Study and Design of the Novel Shunt Liner Active Power Filter for a Superconducting Magnet Power Supply

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Abstract— The superconducting outsert of the 40 T hybrid-magnet in High Magnetic Field Laboratory (HFML) of Chinese Academy of Sciences (CAS) requires a highly stabilized low-voltage high-current power supply. One of the design is a switching power supply with active DC power filter. As the current flowing through a Shunt Active Power Filter (SAPF) is only the ripple current, the power loss caused by the filter can be very low, so SAPF is more and more applied in high-current devices. Usually, a shunt PWM converter can be used to generate current which is equal but oppositely phased to the ripple current. However, EMI noises caused by PWM have great influence on the circuit and the speed of response is limited by the switching frequency. Meanwhile, the load voltage variation makes it very difficult to design parameters of the filter. In this paper, a novel shunt liner active power filter (SLAPF) is designed to overcome the disadvantages of existing dc active filter schemes. Structurally, SLAPF can be divided into two components, one is the current compensator, and the other is the auxiliary power supply. The current compensator is composed of a power supply with fixed output voltage and two parallel branches, each of which consists an adjusting transistor. The auxiliary power supply is used to ensure the voltage across the adjusting transistors keep in a proper range, so the transistors can always operate in the saturation region. Based on the on-resistance variability of adjusting transistors, just as the series linear regulator, the output current of the current compensator can accurately track the oppositely phased out ripple current of main circuit, which leads to a good filter effect. In the paper, the detail structure and working principle of SLAPF are presented at first, then the design flow is described, which includes the control method of the current compensator, the analysis of topology chosen for auxiliary power supply. At last, the experimental results show that the filtering effect of SLAPF is good enough to make the power supply meet the technical requirements.

1. INTRODUCTION

One of the schemes of the power supply for the superconducting outsert in High Magnetic Field Laboratory (HFML) is the switching power supply. The magnet requires highly stabilized current, however, it is hard to depress the low frequency ripple caused by three-phase uncontrolled rectifier which is the input of the switching converter. In order to reduce the output ripple, the passive filter, if used alone, requires much larger output inductance and capacitance, which will increase the cost and volume of the device and exacerbate the dynamic characteristics. Moreover, the low-frequency output ripple cannot be depressed effectively. Accordingly, we consider to add an active DC power filter to the output of the switching power supply [1]. As the current flowing through a Shunt Active Power Filter (SAPF) is only the ripple current, the power loss caused by the filter can be very low, so SAPF is more and more applied in high-current devices [2]. Usually, a shunt PWM converter can be used to generate current which is equal but oppositely phased to the ripple current. However, EMI noises caused by PWM have great influence on the circuit and the speed of response is limited by the switching frequency. Meanwhile, the load voltage variation makes it very difficult to design parameters of the filter [3]. In this paper, a novel shunt liner active power filter (SLAPF) is designed to overcome the disadvantages of existing dc active filter schemes.

2. BASIC STRUCTURE OF SLAPF

Figure 1 shows the basic structure of SLAPF. In this figure, L_f represents the filter inductance, M_1 and M_2 represent series adjusting transistors which consist of multiple MOSFETs connected in parallel in actual design, i_b represents the current of the branch of filter capacitor C_f, i_c represents the current which flows through C_f, $-i_{\mathrm{Ah}}$ represents the output current of SLAPF, APFS1 and APFS2 represent the auxiliary power supply while the voltage across APFS2 is V_{apf} and the voltage across APFS1 is $V_{\mathrm{apf+}} - V_{\mathrm{apf}} = V_{\mathrm{apfs1}}$, R_o represents the load resistance, L_o represents the load inductance, V_o represents the output voltage, I_o represents the output current.

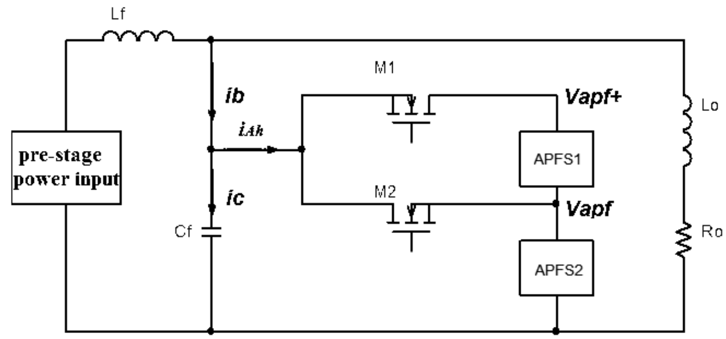

Figure 1: Structure of SLAPF.

