DEVELOPMENT ON HYBRID FILTER FOR HIGH-PRECISION POWER SOURCE TO ACCELERATOR ELECTROMAGNETS

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Abstract

This paper describes a development targeting an ideal power supply to the synchrotron system rated at tens of GeV (deca-GeV) planed jointly by KEK and JAERI in Japan. The developed power supply offers solutions both in the power capacity and in the precision at the same time. The power supply consists of the advanced self-commutated current-source type converter (ACSC) and the "hybrid filter", which has spun out of intensive development efforts. The configuration and performance of the hybrid filter are introduced followed by reports on the successful evaluation results from mini-model tests where the precision requirement of 10^{-6} is achieved.

1 INTRODUCTION

In Japan, KEK and JAERI are proceeding a joint project of a high intensity Proton accelerator facility including a deca-GeV synchrotron. The synchrotron requires large-power and high-precision trapezoidal current pattern. Furthermore, the power supply should minimize the disturbances to the electric network because the power is extremely large compared with the power requirement of the preceding projects.

Corresponding to these requirements, Toshiba has developed a new DC power supply concept fully utilizing cutting-edge power electronics technology. For the power supply, the most advanced power semiconductor device, IEGT, is proposed, which can turn off the current by its gate control and is superior to the power thyristors used in the conventional power supply. The IEGT is also rated at high-voltage and large-current and has potential to offer solutions to satisfy the requirements of the deca-GeV project.

The friendliness to the AC system of the advanced converter with the self-turn-off device is described in another paper. The advanced converter also offers better performance in the trapezoidal current profile with less DC ripple and better tracking response to the pattern order. This paper describes new ripple current compensation method applied with the advanced converter.

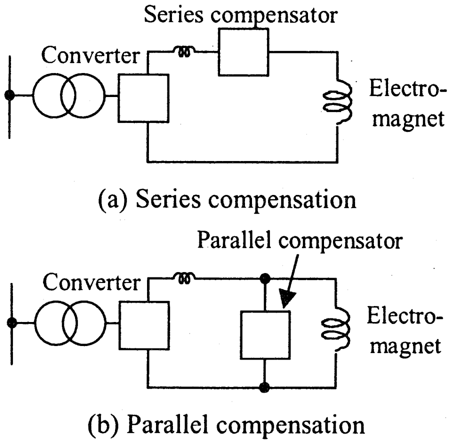


Figure 1: Ripple compensation methods

2 RIPPLE CURRENT COMPENSATION

2.1 *Feasibility of parallel compensation*

To make a ripple-free and precisely shaped trapezoidal current pattern, series compensators, the active filters or the droppers have been applied combined with the converters as shown in Figure 1 (a). As a different approach to this method, the parallel compensator is proposed in this paper as shown in Figure 1 (b).

The series compensator suppresses the voltage ripple to make the DC voltage constant. Since it is connected between the converter and the electromagnet, it should conduct all of the DC current. For a large current application, the series compensator should consist of many small semiconductor devices connected in parallel.

However, the semiconductor technology now yields the high-voltage self-turn-off semiconductor devices, which can be connected in parallel with the electromagnet. Then, the parallel compensator becomes now feasible to manufacture. Furthermore, the parallel compensator current rating can be fairly small since it conducts only the ripple components. The small current rating requires fewer parallel devices and does not affect the converter capacity practically.

2.2 *Operation principle of the parallel compensator*

The parallel compensator operates in the following manner by monitoring the electromagnet current.

- When the current increase, the compensator pulls out the excessive current from the electromagnet.
- When the current decreases, the compensator pushes the current flowing into the electromagnet.

In other words, the parallel compensator bypasses the ripple components and the smooth current is supplied to the electromagnet. Furthermore, the parallel compensator can adjust the difference between the current order and the actual current. The feature contributes to improve the tracking response to the current order.

3 HYBRID FILTER DESIGN

3.1 *Requirements from large-capacity electromagnets*

From the basic idea of the parallel compensation, the compensator might be realized by a current source made of an analogue amplifier or a transistor current controller. However, in the deca-GeV synchrotron with high acceleration speed, the electromagnet voltage ratings will reach several kV. To be connected in parallel with the electromagnet, the compensator should operate at high voltage. Thus, the amplifiers or the transistor equipment are not feasible for that purpose since their voltage ratings are usually too small.

