COMPACT OUTPUT FILTER FOR SWITCHING FREQUENCY ELIMINATION AT THE PLC LINAC NEW MAGNET POWER SUPPLY*

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Abstract

Pohang Accelerator Laboratory Linac magnet power supply (MPS) has been upgraded for the stable beam injection and 4th generation light source research, in 2006. MPSs are developed as compact configuration by using four quadrant switching scheme with power MOSFET. In case of 10V, +/-10A bipolar output operation, main circuit is operated as one or three quadrant, and in case of 50V, 50A unipolar output operation, main circuit is operated as parallel one quadrant. Switching frequency of MOSFET switch is above than 40 kHz. MPS consists of main power board, control power board, regulator board and CPU board. The size of each board has 100mm width and 250mm depth. Main power board made of four-quadrant MOSFET switch, driver and output filter. Output filter must be perfectly eliminating switch frequency and have compact size. In this paper, we report on development and characteristics of compact output filter of the new MPS for PAL linac.

INTRODUCTION

The high-performance magnet power supplies for particle accelerator system require a second-order low-pass filter to reduce the output current ripple within specifications. Because of the large time constant, the load magnet provides very little damping to the second-order output filter. [1] Many switching power converters have applications that require very low high-frequency noise and ripple on the output. A single-stage filter which meets the requirements can become very large and impractical, especially for boost and buck-boost converter which have pulsating output currents. Unfortunately, a second LC filter gives up to 180° additional phase delay in the control-to-output transfer function, and it can make the system unstable if improperly designed. [2] The new MPS of the Linac has been developed by full-bridge four-quadrant scheme. To develop compact MPS, main power conversion is developed as PCB board of 100mm x 250mm size. Main power PCB board is made of MOSFET switch, driver and output LC filter. Therefore, output LC filter must be compact size and eliminate noise from MOSFET switch. In this paper, we report on development and characteristics of compact output filter of the new MPS for PAL linac.

BASIC CONCEPT OF NEW MPS FOR PAL LINAC

Full-bridge four-quadrant DC/DC converter scheme is selected as MPS topology of the PAL Linac. This type converter is able to operate bipolar or unipolar output mode according to PWM switching method. Table 1 shows the specifications of the PAL Linac MPS. The required maximum output current is ±10A and 50A, and output stability is ±100ppm and ±50ppm in the bipolar and unipolar MPS, respectively.

Table 1: Specifications of MPS for upgraded one

	Bipolar	Unipolar	unit
Size (W x H x D)	435x135×450	435×178×450	mm
Input	1ϕ 220V	3ϕ 30V	V
Output	±10/20	50/50	A/V
Stability	±50ppm	±20ppm	< 1 hour
	±100ppm	±50ppm	> 10 hours
Resolution	16		bit
Switch frequency	> 40		kHz
Output Filter Cut-off freq.	< 5		kHz

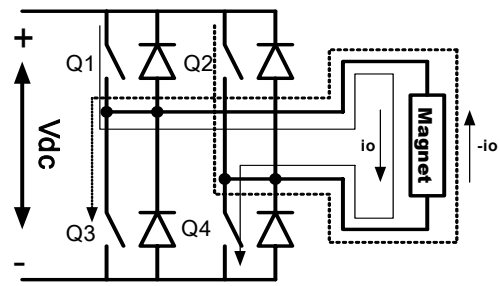

Figure 1: Bipolar output operation of full-bridge four quadrant DC/DC converter.

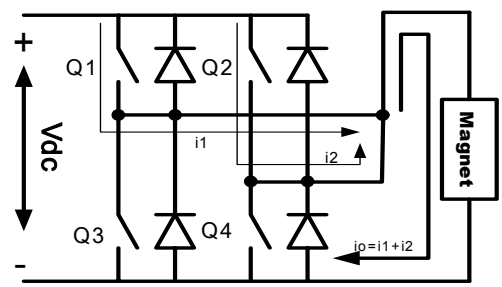

Figure 2: Unipolar output operation of full-bridge four-quadrant DC/DC converter.

Fig 1 and Fig 2 show the basic circuit diagram of bipolar and unipolar MPS operations of a full-bridge four-quadrant DC/DC converter. In Fig 1, output current flows

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to a load as positive or negative direction (i_o or $-i_o$) by on or off its contact point of two-switch pair (Q1-Q4 or Q2-Q3). In Fig 2, output current flows to the load as only positive direction (i_1 or i_2) by on or off its contact point of two-switch leg (Q1-Q3 or Q2-Q4). In this case, if two-switch legs are parallel simultaneously, the current (i_1 + i_2) to the load is double the amount of current in Fig 1. Clean DC current should be supplied to magnet for minimized beam effect by power supply. At Fig 1 and 2, switching noises from main switch occurred at load, and the output filter needs between main switch and load. Size of main power PCB is only 100mm width and 250mm depth and included main circuit and LC output filter. Therefore, LC output filter must develop as compact size.

