

A new shunt DC active filter of power supply in a steady high magnetic field facility^{*}

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Abstract: A DC active power filter is an indispensable part in a high power and high stability power supply system, especially in the power supply system of the Steady High Magnetic Field Facility, which requires that the current ripple should be limited to 50 parts per million. In view of the disadvantages of the series DC active power filter and shunt Pulse Width Modulation DC active filter, this paper puts forward a novel DC active filter by combining the advantages of the transistor regulator and the shunt type. The structure and principle of the new shunt linear active filter are introduced. Meanwhile, the design of several key components that construct the new shunt linear active filter is also analyzed. The simulation model and an experimental prototype of the shunt linear active filter are developed, and the results verify that the parameter design is reasonable and the shunt active filter has a good filter effect.

Key words: high stable power supply, ripple, shunt, linear, DC active filter

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1 Introduction

The Steady High Magnetic Field Facility (SHMFF) is one of the major scientific and technological infrastructure projects in China [1], which will develop and operate a wide variety of high-field magnet systems in support of the institution and private sector research and development in solid state physics, high energy physics, particle accelerators, biology, chemistry, geology, materials science, engineering and medicine.

Up to now, the most commonly used magnet power supply for a high-current load has been the rectifier power supply. This power supply consists of a phase-controlled rectifier and a low-pass filter. A serious problem with this magnet power supply is the low-frequency non-characteristic ripples in the load, which were produced due to the non-ideal operation conditions, such as grid voltage fluctuation [2]. It is impossible for the passive filter to eliminate these low-frequency ripples and to provide fast dynamic responses. Therefore, the DC active filter is an indis-

pensable part in the power supply of SHMFF.

A transformer coupled regulator, which could remove the AC ripple components of the DC supply, was adopted as the DC active filter in the high magnetic field laboratory in Grenoble in France [3]. The design has the advantage that a considerably smaller transistor regulator could have been chosen. This scheme, however, cannot regulate slow drifts or provide for the required set point precision. So, a conventional and proven approach with a pass bank transistor regulator and an industrial type was accepted in the high magnetic field laboratory of the other country [4–6].

The above two series-type DC active filters have the advantages of the faster dynamic response and lower ripple contents in the output current. However, they were designed to carry the high load current, increasing the device rating of the active filter.

In contrast to the series active filter, a shunt active filter is designed to absorb only the compensation ripple and dynamic adjustment currents, and the current rating of the active filter is much lower than that

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of the load. This results in reducing the active filter size and cost, while keeping the load current ripple within the desired level. The addition of the active filter will minimize the size of the passive filter components and it eliminates the need for large damping elements.

Shunt compensation ripple currents are all generated by the Pulse Width Modulation (PWM) method in Refs. [7, 8]. However, the PWM mode has a high-frequency pulse current and serious electromagnetic interference. Meanwhile, different magnetic field intensities require different power system load voltage output, which will bring difficulty to the parameter design of the PWM active filter. Thus, this scheme can't ensure the filter effect under different load voltages [9].

In this paper, a new active filter scheme combining the advantages of the linear and shunt types is put forward. By setting a voltage source that could automatically track the output voltage of the power system in SHMFF, the scheme can ensure that the linear transistors all work in the linear zone without being influenced by the load voltage. By injecting the compensation ripple currents, which have the character of dual polarity and rapid response, the scheme can eliminate the load current ripple within the desired level.

2 System configurations

2.1 Specifications

The water-cooled magnets will be energized by two 10 MW (500 V, 20 kA), highly stabilized power supplies, which can be operated simultaneously or respectively. Research under high magnetic field conditions requires the magnetic field to be as constant as possible. The power supplies were specified to obtain the best performance available at the given high power level and hopefully as high as expected from industrial supplies [10].

The most important power supply specifications of SHMFF are listed below. Precision is the difference between adjacent steps in the current set point, which is limited to 10 parts per million; ripple and noise is the peak variation of the output current over one cycle time period, which is limited to 50 parts per million; stability over an 8 h period is limited to 50 parts per million; accuracy is limited to 100 parts per million; and the efficiency should be larger than 0.9.