According to Figure 1:

$$i_c = i_b - i_{\mathrm{Ah}} \quad (1)$$

$$u_o = i_c \cdot Z_{cf} \quad (2)$$

where Z_{cf} is the impedance of C_f, u_o is the ripple of output voltage.

According to Equation (1) and Equation (2), if i_{Ah} can track i_b well, i_c will approach to 0, then the ripple of i_o will approach to 0 too. When $i_b > 0$, let M_2 be turned on while M_1 be turned off, and V_{apf} be set to be lower than V_o, then the positive half-cycle of i_b will flow through M_1 into APFS2. When $i_b < 0$, let M_1 be turned on while M_2 be turned off, and $V_{\mathrm{apf+}}$ be set to be higher than V_o, then the APFS1 and APFS2 will output compensating current which will flow though M_2 into the original circuit.

The variable on-resistance of MOSFET is used to realize current tracking. When the MOSFET works in the saturation region, its gate-source voltage can adjust the drain current with strongest ability, so V_{apf} need to be kept with a proper value to ensure a proper gate-source voltage so that the MOSFET can always work in the saturation region.

Structurally, SLAPF can be divided into two components, one is the current compensator composed by M_1, M_2 APFS1 and a proper V_{apf}, the other is the auxiliary power supply APFS2.

3. ACTUAL STRUCTURE OF SLAPF

The actual structure of SLAPF is shown as Figure 2, where C_3 is an energy-storage capacitor [4].

The two adjusting transistor T_1 and T_2 could be considered as a bidirectional push-pull controlled current source. The voltage across C_3 will fluctuate when the current flows through the transistors to inject into or sink from C_3. In the ideal situation, the average voltage across C_3 (U_{apf}) remain unchanged, however, the leakage current of C_3 and the irregular harmonic current can lead U_{apf} to be outside of the normal operating range.

When U_{apf} is lower than the lower bound of normal operating range, the constant current charging power supply HP-FS should charge C_3 to make U_{C3} raise back into the normal range. When U_{C3} is higher than the high bound of normal range, we can use a couple of resistors to release the stored energy of C_3 to make U_{C3} fall back into the normal range. Different value of resistance should be connected into the circuit under different U_{C3} to limit the discharge current Synthesizes the above analysis, HP-FS, energy-removal resistor network, and C_3 make up the auxiliary power supply APFS2 in the basic structure.

In some cases, the V_{apf} should be negative to make certain the voltage across the transistor be higher than the ripple voltage The adjustable DC power supply APFS3 can offer this negative voltage if the switch sk is turned on.

4. CALCULATION OF THE NORMAL OPERATING RANGE OF U_{APF}

Assume the drop collector-to-emitter voltage of T_1 is V_{ce1}, the drop collector-to-emitter voltage of T_2 is V_{ce2}, and the minimal drop collector-to-emitter voltage of the IGBT transistor is $V_{\mathrm{ce\_min}}$ to ensure the transistor can always work in the saturation region. Obviously, $V_{\mathrm{ce1}} \geqslant V_{\mathrm{ce\_min}}$, $V_{\mathrm{ce2}} \geqslant V_{\mathrm{ce\_min}}$.

When T_1 is turned on while T_2 is turned off:

