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To cite this article: Guo XU et al 2018 Plasma Sci. Technol. 20 085601

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Power supply for generating frequency-variable resonant magnetic perturbations on the J-TEXT tokamak

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Received 16 March 2018, revised 10 April 2018
Accepted for publication 10 April 2018
Published 6 July 2018

Abstract
To further research the response of the tearing mode (TM) to dynamic resonant magnetic perturbation (DRMP) on the J-TEXT tokamak, a modified series resonant inverter power supply (MSRIPS) with a function of discrete variable frequency is designed for DRMP coils in this study. The MSRIPS is an AC–DC–AC converter, including a phase-controlled rectifier, an LC filter, an insulated gate bipolar transistor (IGBT) full bridge, a matching transformer, three resonant capacitors with different capacitance values, and three corresponding silicon controlled rectifier (SCR) switches. The function of discrete variable frequency is realized by switching over different resonant capacitors with corresponding SCR switches while matching the corresponding driving frequency of the IGBT full bridge. A detailed switching strategy of the SCR switch is put forward to obtain sinusoidal current waveform and realize current waveform smooth transition during frequency conversion. In addition, a resistor and thyristor bleeder is designed to protect the SCR switch from overvoltage. Manufacturing of the MSRIPS is completed, and the MSRIPS equipment can output current with an amplitude of 1.5 kA when its working frequency jumps among different frequencies. Moreover, the current waveform is sinusoidal and can smoothly transition during frequency conversion. Furthermore, the transition time when the current amplitude rises from zero to a steady state is less than 2 ms during frequency conversion. By using the MSRIPS, the expected discrete variable frequency DRMP is generated, and the phenomenon of the TM being locked to the discrete variable frequency DRMP is observed on the J-TEXT tokamak.

Keywords: tearing mode, J-TEXT, series resonant inverter, discrete variable frequency, silicon controlled rectifier

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

1. Introduction

Tearing mode (TM) is an important magnetohydrodynamic instability in tokamak plasmas. It leads to the formation of a magnetic island in plasmas, which decrease plasma confinement. The island may be locked to the intrinsic error field of the tokamak device and cause major plasma disruption [1, 2]. Therefore, the TM should be effectively controlled in tokamaks and future fusion reactors. Externally exerted dynamic resonant magnetic perturbation (DRMP) is an effective method used to control the TM [3–8]. On the J-TEXT tokamak, the phenomenon of the TM
locking to the constant frequency DRMP has been observed [6]. As research progresses, researchers would like to investigate the response of the TM to the discrete variable frequency DRMP. Compared with constant frequency DRMP, discrete variable frequency DRMP means that the frequency of DRMP is not constant but jumps among several frequencies in one shot.

However, the old series resonant inverter power supply (SRIPS) for DRMP coils can only output sinusoidal current with a selected frequency in one shot. Accordingly, DRMP coils can only generate constant frequency DRMP, which cannot meet the new physical experiment requirements. Therefore, a modified series resonant inverter power supply (MSRIPS) with a function of discrete variable frequency is proposed in this work. The rest of this paper is organized as follows. Power supply requirements are shown in section 2. A detailed description of the MSRIPS design is also given in this section. Then, the testing results of the MSRIPS and physical experiment results are shown in section 3. Finally, the conclusion is drawn in section 4.

2. MSRIPS requirements and design

2.1. MSRIPS requirements

Four groups of DRMP coils are designed and distributed symmetrically inside the J-TEXT vessel. The layout and the magnetic field design of the DRMP coils are introduced in the literature [9]. To generate \( m/n = 2/1 \) (\( m \) and \( n \) are poloidal and toroidal mode numbers) magnetic perturbations, four groups of DRMP coils are divided and connected into two parts, and each part of the DRMP coils is energized by a SRIPS (as shown in the literature [10]).