2.2 Requirements of the active filter

To achieve the goal of low ripple, an active filter

is indispensable; it attenuates the low current ripple that a passive filter can't filter out, such as 50 Hz, 100 Hz. Therefore, it can be regarded as a low-pass filter and its cutoff frequency should be less than 20 Hz. The low-frequency ripple current of the load is about several hundred parts per million during rectifier operation [11], so the active power filter should have about 10 times the low-frequency ripple attenuation capability.

Rating of the active filter can also be estimated by

$$S_c \approx V_0 \cdot \sqrt{\sum_{h=1}^n I_h^2}, \quad (1)$$

where V_0 is the magnet voltage, and I_h is the Root Mean Square (RMS) of the ripple currents flow through the passive filter.

2.3 Basic topologies of the active filter

Parallel with the capacitance of the passive filter, a shunt type DC active filter can be regarded as a controlled current source, when its output current is equal to the ripple current produced by the rectifier, it can fully eliminate the load ripple currents. Though the actual shunt type DC active filter can't fully eliminate the load ripple currents, it can make load ripple currents decrease greatly. The shunt type DC active filter is essentially a ripple current generator. The ripple currents are generated by a linear transistor in the scheme proposed in this paper.

A schematic of the power supply with a shunt linear active filter of the SHMFF is shown in Fig. 1.

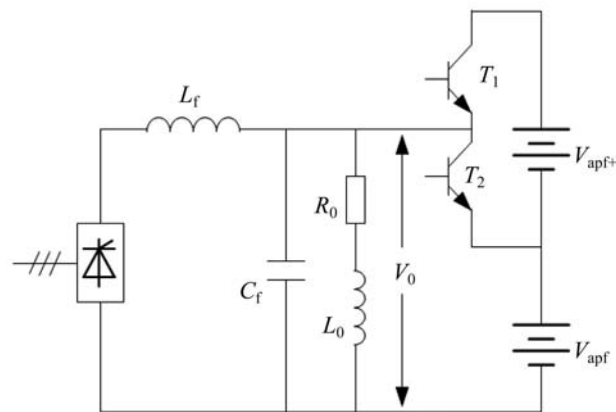


Fig. 1. New active filter topology of the SHMFF.

In Fig. 1, the magnet is represented by an RL combination. In the picture, V_0 is the magnet voltage obtained by a 24-pulse SCR rectifier with an LC filter to reduce the voltage ripple. The mean value of V_0 is determined by the magnet current and the resistance.

T_1 and T_2 are the transistors consisting of power injection devices in the shunt linear active filter. Two transistors turned on in turn can be regarded as a push and pull circuit controlled current source, and produce dual polarity compensation ripple currents to restrain the load ripple currents. When there is a positive ripple component in the load, T_2 is turned on, T_1 is turned off and the ripple current flow through T_2 is controlled. But when there is a negative ripple component in the load, T_1 is turned on and T_2 is turned off, and the ripple current flow through T_1 is controlled.

In order to ensure that the two transistors are not affected by the different load voltages so as to work stably in the linear zone, two voltage sources V_{apf} and V_{apf+} are required. The value of the former tracking with load voltage is relatively flexible and smaller than the load voltage. Meanwhile, there is a fixed voltage difference between the two voltages. The value of the latter is a stable DC voltage output, which provides the DC bias voltage for two transistors,

$$\begin{bmatrix} V_{apf} \\ V_{apf+} \end{bmatrix} = \begin{bmatrix} 1 & -1 \\ 1 & 1 \end{bmatrix} \begin{bmatrix} V_0 \\ V_{ce} \end{bmatrix}, \quad (2)$$

where V_{ce} is the permissible voltage drop of the transistors, generally about 5–15 V.

In contrast to the shunt PWM control, the essence of the above so-called linear is to ensure that T_1 and T_2 work in the cut-off or linear zone reliably by making the V_{apf} track the load voltage V_0 . So, the shunt linear active filter has the characters of working in the linear zone and dual polarity amplification. The advantages are 1) faster dynamic response and 2) smaller losses.