LC OUTPUT FILTER OF PAL LINAC NEW MPS

Two-stage LC filter is used for the new MPS of the PAL Linac. The configuration of the output filter is two-stage LC and RC damping filter. Fig 3 shows circuit diagram of the output filter. In fig 3, 1st stage LC filter (L_{11}, L_{12},C_{11}, C_{12}(C_1)) must be arranged within 95 mm x 70 mm at main power module PCB and 2nd stage LC filter (L_{21}, L_{22},C_{21}, C_{22}) must be arranged within 86 mm x 110 mm as other PCB.

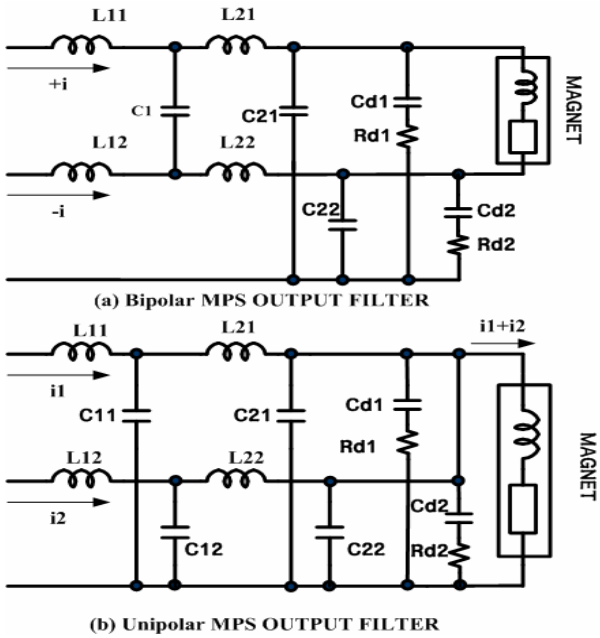

Figure 3: Filter circuits of the PAL Linac new MPS

Component selection

Key design points of two-stage LC output filter design are control bandwidth, switching frequency of the power supply, and cut-off frequency of the filter. 1st filter cut-off frequency must be more about five times than that of control bandwidth, and 2nd filter cut-off frequency must be closely control bandwidth. Switching frequency must be more than ten times compare with control bandwidth. Control bandwidth is decided in accordance with MPS application.

Inductance of the output filter

The first consideration item is inductor choice in filter design. Inductor value controls the amount of ripple current that the capacitor. Inductance is calculated by Eq. 1.

$$L = \frac{V_{out} \times (V_{in\_\max} - V_{out})}{V_{in} \times f_{sw} \times I_{out} \times K} \qquad (1)$$

Here, K = 0.3 of the output current. Desirable value of the inductor might to have a very small value of inductance greater than 30% for high current application. Recommend inductance value is several ten- μH . In output filter, an inductor is important factors to make small size and low-cost of power supply. Normally inductor has above two-times size and above three times cost compare with capacitor.

Capacitance of the output filter

The capacitance of the output filter should be high value for cut-off at low frequency. And capacitor ESR (Equivalent Series Resistance) not only contributes to the ESR zero but also contributes significantly to the damping factor of the filter. The drawback of a high ESR capacitor is that to have low ripple and good transient response, the output filter needs to have lower ESR values. [4]

Inductors and capacitors for the filter

1st stage LC-filter is arranged at main power module PCB. The inductor of 1st and 2nd stage filter used the same core. R-material ferrite core (R-44022-EE) of Magnetics companies is selected as the core of the inductor. Switching frequency of the MPS is 50 kHz. Therefore, winding wire must consider skin effect to occur on high frequency switching. 0.2 mm thickness x 26 mm copper foil is used as wire. Winding is 25 turns. An inductor has 72 cm^3(4.0 x 4.0 x 4.5) volume, and DC resistance is 20 $m\Omega$. Inductance valu of 1st and 2nd filter is controlled according to gap thickness. An capacitor is selected with PCB mountable type. WIMA MKS4 15 μF capacitor is adopted as a filter capacitor. The capacitor ESR is 10 $m\Omega$. Table 2 describes output filter parameters. Fig 4 shows fabricated output filter.