The SRIPS is an AC–DC–AC converter, including a phase-controlled rectifier, an LC filter, an insulated gate bipolar transistor (IGBT) full bridge, a matching transformer, three resonant capacitors with different capacitance values, and three corresponding mechanical switches [10, 11]. The SRIPS has three RLC resonant branches, and each branch is composed of a resonant capacitor, a corresponding mechanical switch, and DPMP coils. The detailed parameters of each branch are tabulated in table 1. In one shot, one of the three RLC resonant branches is selected to be placed into operation by a corresponding mechanical switch. The ideal working state of the SRIPS is the resonance state, which requires that the working frequency of the SRIPS (or the driving frequency of the IGBT full bridge) is equal to the resonant frequency of the selected RLC resonant branch. However, it is difficult to achieve this requirement perfectly in engineering practice. Therefore, under the premise of zero voltage switching of the IGBT in the H-bridge, the working frequency of the power supply is normally slightly higher than the corresponding resonant frequency. As the mechanical switches cannot change the selected RLC resonant branch at the electrifying state, the working frequency of the SRIPS in one shot is constant and cannot jump among three different frequencies.

To meet the new research requirements proposed in section 1, the working frequency of the MSRIPS should jump among three different frequencies that are slightly higher than three resonant frequencies in one shot. In the J-TEXT typical discharges, the time when the TM is unlocked from DRMP to initial state is approximately 3–6 ms [6]. Thus, to avoid the TM reaching the initial state during frequency conversion, and under the premise of reserving some redundancy, the transition time when the current amplitude rises from zero to steady state after frequency conversion is expected to be less than 2 ms. For the DRMP coils on the J-TEXT tokamak, sinusoidal AC current with an amplitude of 1.5 kA will produce approximately 0.71 Gauss \( m/n = 2/1 \) magnetic perturbations, which is adequately large to induce obvious effects on the TM [9]. The specific requirements of the MSRIPS are shown in table 2.

2.2. Main topology of the MSRIPS

For the MSRIPS, the key point to realize the function of discrete variable frequency in one shot is to change the

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**Table 1.** Detailed parameters of the RLC resonant branches.

<table>
<thead>
<tr>
<th>Power supply number</th>
<th>Branch number</th>
<th>Resonant frequency</th>
<th>Capacitance</th>
<th>Inductance</th>
<th>Resistance</th>
<th>Quality factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>PS1</td>
<td>#1</td>
<td>2.75 kHz</td>
<td>264 μF</td>
<td>12.69 μH</td>
<td>39.87 mΩ</td>
<td>5.50</td>
</tr>
<tr>
<td></td>
<td>#2</td>
<td>3.74 kHz</td>
<td>153 μF</td>
<td>11.84 μH</td>
<td>45.68 mΩ</td>
<td>6.09</td>
</tr>
<tr>
<td></td>
<td>#3</td>
<td>4.76 kHz</td>
<td>100 μF</td>
<td>11.12 μH</td>
<td>50.98 mΩ</td>
<td>6.54</td>
</tr>
<tr>
<td>PS2</td>
<td>#1</td>
<td>2.69 kHz</td>
<td>264 μF</td>
<td>13.26 μH</td>
<td>40.22 mΩ</td>
<td>5.57</td>
</tr>
<tr>
<td></td>
<td>#2</td>
<td>3.70 kHz</td>
<td>153 μF</td>
<td>12.10 μH</td>
<td>46.61 mΩ</td>
<td>6.03</td>
</tr>
<tr>
<td></td>
<td>#3</td>
<td>4.71 kHz</td>
<td>100 μF</td>
<td>11.42 μH</td>
<td>52.76 mΩ</td>
<td>6.41</td>
</tr>
</tbody>
</table>

*Measured results using a 3260B Precision Magnetics Analyzer (Wayne Kerr Electronics).*

**Table 2.** MSRIPS requirements for DRMP coils on the J-TEXT tokamak.

<table>
<thead>
<tr>
<th>Items</th>
<th>Parameters or requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Working frequency</td>
<td>Jump among three different frequencies in one shot (slightly higher than the three resonant frequencies)</td>
</tr>
<tr>
<td>Transition time</td>
<td>&lt;2 ms</td>
</tr>
<tr>
<td>Current amplitude</td>
<td>1.5 kA</td>
</tr>
<tr>
<td>Current waveform</td>
<td>Sinusoidal</td>
</tr>
<tr>
<td>Working duty cycle</td>
<td>0.3 s/3 00 s</td>
</tr>
</tbody>
</table>
selected resonant branch rapidly by switching over different resonant capacitors at the electrifying state and match the corresponding driving frequency of the IGBT full bridge. Therefore, the mechanical switches in the SRIPS must be replaced by electronic switches. As a type of electronic switch, the silicon controlled rectifier (SCR) is suitable for switching over resonant capacitors. The reasons are as follows:

