the voltage waveforms of IGBT). From the figure, the maximum voltage of each IGBT is about 840 V, which is only 7% smaller than the simulation results. The rise time of the voltage is about 2.4 µs from 0 V to 840 V, which is basically equivalent to the simulation results and can satisfy the design requirements.

Fig. 13 shows the output current and trigger signal of the IGBTs (CH1 is the output current, CH2 is the trigger signal of the IGBTs) under the over-current condition. From the figure, the maximum current is about
In order to ensure safety, the dummy load is partly cut off from 30 Ω to 5 Ω (the maximum current is about 240 A so the SMPS wouldn’t be broken, even if the IGBT is not switched off). Because of the larger impedance of the load, the decreasing and rising time of the output current is longer. However, this ensures reliability for the SMPS to switch off under the over-current condition.

![Fig.12](image1)

**Fig.12** Turn-off of both IGBTs in the short-circuit condition

![Fig.13](image2)

**Fig.13** The output current wave under the over-current condition (CH2: 20A/div)

### 5 Summary

From an experimental point of view, we have ensured steady operation with a 50 kV HVPS, as well as under the rated condition, and both IGBTs were not asynchronous. This indicates that the new topology is reliable and feasible.

As for the cost-effectiveness, the three-phase full-wave rectifier module with neutral point clamping costs less than the three-phase full-wave rectifier module. Meanwhile, the volume is up to 27% smaller than that of previous modules. From the topology point of view, it can be applied in the large current field, and satisfy the design requirements.

Finally, from comparisons between the simulation and experiment, both results are consistent with each other.

### Acknowledgments

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