$$V_o - V_{\mathrm{ce2}} = V_{\mathrm{apf}} \quad (3)$$

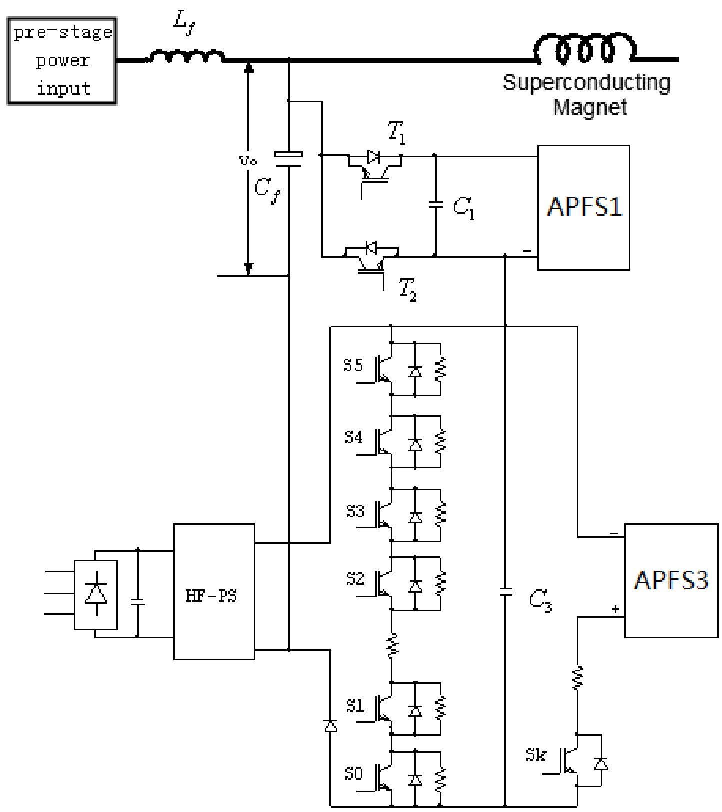

Figure 2: Actual structure of SLAPF.

When T_2 is turned on while T_1 is turned off:

$$V_{\text{apf}} + V_{\text{apfs1}} - V_{\text{ce1}} = V_o \tag{4}$$

According to Equations (3) and (4), we obtain:

$$V_o - V_{\text{ce2}} + V_{\text{apf}} + V_{\text{apfs1}} - V_{\text{ce1}} = V_{\text{apf}} + V_o \tag{5}$$

Thus,

$$V_{\text{apfs1}} = V_{\text{ce1}} + V_{\text{ce2}} \geq 2V_{\text{ce\_min}} \tag{6}$$

According to Equation (3), we obtain:

$$V_{\text{ce2}} = V_o - V_{\text{apf}} \geq V_{\text{ce\_min}} \Rightarrow V_o - V_{\text{ce\_min}} \geq V_{\text{apf}} \geq U_{\text{apf}} - \Delta V \Rightarrow U_{\text{apf}} \leq V_o - V_{\text{ce\_min}} + \Delta V \tag{7}$$

According to Equation (4), we obtain:

$$\begin{aligned} V_{\text{ce1}} &= V_{\text{apf}} + V_{\text{apfs1}} - V_o \geq V_{\text{ce\_min}} \Rightarrow V_o + V_{\text{ce\_min}} - V_{\text{apfs1}} \leq V_{\text{apf}} \leq U_{\text{apf}} + \Delta V \\ &\Rightarrow U_{\text{apf}} \geq V_o + V_{\text{ce\_min}} - V_{\text{apfs1}} - \Delta V \end{aligned} \tag{8}$$

According to Equations (6) and (8), we obtain:

$$V_o + V_{\text{ce\_min}} - V_{\text{apfs1}} - \Delta V \leq U_{\text{apf}} \leq V_o - V_{\text{ce\_min}} + \Delta V \tag{9}$$

where $V_{\text{apfs1}} \geq 2V_{\text{ce\_min}}$.

APFS1 is a DC power supply with adjustable output voltage in practice. On one hand, we can use Equation (9) to calculate the normal operating range of U_{apf} if V_{apfs1} is set to a fixed value, on the other hand, according to Equation (6), we obtain:

$$V_o + V_{\text{ce\_min}} - V_{\text{apfs1}} - \Delta V \leq V_o + V_{\text{ce\_min}} - 2V_{\text{ce\_min}} - \Delta V = V_o - V_{\text{ce\_min}} - \Delta V \tag{10}$$

According to Equations (8) and (10), if U_{apf} satisfies the flowing equation:

$$U_{\text{apf}} \geq V_o - V_{\text{ce\_min}} - \Delta V \tag{11}$$

Then V_{apf1} satisfies Equation (8) certainly, which means if the normal operating range of U_{apf} is:

$$V_o - V_{\text{ce\_min}} - \Delta V \leq U_{\text{apf}} \leq V_o - V_{\text{ce\_min}} + \Delta V \tag{12}$$

Then the adjusting transistor can always work in the saturation region.

5. STRUCTURE OF HFPS

As shown in Figure 3, HF-PS is composed of a pair of ZVS switching converter with full bridge rectifier, the first windings of transformers is connected in parallel so that the current stress of the switch tubes can be less, the second windings of transformers is connected in series so that the voltage stress of the diodes can be less.

