Switching Mode Power Supply for the Synchrotron Magnet

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Abstract

A switching mode power supply which uses IGBT is developed to look into the detailed investigation for the synchrotron application. Its operation frequency is 18 kHz and it is equipped with both the LCR filter and the EMI filter to reduce the switching noise. It has enough output capacity to excite a string of local quadrupole magnets. Current setting using 18 bit DAC is precise enough to measure the stability. Its current stability, ripple and interference noise are treated in addition to the VME control of the power supply.

INTRODUCTION

Application of the switching mode power supply to the synchrotron magnet excitation was initiated by CERN in 1982 and it was successfully demonstrated with the beam test of LEP in 1988. In this case MOSFET (Metal Oxide Semiconductor Field Effects Transistor) or GTO (Gate Turn Off thyristor) was used for the switching element [1,2,3]. The switching power technology was established in early 1980's for the light-weight power supply which was loaded in the airplane and man-made satellite. In order to apply this type of power supply to the synchrotron it is essential to cover a wide range of output, from a few 100 W to 100 kW, hopefully to 1 MW. The output current more than 10,000 A has been developed in the Aluminum industry using MOSFET but the output voltage is low. Maximum output power was 37.5 kW for LEP quadrupole and sextupole magnets using GTO.

For the higher power application [4,5], we have introduced 1500A, 40V output switching mode power supply using IGBT (Insulated Gate Bipolar Transistor) from Inverpower Controls Ltd. of Canada to test the power limit, performance, reliability, current stability and etc. The IGBT allows the 18 kHz square wave switching which reduces complication in PWM (Pulse Width Modulation) control.

The trend of the power converter technology is to attain higher efficiency and to reduce the size to save the space. This demand turns our attention to the PWM control of the regulated dc voltage. The switching is based on the square wave form with more than 10 kHz. But the problems are its inherent switching noise and the large switching loss. To overcome these problems the resonant converter is introduced. However, it has complexities in the frequency control and the conductive loss during switching which requires the ZVS (Zero Voltage Switching) PWM converter. In this manner the PWM switching becomes more and more complicated for the higher power converter to control the many elements connected in parallel.

If the power IC (Integrated Circuit transistor) such as IGBT is used, the switching circuit becomes simple and compensates for the cost imposed by the complicated switching circuit. Thus this study concerns the PWM power supply using IGBT switching element.

COMPARISON OF POWER CONVERTERS

So far the SCR (Silicon Controlled Rectifier) has been mainly used for the power converter of the synchrotron power supply. The rectified current is regulated to the order of 10^{-4} or 10^{-5} which is required to accelerate the particle beam stably.

Table 1 Comparison of the switch mode and SCR power supplies

	Switch mode	SCR
Output range	< ~100 kW	> ~10 kW
Application	local quad sextupole steering magnet	local & main quad sextupole main dipole
Feature	precise for full range	linear for 20~100 % range
Efficiency	> 80 %	~50 %
Power factor	~90 %	~70 %
Its regulation	can be omitted	required
Accommodation space	small	large
Control frequency	10~100 kHz	1.2 kHz for 24-pulses
Current stability	5×10^{-5}	1×10^{-4}
Maximum current	> 10,000 A	> 10,000 A

Current is usually regulated either by an active filter or series dropper. The latter regulation is applied for the several 10 kW class. For the power supply more than 100 kW, the former regulation becomes cost effective. While the switching mode power supply is limited under 100 kW at present. So the comparisons should be made for the similar output class which will be used to excite the local quadrupole magnets. In Table 1, two types of power supplies are compared.

Efficiency is defined as $\eta = P_0 / (P_0 + P_L)$, where P_0 is the output power and P_L the power loss. It is improved by using the power transistor with low conducting resistivity and low loss rectifying diode. The IGBT is suitable for the high voltage and large current output. For this application, GTO is one of the candidates but the switching loss is large and the switching frequency is low (~500 Hz) to obtain smooth regulation and leads to big acoustic noise.

In both cases the switching noise appears in the output current and is transmitted back to the primary ac line. The control frequency of SCR is low, so the ripple frequencies are the control one, the multiples of the fundamental one due to the voltage unbalance and error in the firing angle, and the high frequency around ~1 MHz which results from the current oscillation in the snubber circuit to suppress the switching surge. The high frequency ripple current can be reduced by both the low pass filter and the large inductance of the magnets, and the low frequency ripple is suppressed by the active filter. Thus the current stability including ripple is $\sim 1\times10^{-4}$ or less.

In the case of the switch mode power supply, main ripple comes from the switching frequency and generates higher harmonics of this frequency more than 100 MHz. The EMI (ElectroMagnetic Interference) noise which must be suppressed under the regulation limit. Otherwise, it couples with the electric devices with capacitance and inductance, and generates troubles in the worst case. Therefore this EMI noise measurement is one of the main problems of this study.