Table 2: Output filter parameters

	inductance	capacitance	Cut-off frequency
1st stage filter	120 μH	30 μF (15 μF x 2)	3.0 kHz
2nd stage filter	60 μH	45 μF (15 μF x 3)	2.6 kHz

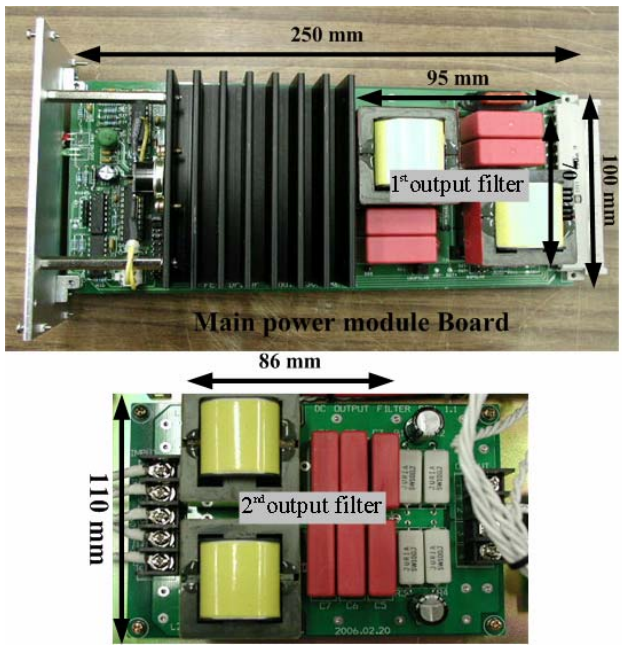

Figure 4: Fabricated output filter

Frequency characteristics and effect of the output filter

A dynamic signal analyser, Stanford Research SR780, was used for frequency characteristics measurement of filter and output current. Total cut-off frequency of the output filter is measured about 1.5 kHz. Attenuation is below than –70 dB at MPS switching frequency. Therefore, generated any noise from PS is completely eliminated and clean DC current may be supplied to the magnet. Fig 5 shows frequency characteristics of output filter measured from bipolar and unipolar MPS, respectively. Fig 6 shows effect of output filter at output current. After filter output current not included any noise from MPS.

Output stability of PAL Linac new MPS

The measured points were short and long-term stability, and frequency characteristics that are important factors for determining PS performances. For the measurements of performance, Keithley2700 6.5digit digital multi-meter (DVM) is used. Long-term stability is keeping in ±40 ppm and ±6.5 ppm during 19 hours, and short-term stability is keeping in ±15 ppm and ±2 ppm during 1 hour for the bipolar and unipolar MPS, respectively.

SUMMARY

The new compact MPS with a full-bridge 4-quadrant DC/DC converter scheme has been developed for PAL Linac. In order to maintain easily, standardized PCB was used for both bipolar and unipolar mode in the power supply. Configuration of the output filter is adopted 2-stage LC filter. Output filter is developed as compact size. Output filter is perfectly eliminated generated noise from power supply. Therefore, clean output DC current can be supplied to the magnets. Long-term stability is keeping in ±40 ppm and ±6.5 ppm during 19 hours, and short-term stability is keeping in ±15 ppm and ±2 ppm during 1 hour for the bipolar and unipolar MPS, respectively.

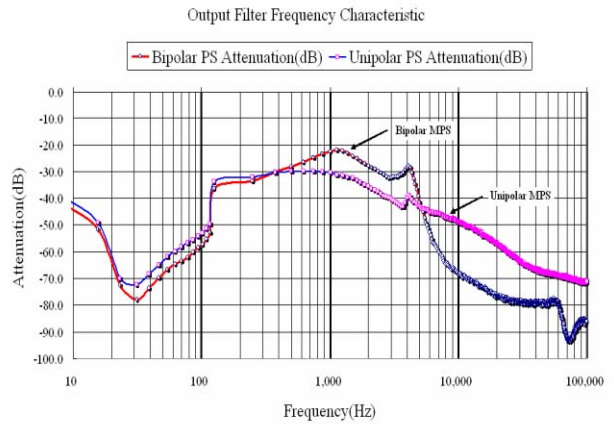

Figure 5: Frequency characteristics of the output filters

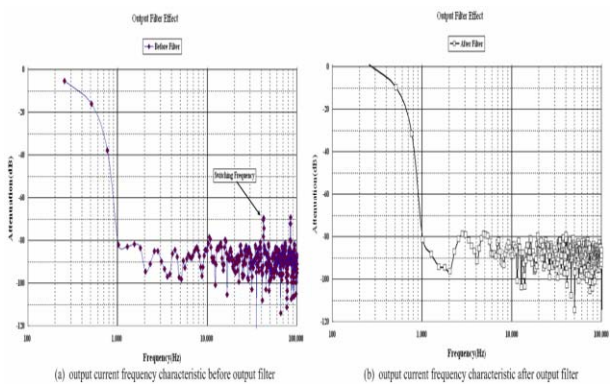

Figure 6: filter effect at output current

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