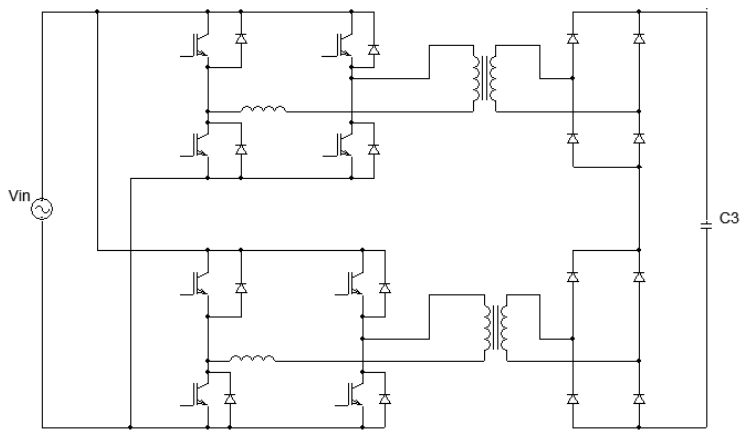

Figure 3: Structure of HF-PS.

6. EXPERIMENTAL VERIFICATION

In order to verify the filtering effect of SLAPF, a 10 V/1 kA prototype with $C_f = 50\,\text{mF}$, $R_o = 10\,\text{m}\Omega$ and $L_o \approx 5\,\mu\text{H}$ is designed. The input of the switching converter is a 380 V/50 Hz three-phase uncontrolled rectifier. The current measurement is based on the high precision DCCT. In the prototype, a ZVS-CV converter is used to take the place of HP-FS and energy-removal resistor network [5].

The wave of output ripple without SLAPF comparing to that with SLAPF are shown in Figure 4 and Figure 5.

According to the Figure 4 and Figure 5, the ripple factor of output voltage without SLAPF is about 120 mV/10 V = 1.2%, and the ripple factor of output voltage with SLAPF is about 10 mv/10 V = 0.1% which is smaller than the maximum voltage ripple coefficient (1%).

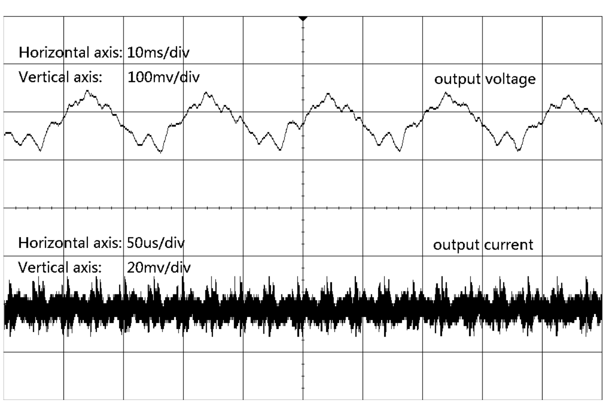

Figure 4: Output waveforms without SLAPF.

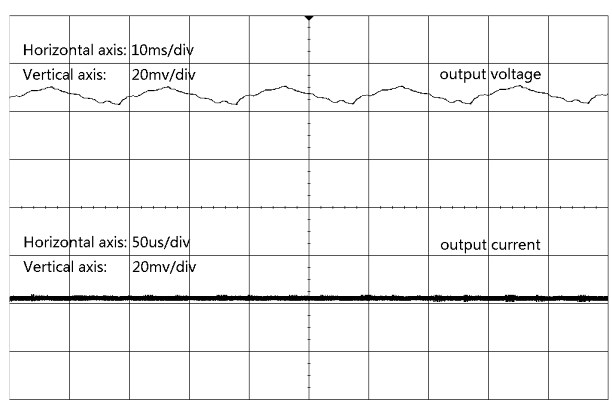

Figure 5: Output waveforms with SLAPF.

The peak-peak ripple of output current without SLAPF is about 3 A (0.03×100) while the ripple factor is $3/1000 = 0.3\%$, and the peak-peak ripple of output current with SLAPF is about 0.4 A (0.004×100) while the ripple factor is $0.4/1000 = 0.04\%$ which is smaller than the maximum current ripple coefficient (0.1%). The results show that the output current and voltage ripple are reduced by SLAPF dramatically.

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