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Effect of Common Mode Static Filter in High-Performance Synchrotron Power Supply

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Abstract

The power supply for synchrotron magnets was produced to test its performance. It has a common mode static filter of reactor type, and this filter can be bypassed. In this paper, an equivalent circuit model of the power supply can explain those measurement results.

1 Specifications, Features, and Environments of Test

Specifications are listed in Table 1, environments of performance test in Table 2, respectively.

Table 1
Specifications of power supply

Rectifier	12-Pulse Thyristor Rectifier
Maximum Current	3000A, DC
Maximum Voltage	210V

Table 2
Environments of performance test

Load	TRISTAN 2 quadrupoles
Inductance	24mH
Resistance	26mΩ

This power supply has the following features;

a) All elements are disposed symmetrically up and down to the ground line.(see Fig 1)

b) It has two kinds of static filters around the ground line. One is of normal mode reactor type and the other is of common mode one. The common mode filter can be bypassed to measure the frequency characteristics without it.

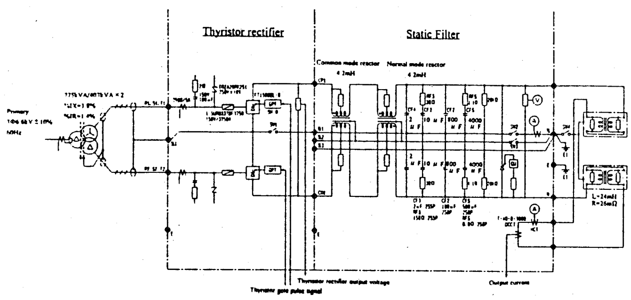

Fig. 1 Single line diagram of the power supply

2 Measurement Results

The output voltage between positive and negative lines, that is to say, a normal mode output voltage was measured by using FFT analyzer at a current of 1500A without pattern operation. Output ripple voltage without common mode reactor is shown in Fig 2, with it in Fig 3, respectively. When common mode filter was equipped, 4μF capacitor was inserted between the magnet coil and the ground line to emphasize the common mode.

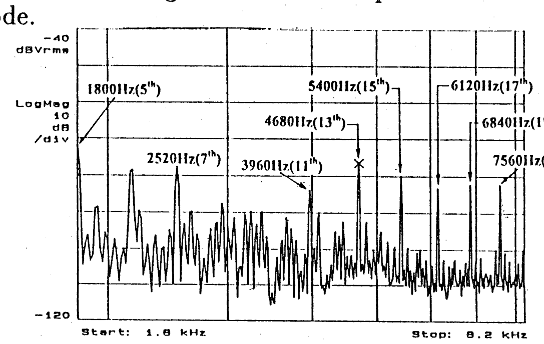

Fig. 2 Output ripple voltage without common mode reactor

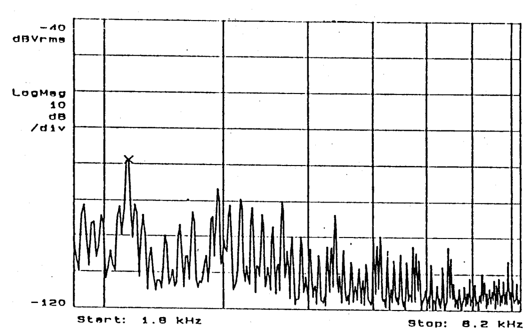

Fig. 3 Output ripple voltage with common mode reactor

These mean the following;

(A) Common mode filter cannot reduce the amplitude of the ripple of $720n$ [Hz] (n is integer).

(B) Though normal mode output voltage was measured, common mode filter can reduce the amplitude of the $360(2n-1)$ [Hz] components.

(C) With the common mode reactor, for $360(2n-1)$ [Hz] components, the higher the frequency is, the larger the attenuation ratio of ripple voltage becomes.

To explain these phenomena, we assume the following equivalent circuit model of a power supply.

3 The Model of Power Supply

The stray capacitances exist between the midpoint of each thyristor bank and the ground line. It is proved that the commutation spike appears only when outer thyristors are turned on, since there are difference between outer thyristor bank and inner one. [1]

But our measurement results are explained if thyristor banks up and down to the ground line are slightly different. Thus, for simplicity, we will analyze the circuit model which have asymmetrical input part to the ground line and symmetrical two filters and loads.