MODEL SWITCH MODE POWER SUPPLY

The maximum rating of the model switch mode power supply is determined to excite synchrotron magnet. The converter section consists of two IGBT switches, transformer reset diodes, high frequency step down transformer and secondary ultra fast rectifier/free wheeling diodes. To protect IGBT from voltage overshoot during off transition period, the RDC snubber circuit with fast diodes and high current pulse capacitors, is connected.

The output current of the secondary rectifier stage has a square voltage waveform with 18 kHz which is filtered by a two stage LC filters to a low level. The output current is monitored with DCCT of DANFYSIK (2 ppm accuracy) with 1500A/1A ratio. Fig.1 gives the skeleton of the main circuit.

MEASUREMENT OF SWITCHING NOISE

Noise of the switch mode power supply has two sources. One is the noise from the rectifying the ac input and another is the switching noise. If these noises leak in the primary line, they are transmitted as the conduction and the radiation noises. The ac line acts as an antenna to emit electromagnetic radiation when the high frequency current flows. And if noises leak in the output side, they give the current ripple. Therefore the switch mode power supply must be equipped with the EMI filter to suppress both normal and common mode noises at both sides of input and output.

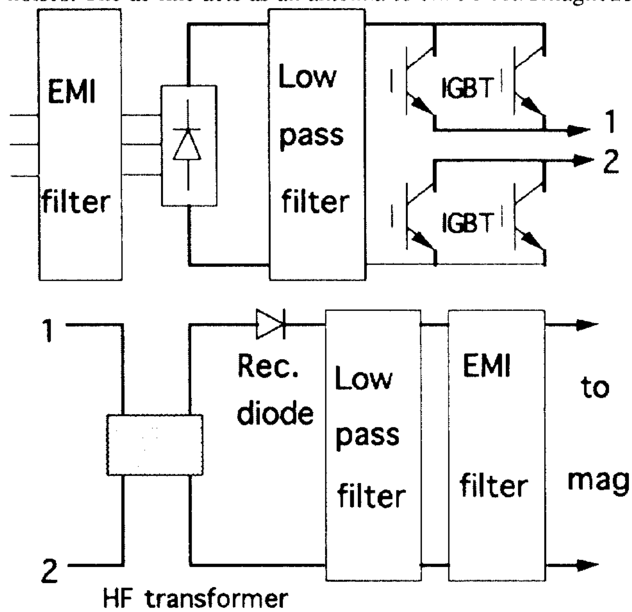

Fig.1 Skeleton of the main circuit.

The conduction noise in the ac line measured as the terminal voltage is compared with the Class 1 regulation of VCCI (Voluntary Control Council for Interference by information technology equipment in Japan), 79dBμV for 0.15~0.5MHz and 73dBμV for 0.5~30MHz and the radiation noise is regulated for 30 ~ 1000 MHz but compared with the VDE (Verband Deutscher Electrotechnike) regulation for the Class A, 63.5~53dB(0dB=1μV/m) at 3m from EUT (Equipment Under Test) for 1~30MHz because the higher frequency more than 35MHz is not observed. In many cases radiation noise is considered up to ~300 MHz, so the frequency range of the EMI filter is 0.15 ~ 300 MHz. The EMI noise spectrum was measured with MS2601 of Anritsu Co. and the field strength with KNM-2402 and 5002 of Kyoritsu Elec. Co. using a LISN (Line Impedance Stabilization Network) KNW-2441 of YHP or an EMI clamp KT-10/20 of Kyoritsu Elec. Co. or a loop antenna KBA-2402 of Kyoritsu Elec. Co. They covers the frequency range of 100 Hz ~ 1000 MHz and the typical result is given in Fig.2 for the maximum current, 1500 A.

CURRENT STABILITY

The stability of the output current was measured with DCCT (DC Current Transformer), Type TOPACC 1700-ITS, of HOLEC. According to the specification, its accuracy is less than 5 ppm, the temperature coefficient is less than 0.25 ppm/K and the drift is less than 5 ppm/year.

The short time peak-to-peak current variation is ~50 ppm. The gradual change of the output current due to drift is ~20 ppm over one hour. If the ac line voltage fluctuates, its effect will appear in the output current. The current fluctuation when the primary voltage changed by 5% is given in Fig.3.

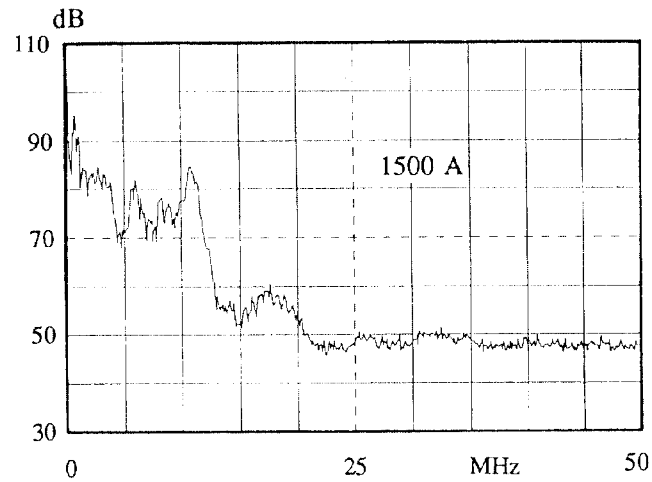

Fig.2 Conduction noise in the AC line.