On the other hand, high-voltage semiconductor devices for switching use are now commercially available. One of the most advanced devices is the IEGT rated now up to 4.5kV with a single device. Therefore, it is considered to be reasonable to apply the switching device for the parallel compensation purpose.

3.2 *Hybrid filter concept*

Based on the preceding consideration, the "hybrid filter" has been innovated. The hybrid filter consists of a switch and resistor as shown in Figure 3. The simple configuration operates as a variable resister in principle. The switch operates at a frequency of several kHz and the duty ratio d is controlled. Then, the equivalent resistance R_{eq} of the hybrid filter can be calculated by the following equation.

$R_{eq}=d \times R_0$ ... (1)

, where R_0 is the resistance of the resistor.

3.3 *Prototype hybrid filter*

In order to evaluate the performance of the hybrid filter, a prototype was manufactured for a converter-electromagnet mini-model rated at 1600A and 88V driven by the ACSC described in another paper. The prototype consists of eight strings of an IGBT switch and resistors connected in series. The IGBT was used in place of the IEGT considering the voltage rating of the mini-model. The switching interval was 0.5ms (2kHz) and the switching phase was displaced 1/8 of the interval one another to make the equivalent switching frequency to be 16kHz (2kHz $\times$ 8). This configuration can change the equivalent resistance in every 0.0625ms (1/16kHz). The sub-mili-second response time means that the hybrid filter can suppress the current ripple frequency at several Hz or even kHz.

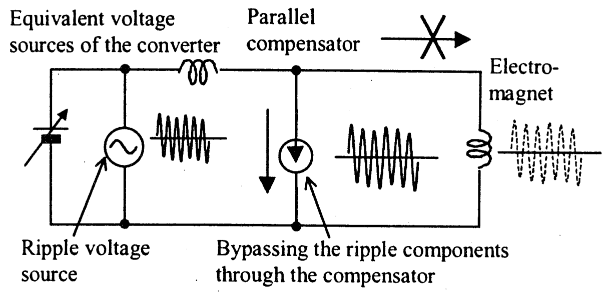


Figure 2 Operation of the parallel compensator

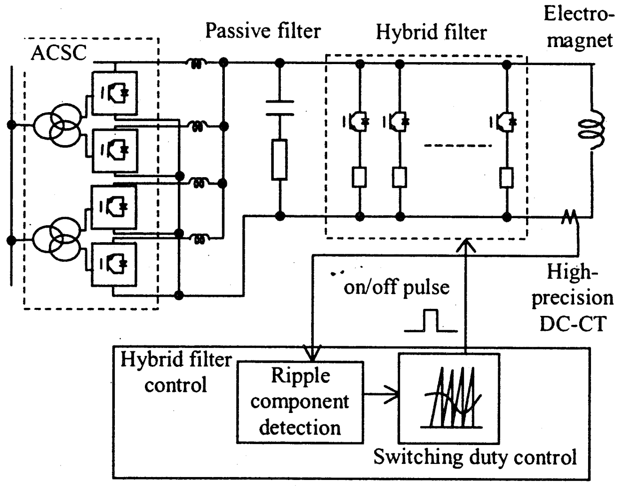


Figure 3 Prototype hybrid filter for mini-model

The resistance value is selected considering the electromagnet impedance value. If the values are comparable, the current sharing ratio between the hybrid filter and the electromagnet is not sufficient quickly to pull or to push the current from or to the electromagnet. The equivalent resistance value R_{eq} is designed to be smaller than the ratio between the voltage across the electromagnet V_m and the expected current ripple amplitude I_r.

$R_{eq}<V_m/I_r$ ... (2)

The R_{eq} is synthesized by the eight strings. The resistance R_{eq}' of one string will be determined by the following equation.

$R_{eq}'=8R_{eq}$ ... (3)

If the average duty ratio is assumed to be 0.5, then, the resistance R_0' of each string is calculated as follows from equations (1) and (3).

$R_0'=2R_{eq}'=16R_{eq}$ ... (4)

3.4 *Hybrid filter control*

A high-precision DC-CT measures the current in the electromagnet. From the DC-CT signal, the ripple components are detected. The ripple signal is amplified and used to determine the duty ratio d of the switch as shown in Figure 3.

For the mini-model tests, the control is implemented in fully digital controller driven by the 32-bit CPU and DSP.