3 Detection and control

Equivalent circuit of shunt linear active filter in SHMFF is shown in Fig. 2.

The parameters used in the figure are defined as follows. i_s is the ripple current produced by the rectifier, i_{cf} is the ripple current flow through the capacitor, i_{apf} is the ripple current produced by the active filter, i_0 is the load ripple current, Z_{cf} is the ripple impedance of the capacitor and Z_0 is the ripple impedance of the load.

In view of the capacitance, the ripple impedance is far less than that of the load. The current i_{cf} flow through the capacitance contains not only the low ripple currents but also some negligible currents, which are produced during the rise and fall of the charging

and discharging capacitance current and the leakage current. So, i_{cf} is more easily detected than other electricity components, such as the load ripple voltage.

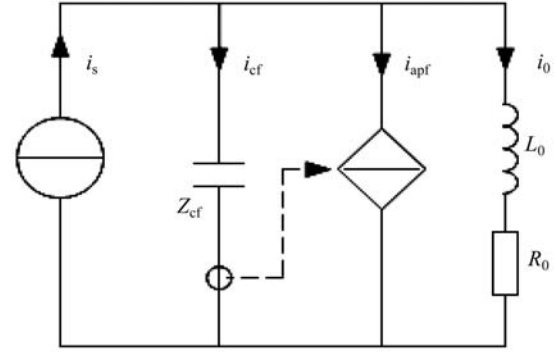


Fig. 2. The shunt linear active filter.

The accuracy and stability of i_{cf} eventually determines the effect of an active filter and accuracy and stability of the power supply. Therefore, to gain 50 parts per million low ripples, the current sensor must ensure detection accuracy of more than 50 parts per million.

One method of harmonic current detection has adopted the high-precision shunt. The shunt is simple and reliable, and has high accuracy and good frequency response, and the output voltage directly reflects the current. So, it has been widely used in highly steady power supplies. However, when the current is larger, the power consumption of the shunt is high. Moreover, the main circuit and control circuit of the shunt are not isolated. Therefore, high precision shunts are used as a current sensor is not appropriate.

The other method of harmonic current detection is a zero magnetic flux current sensor, which has a Hall-effect current sensor and a DC current comparator. Because of the zero drift, the poor precision of the former cannot satisfy the high precision current detection at 50 parts per million. The latter is composed of a measure head and closed-loop control electronic circuit, which has the advantages of high precision, low noise, wide current measurement range and good stability.

Basic performances of the current sensor, which is used to detect i_{cf} in SHMFF, are listed below. The band width is between 0 and 500 kHz, rated current is 500 A, over current is 13 percent higher than the rated current, short circuit current is ten times larger than the rated current, precision is 1×10^{-6} and the output voltage is ± 24 V.

The output compensation ripple current i_{apf} of

the active filter proportioned to i_{cf} is given by

$$i_{apf} = k_p i_{cf}, \quad (3)$$

where the ratio is k_p .

As shown in Fig. 2, two current sources, i_s and i_{apf} , are used on the main circuit, therefore

$$i_0 = i_s \frac{Z_{cf}}{Z_{cf} + Z_0} - i_{apf} \frac{Z_{cf}}{Z_{cf} + Z_0}, \quad (4)$$

$$i_{cf} = i_s \frac{Z_0}{Z_{cf} + Z_0} - i_{apf} \frac{Z_0}{Z_{cf} + Z_0}. \quad (5)$$

Combining the above three formulas yields

$$\frac{i_0}{i_s} = \frac{Z_{cf}}{Z_{cf} + (1 + k_p)Z_0}. \quad (6)$$

The transfer function of the ripple current can also be acquired,

$$G(s) = \frac{i_0(s)}{i_s(s)} = \frac{1}{[(1 + k_p)L_0C]s^2 + [(1 + k_p)R_0C]s + 1}. \quad (7)$$

The cutoff frequency of the transfer function is

$$f_c = \frac{1}{2\pi\sqrt{(1 + k_p)L_0C}}. \quad (8)$$

With an increase in k_p , the cutoff frequency of the above transfer function is reduced greatly. Mean-

while, the ripple suppression ability is enhanced greatly.