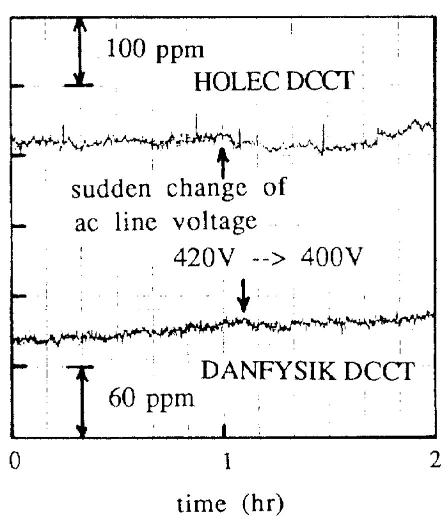

Fig.3 Fluctuation of the output current when the ac line voltage changed by 5%. (Upper trace: HOLEC DCCT, Lower trace: Built-in DANFYSIK DCCT).

The switch mode power supply shows a good performance as regard to the current stability. It can safely be used for the power supply of the synchrotron magnet. Long-term reliability will be checked assuming the actual operation.

CURRENT CONTROL

The VME-bus (Versa Module Euro) system is used for the PWM control and monitoring the status and fault. The pulse width is determined from the output level of the voltage regulator of which output is connected to the input of the PWM stage.

The 18-bit DAC (Digital-to-Analog Converter) for the current reference is adopted to measure the accuracy of the output current which is increased or decreased by the UP/DOWN push buttons under the coarse or fine adjustment mode. Whereas the output current monitor adopts the 16-bit ADC (Analog-to-Digital Converter). Current is measured precisely using the external HOLEC DCCT but controlled by the inside DCCT described above. The total current regulation is less than 50 ppm including the line fluctuation and ambient temperature variation. The current drift over 8 hr is about ±100 ~ ±1000 ppm depending on the output current. Fig.4 shows the current drift measured at the maximum current without waiting the warming-up time (cold start).

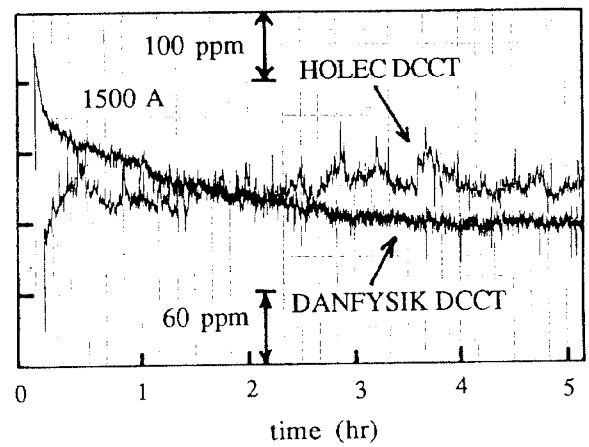

Fig.4 Current drift at the maximum current

The current ripple is ±20 ppm for the magnet load at the maximum current as seen from Fig.4. In this measurement, the spare quadrupole magnet of the AR (Accumulation Ring) of TRISTAN was used. Its inductance is 5.8 mH and resistance 6.2 mΩ. Discrepancy between two DCCT traces is now being investigated.

REFERENCES

[1] H.W. Isch, A. Dupaquier, K. Fischer, R. Forrest, J. Pett and P. Proudlock, 'Switch Mode Power Converters; Present and Future,' Proc. 1989 IEEE Particle Acc. Conf., Chicago, 1989, pp.1151-53.

[2] P. Proudlock, H.W. Isch and J.G. Pett, 'The Use of Switch-mode Power Converters for the LEP Main Ring Power Converter System,' Proc. 1987 IEEE Particle Acc. Conf., Washington D.C., 1987, pp.1511-13.

[3] K. Fischer, P. Proudlock, B. Alberdi and J. Zabaleta, 'An AC/DC Converter using MOSFETs for a 2000A, 10V Output with High Stability,' Proc. 3-rd EPE Conf., Aachen, 1989.

[4] M.M. Berndt and D. MacNair, 'DC Magnet Power Supply for the FFBT at SLAC,' 1993 IEEE Conference Record of Nuclear Science Symposium, San Fransisco, 1993, pp.184~187.

[5] D. MacNair, M. Berndt and A. Saab, 'The Design of a Precision Current Regulation Power Supply Controller,' ibid, pp.397~400.