(1) Compared with a mechanical switch, the SCR features the advantage of short switching time (microsecond level). The SCR can switch over different resonant capacitors rapidly in one shot, which is the key point to realize the function of discrete variable frequency. The main parameters of the SCR can also meet the MSRIPS design requirements, including working frequency (kilohertz level), rated current (kiloampere level), and rated voltage (kilovolt level).

(2) Compared with full-controlled electronic switches such as the IGBT, the SCR shows the advantage of control strategy simplicity. The SCR is a kind of half-control power device, and it has a self-commutated characteristic when its current reaches zero. When the MSRIPS is working, zero current switching of the SCR switch can be automatically realized without complex control.

The main topology of the MSRIPS is proposed, as shown in figure 1. Compared with the main topology of the SRIPS, every resonant capacitor in the MSRIPS is equipped with a pair of anti-parallel SCRs to replace the old mechanical switch.

### 2.3. Switching strategy of the SCR switch

The detailed circuit of the series resonant inverter in the MSRIPS is shown in figure 2. The SCR switch $S_1$ (or $S_2$), which is composed of positive SCR $S_{1+}$ (or $S_{2+}$) and negative SCR $S_{1-}$ (or $S_{2-}$), is used for switching over the resonant capacitor $C_1$ (or $C_2$). The switching strategy of the SCR switch is important for obtaining sinusoidal current waveform and realizing the function of discrete variable frequency. For the series resonant inverter in the MSRIPS, two operation modes, namely, constant frequency operation mode and frequency conversion operation mode, are used. The trigger strategy at constant frequency operation mode and switch-over strategy at frequency conversion operation mode are designed below.

When the MSRIPS is at the constant frequency operation mode, a sync trigger strategy is designed to obtain the sinusoidal current waveform. As shown in figure 3(a), sync trigger strategy means that the trigger signal of $S_{1+}$ (or $S_{2+}$) is synchronous with the positive (or negative) voltage of $u_{AB}$. The IGBT full bridge driving frequency is slightly higher than the resonant frequency of the RLC resonant branch. Therefore, the phase of the RLC resonant branch voltage $u_{AB}$ is slightly ahead of the phase of load current $i_c$. Thus, the sync trigger strategy can guarantee that $S_{1+}$ (or $S_{2+}$) is triggered slightly ahead of the phase of load current $i_c$. However, even if the sync trigger strategy is adopted in engineering practice, the actual trigger moment of $S_{1+}$ (or $S_{2+}$) may be behind the negative (or positive) current zero-crossing moment, which can be regarded as the lag trigger and may lead to the discontinuity of the current waveform. Lag trigger happens because the trigger circuit of the SCR has a time delay $t_d$, and $t_d$ is bigger than the time for
which $u_{AB}$ leads $i_c$. Lag trigger should be avoided in engineering practice. The typical waveforms are shown in Figure 3(b).

When the MSRIPS is at the frequency conversion operation mode, a sync switch-over strategy is designed to realize frequency conversion and current waveform smooth transition. As shown in Figure 4(a), $t_{so}$ is the moment where the trigger signal of the SCR switch is switched over from $S_1$ to $S_2$, $t_i$ is the frequency conversion moment of the RLC resonant branch voltage $u_{AB}$, and $t_u$ is the frequency conversion moment of the load current $i_c$. The phase of the RLC resonant branch voltage $u_{AB}$ is slightly ahead of the phase of the load current $i_c$. As a result, $t_u$ is slightly ahead of $t_i$. Sync switch-over strategy means that $S_2$ is triggered slightly ahead of $t_u$, which is the key point to realize current waveform smooth transition during frequency conversion. If $t_{so}$ is more than the half-current period ahead of $t_i$ (lead switch-over strategy), or if $t_{so}$ is behind $t_i$ (lag switch-over strategy), then current distortion will happen. Current distortion happens because the IGBT full bridge driving frequency does not match the resonant frequency of the selected RLC resonant branch, which should be avoided. The typical waveforms are shown in Figure 4(b).