Here, C_u stands for the capacitance of the thyristor bank disposed up to the ground line, C_l down to the ground line and C_1 is the capacitance of the midpoint of the both thyristor banks, respectively. The leakage inductances of transformer is L_u and L_l, voltage of upper and lower thyristor banks are v and u, respectively. These capacitances and inductances are slightly different from each other. And static filters and magnets are disposed symmetrically to the ground line. (see Fig 4)

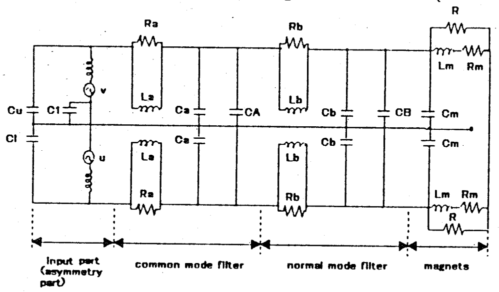

Fig. 4 The all-in-one diagram of the model of power supply and equivalent circuit of magnets

3.1 The Normal and Common Mode Admittances of Symmetric Part

When elements are disposed symmetrically to the ground line, normal and common mode are decoupled. [2],[1] Y_n and Y_c express the normal and common mode admittances of symmetric part that consist of the two static filters and magnets. So,

$$\begin{aligned} I+J &= Y_n\,(V+U) \\ I-J &= Y_c\,(V-U), \end{aligned}$$

where Y_n and Y_c are the function of Laplace differential parameter p. (In our power supply, the resonant frequency of normal and common mode reactor are 10kHz, 8kHz, respectively. [3])

3.2 Input Part (Asymmetric Part)

By applying the Kirchhoff's law the following set of equations are obtained. (see Fig 5)

$$\begin{aligned} V &= W + v - p\,L_u\,I_0 \\ U &= -W + u - p\,L_l\,J_0 \\ J_0 - I_0 &= p\,C_1\,W \\ I_0 - I &= p\,C_u\,V \\ J_0 - J &= p\,C_l\,U \\ I+J &= Y_n\,(V+U) \\ I-J &= Y_c\,(V-U) \end{aligned}$$

The solutions of these equations are as follows;

$$\begin{aligned} a\,(V+U) &= A\,(v+u) + B\,(v-u) && (1) \\ a\,(V-U) &= M\,(v+u) + N\,(v-u), && (2) \end{aligned}$$

where

$$\begin{aligned} a &= 2(2C_1 + C_u + C_l)\,p \\ &\quad +2\,(C_u\,C_l\,(L_u + L_l) + 2C_1\,(C_u\,L_u + C_l\,L_l))\,p^3 \\ &\quad +4C_1\,C_u\,C_l\,L_u\,L_l\,p^5 \\ &\quad +\left(4 + (2C_1 + C_u + C_l)\,(L_u + L_l)\,p^2\right. \\ &\quad \left.+2C_1\,L_u\,L_l\,(C_u + C_l)\,p^4\right)\,Y_c \\ &\quad +\left((2C_1 + C_u + C_l)\,(L_u + L_l)\,p^2\right. \\ &\quad \left.+2C_1\,L_u\,L_l\,(C_u + C_l)\,p^4\right)\,Y_n \\ &\quad +\left(2(L_u + L_l) + 4C_1\,L_u\,L_l\,p^2\right)\,p\,Y_n\,Y_c && (3) \\ A &= 2(C_1 + C_u + C_l)\,p + 2C_1\,(C_u\,L_u + C_l\,L_l)\,p^3 \\ &\quad +2\left(2 + C_1\,(L_u + L_l)\,p^2\right)\,Y_c && (4) \\ B &= 2C_1\,p^2\,\left((C_l\,L_l - C_u\,L_u)\,p + (L_l - L_u)\,Y_c\right) && (5) \\ M &= 2(C_l - C_u)\,p + 2C_1\,(C_l\,L_l - C_u\,L_u)\,p^3 \\ &\quad +2C_1\,(L_l - L_u)\,p^2\,Y_n && (6) \\ N &= 4C_1\,p + 2C_1\,(C_u\,L_u + C_l\,L_l)\,p^3 \\ &\quad +2C_1\,(L_l + L_u)\,p^2\,Y_n. && (7) \end{aligned}$$

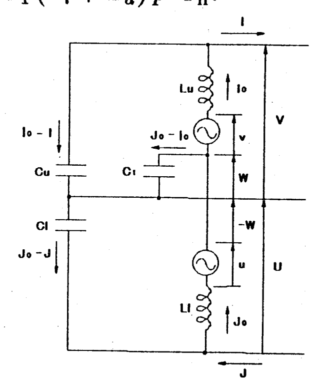

Fig. 5 Block diagram of input part

3.3 Input Voltage

For simplicity, controlled angle $\alpha = 0$ is assumed. In the case of 12-pulse rectification, the basic ripple frequency of power supply is $12 \times f_0$[Hz] for normal mode and $6 \times f_0$[Hz] for common mode(f_0 = 60 Hz). (See Fig 6, where the maximum amplitude of normal mode input voltage is set equal to 1 Volt.)