The polarity and magnitude of the ripple current i_{cf} flow through the capacitance are taken as the control signals of the active filter. Thus, two transistors generate the compensation ripple current of two-way to restrain the load ripple currents, in the positive half cycle of i_{cf} , T_2 is turned on and T_1 is turned off, and the ripple current flow through T_2 is controlled according to formula (3), turn-off, and vice versa.

4 Power devices

The compensation ripple current magnitude of the shunt active filter in SHMFF is as large as several hundred amperes [11]. So, T_1 and T_2 must be constructed by the combination of some Metal-Oxide Semiconductor Field Effect Transistors (MOSFETs). Although the current sharing effect is good when MOSFET, which has a positive temperature coefficient, is connected in parallel, special attention was given to ensure the current sharing and the radiation request. The linear current compensation circuit consisting of some parallel MOSFETs is shown in Fig. 3.

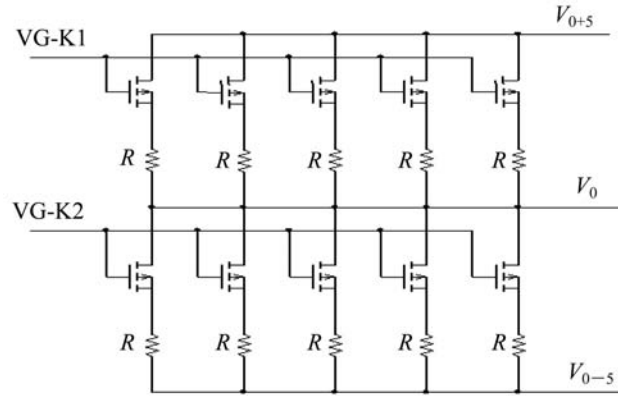


Fig. 3. The linear current compensation circuit.

The withstand voltage of the MOSFET is not high and its rated current is large. The terminals VG-K1 and VG-K2 are the drive signals. Terminal V_0 is the common lead of T_1 and T_2 in Fig. 1, which is connected to the magnetic load directly. And the other two terminals are the leads connected to two auxiliary power supplies.

5 Auxiliary power supplies

As mentioned above, U_{apf+} and U_{apf-} are the auxiliary power supplies, which provide suitable working

conditions for a shunt linear active filter. The former is an ordinary stable power supply, of which the power is not high because its voltage is low, usually 10 V is selected, about double the voltages of the MOSFET is working in the linear zone. The latter one should be paid more attention because its function is not only the voltage transform but also the transform of the bidirectional energy under a stable voltage level.

U_{apf} is obtained by DC-DC conversion, which should meet the following basic requirements:

1) A soft-switching DC-DC converter should be adopted because the power of the convert is high.

2) The output voltage of the converter could track the load voltage dynamically and should have good dynamic and stable performance.

3) The converter could provide bidirectional current.

A ZVS-CV soft-switching DC-DC converter based on the current hysteresis control is suitable in the active filter scheme proposed in this paper. The equivalent circuit is shown in Fig. 4.

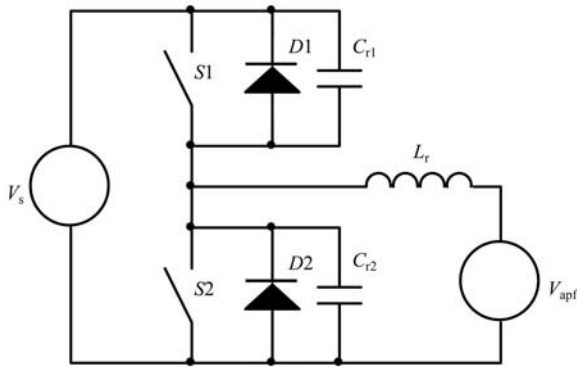


Fig. 4. The ZVS-CV DC-DC converter.

There, $S1$ and $S2$ are the force-commutated switches, $D1$ and $D2$ are the reverse diodes parallel to the switches respectively, C_{r1} and C_{r2} are the resonant capacitance of the two switches and L_r is the resonant inductance.