### 2.4. Circuit analysis of the MSRIPS

Figure 5 shows the circuit model of the series resonant inverter in the MSRIPS. The DRMP coils and the connection cables are simplified as inductive loads consisting of $R_c$ and $L_c$, and the resonant capacitor is represented by $C_s (s = 1, 2)$. $N$ is the matching transformer ratio, and the parasitic parameters of the matching transformer are neglected because of its low working frequency. $u_H$ is the full bridge output voltage, which can be expressed in terms of the Fourier series in formula (1), where $E$ is the DC bus voltage, and $\omega_s$ is the driving angular frequency of full bridge.

For the aforementioned circuit model, the transient response of the load current at constant frequency $f_s$ ($s = 1, 2$) can be analyzed in terms of the complex frequency domain. The quality factor $Q$ of the selected resonant branch is approximately 5–7 (measured by a 3260B Precision Magnetics Analyzer), and the MSRIPS is at the state of quasi-resonance. Thus, the excitation can be approximately regarded as the fundamental component of $u_H$ [12]. In addition, the initial state of capacitance and inductance is zero, which means that $U_{C}(0) = 0$ and $I_{L}(0) = 0$. The transient response of the load current $i_{c,1}$ can then be obtained using formula (2),

$$i_{c,1}(t) = \frac{4E}{\pi N R_c} \left[ \sin (\omega_d t) - \frac{\omega_s}{\omega_d} e^{-\alpha t} \sin (\omega_i t) \right],$$

where

$$\omega_d = \sqrt{\omega_s^2 - \alpha^2},$$

$$\omega_i = \frac{1}{\sqrt{L_c C_s}},$$

$$\alpha = \frac{R_c}{2L_c},$$

where $\alpha$ is a damping factor, and $\omega_i$ is the natural resonant angular frequency.
The inequality in (4) is satisfied because the quality factor $Q$ of the selected resonant branch is approximately 5–7,

$$\frac{\alpha}{\omega_i} = \frac{R_c/2L_c}{1/\sqrt{L_cC_i}} = \frac{R_c}{2} \sqrt{\frac{C_i}{L_c}} = \frac{1}{2Q} \ll 1. \quad (4)$$

Thus, formula (2) can be rewritten as formula (5)

$$i_{c,1}(t) = \frac{4E}{\pi NR_c}(1 - e^{-\alpha t})\sin(\omega_i t). \quad (5)$$

According to formula (5), the transient response of the load current amplitude $i_{AMP}$ can be obtained in formula (6),

$$i_{AMP} = \frac{4E}{\pi NR_c}(1 - e^{-\nu t}), \quad (6)$$

where the time constant $\tau_i = 1/\alpha$ and the transition time when $i_{AMP}$ increases from zero to steady state is $t_s = (3-4) \tau_i$.

During the frequency conversion, the current of inductance and the voltage of the new selected capacitor are both zero at the current frequency conversion moment $t_i$. Thus, the transient response of the load current after frequency conversion can be regarded as a new zero-state response. During the entire frequency conversion from $f_1$ to $f_2$, the transient response of the load current can be regarded as the composition of the load current transient response at the frequencies of $f_1$ and $f_2$, as shown in figure 6.

### 2.5. RT bleeder of the resonant capacitor in the MSRIPS

The series resonant inverter in figure 2 shows that the voltage phase of the selected resonant capacitor is 90° behind the current phase of inductance when the MSRIPS working. During the frequency conversion from $f_1$ to $f_2$, the current of inductance is zero at the current frequency conversion moment $t_i$. In the same moment, the voltage of the selected capacitor $C_1$ reached a negative peak. A residual voltage $u_{C1}$ in the resonant capacitor $C_1$ is observed after frequency conversion. Thus, $u_{C1}$ can approximately be obtained by formula (7),

$$u_{C1} \approx \sqrt{\frac{L_1}{C_1}} \cdot I_{p1}, \quad (7)$$

where $I_{p1}$ is the peak value of the load current $i_{c}$ at frequency $f_1$. Because of the presence of residual voltage $u_{C1}$, the voltage of the SCR switch $S_1$ ($u_{S1}$) has DC bias when the MSRIPS operates at frequency $f_2$. The DC bias has an adverse effect on the SCRs in $S_1$ and may damage the SCRs for overvoltage.