So, $(v+u)(t)$ and $(v-u)(t)$ are expressed as follows.

$$\begin{aligned} (v+u)(t) &= \sum_{n=0}^{\infty} V_n \exp(2\pi i \cdot 12 n f_0\,t) \\ (v-u)(t) &= \sum_{n=0}^{\infty} V'_n \exp(2\pi i \cdot 6 n f_0\,t) \end{aligned}$$

Fourier transforms of them are as follows.

$$(v+u)(f) = \sum_{n=0}^{\infty} K_n\,\delta(f-12nf_0) \quad (8)$$

$$(v-u)(f) = \sum_{n=0}^{\infty} K'_n\,\delta(f-6nf_0) \quad (9)$$

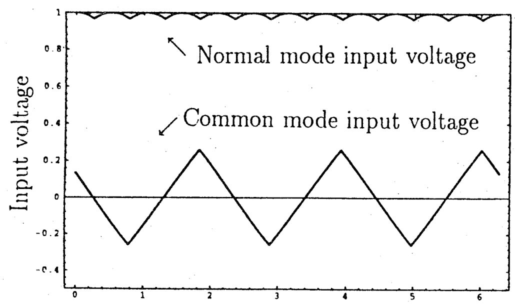

Fig. 6 input voltage

3.4 Attenuation Ratio with Common Mode Reactor

The values of Y_c, a, A, B change with common mode filter. Those parameters with it are expressed as Y'_c, a', A', B', respectively. G is defined as attenuation ratio of amplitude of ripple voltage with it at output of the power supply. From (1),(2),(8),(9), G is formulated as follows.

$$G^{\text{normal}} \equiv \frac{|V+U|_{\text{with com. filter}}}{|V+U|_{\text{without com. filter}}} = \sqrt{\frac{|a|^2}{|a'|^2}\,\frac{|A'|^2\,|v+u|^2+|B'|^2\,|v-u|^2}{|A|^2\,|v+u|^2+|B|^2\,|v-u|^2}}$$

$$G^{\text{common}} \equiv \frac{|V-U|_{\text{with com. filter}}}{|V-U|_{\text{without com. filter}}} = \sqrt{\frac{|a|^2}{|a'|^2}\,\frac{|M'|^2\,|v+u|^2+|N'|^2\,|v-u|^2}{|M|^2\,|v+u|^2+|N|^2\,|v-u|^2}}$$

1. Normal mode output

(a) For the $360(2n-1)$[Hz] ripple,

$$G^{\text{normal}}_{2n-1} = |B'/B||a/a'|.$$

Here, $|Y_c| \ll |Y'_c|$, difference between L_u and L_l is slight and $|p| \sim (10^3 \sim 10^4)$, so $|B'/B| \simeq 1$. Thus

$$G^{\text{normal}}_{2n-1} \simeq |a/a'| \ll 1.$$

Moreover, if we assume $C_u \approx C_l = C$, $L_u \approx L_l = L$, $|A| \approx |4Cp(2+CLp^2)+4(1+CLp^2)Y_c|$, then

$$\left|\frac{A}{A'}\right| = \left|\frac{Cp(2+CLp^2)+(1+CLp^2)Y_c}{Cp(2+CLp^2)+(1+CLp^2)Y'_c}\right|.$$

Typically, $C \sim 10^{-9}$F, $L \sim 10^{-2}$H. Thus, when $|(1+CLp^2)Y'_c|$ increases as frequency is higher, $|A/A'|$ becomes smaller. And from (3),(4), for $C_u \approx C_l = C$, $L_u \approx L_l = L$, $|a| \approx |1+CLp^2+pLY_n||A|$. Since $|1+CLp^2+pLY_n|$ is invariant with common mode filter, $|a/a'| \approx |A/A'|$. Thus $|a/a'|$ also becomes smaller, G^{normal}_{2n-1} becomes smaller in high frequency region.

(b) For the $720n$[Hz] ripple, from (8),(9), both the first and second term of the right side of (1) relate to G. But since slight are the differences between C_u and C_l or L_u and L_l, $|B| \ll |A|$, $|B'| \ll |A'|$. So

$$G^{\text{normal}}_{2n} = \frac{|A'/a'|}{|A/a|}$$

Because of $|a/a'| \approx |A/A'|$, $G^{\text{normal}}_{2n} \approx 1$.

As mentioned above, we can explain the measurement results (A), (B), (C).

2. Common mode output

$|M'| = |M|$ and $|N'| = |N|$, for the $360n$Hz ripple. Thus

$$G^{\text{common}} = |a/a'| \ll 1.$$

But there is no measurement data of common mode output voltage.

4 Discussion

If $C_u \neq C_l$,$L_u \neq L_l$ are assumed, the present measurement data is explained. Common mode filter is effective in improving the performance of power supply, as shown in the measurement data. We propose that common mode filter should be equipped with every power supply.

By this analysis, we show that common mode reactor is effective even if C_1 is a finite value. But since there is no data when C_1 is finite, output voltage should be measured when C_1 is finite and infinite. If C_1 is allowed to be a finite value, disposition of power supply become simple.

Acknowledgement

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[1] K. Sato, private communication.
[2] M. Kumada, "ANALYSIS OF RIPPLE CURRENT AND ITS PERFORMANCE IN HIMAC SYNCHROTRON POWER SUPPLY",1996.
[3] J. Matsui et al, "Performance of the test power supply for synchrotron magnets,1996.