4 HYBRID FILTER PERFORMANCE

4.1 Hybrid filter characteristics

The characteristics of the hybrid filter characteristics was calculated in the frequency domain considering the mini-model main circuit characteristics and the control functions. The DC circuit impedance characteristics is shown in Figure 4. The impedance seen from the converter takes small amplitude in the wide range from 1^0 Hz to 10^2 Hz, where the major ripple current components stay. The characteristics is difficult to obtain only by the conventional passive filters.

In parallel with the analysis in the frequency domain, the time domain analysis is also performed. The EMTDC™ is used as the simulation tool. In the digital simulation, all of the components and the control functions are simulated as is in the mini-model. In the digital simulation, the hybrid filter parameters are finally confirmed.

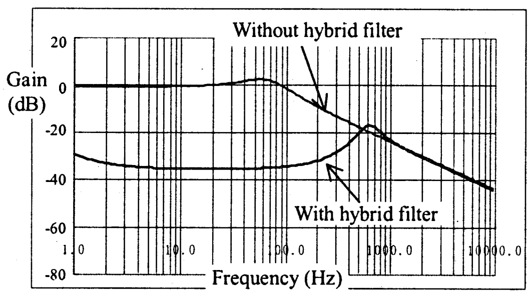


Figure 4 Frequency characteristics of hybrid filter

4.3 Experimental results

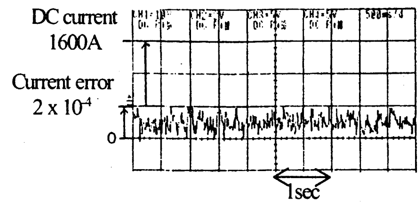
Some of the mini-model test results are shown in Figures 5 and 6. Figure 5 visually indicate that the current ripple is clearly suppressed with the hybrid filter operation. The results are in well consistent with the digital simulation.

Figure 6 shows the FFT analysis of the DC voltage. The DC voltage profile resembles the characteristics obtained by the frequency domain analysis. From the profile, the ripple current is calculated to be less than 10^{-6} when it is applied to the actual deca-GeV synchrotron system. The improvement in the tracking performance is also confirmed in the mini-model tests as shown in Figure 7.

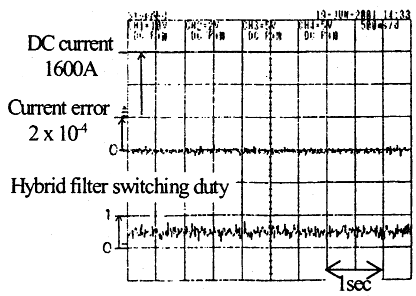
4 CONCLUSION

A new power supply is proposed and developed for deca-GeV synchrotron planned in near future. The power supply applied the most advanced and innovative power electronics technology. The concept of the hybrid filter is introduced and the performances are successfully evaluated through the simulations and the mini-model tests.

The authors are now developing the IEGT switch used in the actual high-voltage system. Combined with the hybrid filter concept and the high-voltage switch hardware, the authors believe to realize a high-performance DC power supply and to contribute to development of the deca-GeV synchrotron project.

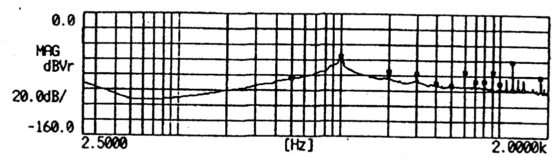


(a) Without hybrid filter

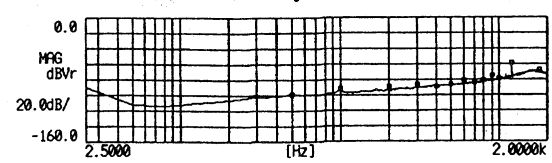


(b) With hybrid filter

Figure 5 Current ripple waveforms



(a) Without hybrid filter



(b) With hybrid filter

Figure 6 DC voltage spectrum

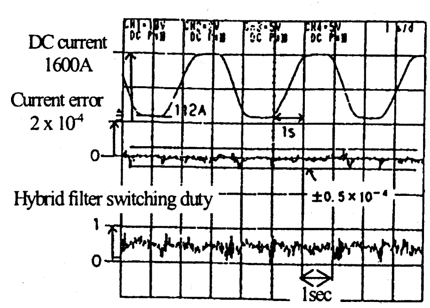


Figure 7 Tracking performance improvement

REFERENCES

[1] Takami Sakai et.al, "Consideration on Self-Commutated Convertor Characteristics for DC Power Supply", IPEMC'2000 Beijing, Aug. 2000