Figure 7 shows that a resistor and thyristor (RT) bleeder is designed to eliminate the DC bias of $u_{S1}$. Each resonant capacitor is in parallel with a RT bleeder, which is composed of a resistor $R_b$ and a thyristor $T_b$. When the driving frequency of the IGBT full bridge is changed at the moment of $t_i$, a wide pulse trigger signal is provided to the thyristor $T_{b1}$ in the RT bleeder $RT_1$. At this moment, the resonant capacitor $C_1$ and resistor $R_{b1}$ compose an RC first-order circuit to bleed the residual voltage $u_{C1}$, and the DC bias of $u_{S1}$ can be eliminated soon, as shown in figure 8.

When the RT bleeder is working, the transient response of residual voltage $u_{C1}$ in the resonant capacitor $C_1$ can be obtained,

$$u_{C1} \approx \sqrt{\frac{L_1}{C_1}} \cdot I_{p1} \cdot e^{-\frac{t}{\tau}}, \quad (8)$$

where $I_{p1}$ is the peak current at frequency $f_1$. Because of the presence of residual voltage $u_{C1}$, the voltage of the SCR switch $S_1$ ($u_{S1}$) has DC bias when the MSRIPS operates at frequency $f_2$. The DC bias has an adverse effect on the SCRs in $S_1$ and may damage the SCRs for overvoltage.

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When the RT bleeder is working, the transient response of residual voltage $u_{C1}$ in the resonant capacitor $C_1$ can be obtained,
should be less than one current period at frequency $f_2$. Resistance $R_{b1}$ in the RT bleeder RT$_1$ should satisfy formula (9),

$$R_{b1} \leq \frac{1}{(3 \sim 4) \cdot C_1 \cdot f_2}.$$  \hspace{1cm} (9)

\section*{3. Experimental results}

The manufacturing of the MSRIPS has been completed and applied to physical experiments. The MSRIPS consists of a rectifier cabinet, an inverter cabinet, a resonant capacitor cabinet, and an output cabinet. The output current amplitude of the MSRIPS is determined by the DC bus voltage and the H-bridge load impedance amplitude, and the control of the current amplitude is realized by setting different phase shift trigger angles for the rectifier and then adjusting the DC bus voltage, which is an open-loop control method. In fact, a closed-loop control method could also be used. A possible way is first detecting the output current amplitude and then controlling the DC bus voltage in a feedback way. The closed-loop control method will be researched and used in the next stage.

In the output cabinet, three SCR switches and three RT bleeders have been installed, as shown in figure 9. Considering the adequate surge absorption capability, voltage endurance capability, and working frequency of the MSRIPS, a medium frequency thyristor (rating 2000 V/1489 A) with a model number of 5STF 15F2040 from the ABB Company is selected to act as the switch transistors in the SCR switches and RT bleeders. The resistors in the RT bleeders are made of graphite. Compared with common metal materials, graphite has high resistivity ($17 \mu \Omega \cdot m$) and large heat capacity ($710 \text{ J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$), which is very suitable for building a large power resistor. The resistance and inductance of the resistors in the RT bleeders are $R_{b1}$ ($0.3 \Omega/0.12 \mu \text{H}$), $R_{b2}$ ($0.4 \Omega/0.23 \mu \text{H}$), and $R_{b3}$ ($0.5 \Omega/0.37 \mu \text{H}$).