Analysis of the current wave flowing through the resonant inductance is carried out during each working cycle. From the analysis, it can be concluded that the wave of the output current is magnitude controlled triangular. By controlling the output current, a stable output voltage is obtained.

6 Simulation and experimental study

With the simulation software Simplo6.0, simulation aiming at the actual drive circuit and shunt

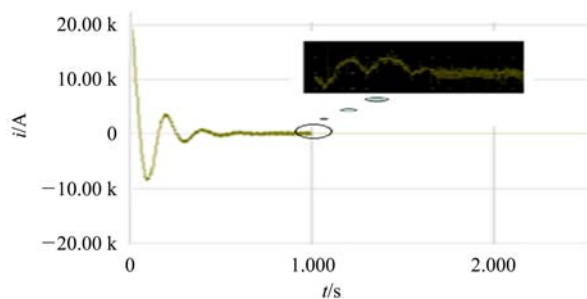


Fig. 5. (color online) Simulation waveform of load ripple current.

active filter was carried out. The load ripple current is shown in Fig. 5.

One can see from Fig. 5 that when the shunt linear active filter is put into at 1 s, the load ripple current is decreased to about 1 A, which meets the load current ripple requirement of 50 parts per million.

Based on the simulation, experiments are carried out in the prototype whose output power is 5 kW (DC50 V, 100 A). During the experiment, some low frequency ripples are obtained easily by making some non-ideal operation conditions. The output ripple waveforms of the load are shown in Fig. 6, the upper and the bottoms are the waveforms of load voltage and current, respectively.

Figure 6 shows the variation in the load ripple component after the shunt linear active filter is in operation. In contrast to the shunt PWM active filter [12], the ripple current and voltage of the load do not consist of high frequency components obviously, so the EMI is nonexistent in the power supply.

Under a 100 A load working current, the load ripple current of 50 Hz, 100 Hz and 150 Hz are 20 mA, 9 mA and 1.8 mA, respectively, which are attenuation to 1.2 mA, 0.8 mA and 0.2 mA when the shunt active filter is adopted. Estimating conservatively, assuming all of the ripple components are in the same phase angle, the maximum peak ripple current is 4.4 mA. So, the ripple current factor in the load achieves 44 parts per million. Therefore, the rigor requirements of low output current ripple are satisfied.

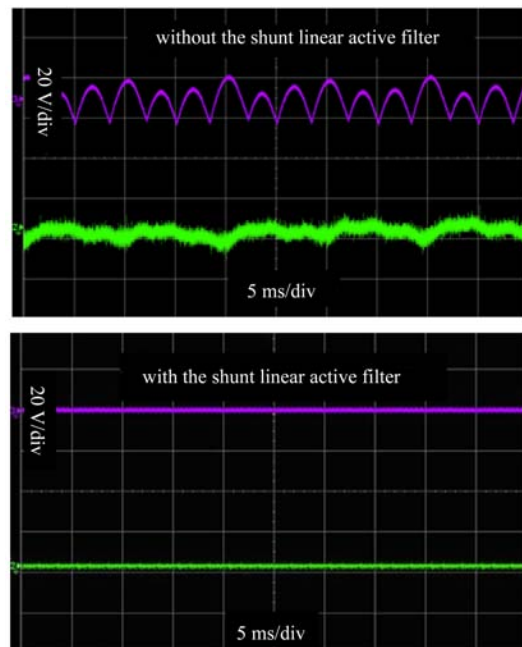


Fig. 6. (color online) The load ripples waveform.

7 Conclusion

This paper puts forward a new kind of shunt linear active filter that is applied in the power supply of the SHMFF. The new scheme can overcome the shortcomings of the series active filter and the shunt PWM active filter. The structure and the working principle of the new shunt linear active filter are introduced, and the implementation scheme design is

also analyzed. In contrast to the traditional active filter, the shunt linear active filter can guarantee the filtering requirement and greatly reduce the capacity of the device. The simulation and experiments all show that the active filter scheme proposed in this paper has good ripple filter effects. The results of this paper can provide some references for the design of active filters in SHMFF and other high power, high stability power supplies.

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