Figure 10 shows a detailed image of the frequency conversion for the two sets of MSRIPS (PS 1# and PS 2#). To obtain $m/n = 2/1$ DRMP with adequate spectral purity, the phase difference of the load current between PS 1# and PS 2# should be approximately 90° [10, 13]. Because the load parameters of PS 1# and PS 2# are almost similar, the phase difference between $i_{c1}$ and $i_{c2}$ can be controlled at approximately 90° when the phase difference between $u_{AB1}$ and $u_{AB2}$ is set at 90°. Figure 10 shows that PS 1# and PS 2# have the capability of outputting current with an amplitude of 1.5 kA when the working frequency of the MSRIPS jumps from 2.82 kHz (or 4.68 kHz) to 4.68 kHz (or 2.82 kHz). In addition, the current waveforms are sinusoidal and can smoothly transit during frequency conversion. Moreover, the transition time when the current amplitude increases from zero to a steady state is less than 2 ms during frequency conversion. Figure 10 indicates that the MSRIPS is in agreement with the design requirements.

Figure 11 shows the testing results in the MSRIPS with and without the RT bleeder. During the frequency conversion from 2.82 kHz to 4.68 kHz, the residual voltage $u_{c1}$ in the resonant capacitor $C_1$ can be bled by the RT bleeder within one current period, and the DC bias of $u_{S1}$ can also be eliminated within one current period. If the RT bleeder is not adopted, then a DC bias in $u_{S1}$—which will limit the obtainment of higher output current—is observed. Figure 11 indicates that the RT bleeder can achieve a good effect on the elimination of the DC bias of the SCR switch.
Figure 12 shows some physical experiment results in the response of the TM to discrete variable frequency DRMP. The plasma parameters of discharges were selected as follows: plasma current $I_p = 175$ kA, toroidal magnetic field $B_t = 1.74$ T, which provided an average edge safety factor $q_a \sim 3.45$. The center line-averaged electron density was kept at $1.35 \times 10^{19}$ m$^{-3}$. Figure 12(a) shows that the current frequency $f_c$ jumps from 4.68 kHz to 4.05 kHz, and then to 2.82 kHz in one shot. Figure 12(b) shows that the current frequency $f_c$ jumps repeatedly between 2.82 kHz and 4.68 kHz in one shot. The two aforementioned cases suggest that the TM can be well locked to DRMP, and the frequency of the TM $f_{TM}$ can follow the frequency of DRMP rapidly when the frequency of DRMP is changed. The current waveform during frequency conversion in the enlarged graph is similar to the waveform in figure 10, which indicates that the plasma has no obvious influence on the frequency conversion of the MSRIPS. The current amplitude of DRMP coils in figure 12 changes while the current frequency is constant. This is an engineering problem, and the reason is: the DC bus voltage of the MSRIPS is not stable while the open-loop control method is used for controlling the current amplitude. Figure 12 shows that the TM mode locking does not appear to be influenced by the change of current amplitude (or DRMP amplitude), which probably indicates that the TM mode locking threshold is well below the DRMP amplitude. The current with an amplitude of 1–2 kA in figure 12 will produce approximately 0.47–0.94 Gauss $m/n = 2/1$ magnetic perturbations [9]. In one of the experimental results on the J-TEXT, the TM can be locked to DRMP when the current amplitude of the DRMP coils reaches approximately 0.6 kA [6].

4. Conclusions

A MSRIPS with a function of discrete variable frequency for DRMP coils on the J-TEXT tokamak has been completed. The MSRIPS can output current with an amplitude of 1.5 kA when its working frequency jumps among several frequencies. In addition, the current waveform is sinusoidal and can smoothly transition during frequency conversion. Moreover, the transition time when the current amplitude increases from zero to a steady state is less than 2 ms during frequency conversion. The expected discrete variable frequency DRMP is generated using the MSRIPS. Consequently, the phenomenon of the TM being locked to discrete variable frequency DRMP has just been observed on the J-TEXT tokamak.

In the MSRIPS, the control method of the output current amplitude is an open-loop control, which is not adequately rapid and accurate. In addition, physical experiments at the next stage require that the MSRIPS can jump among more frequencies. Thus, further study on the MSRIPS, such as the rapid and accurate amplitude control method and the addition of more resonant capacitors, needs to be continued.

Acknowledgments

This work was supported by the National ITER Project Foundation of China (No. 2014GB118000) and National Natural Science Foundation of China (No. 11405068).
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