Analysis of the HIMAC Synchrotron Power Supply

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Abstract

The analysis for lattice magnet power supplies of the HIMAC synchrotron is presented. The analysis showed us an advantage of our novel features such as common mode filter, a separation of an upper and lower coil of the load and bypass resistor across the magnet.

I. INTRODUCTION

The design rationale of the HIMAC synchrotron system is described in previous papers [1], [2], where an example of the analysis of the electric characteristics of the power supply and the magnets , an importance of the equivalent circuit of 6-terminal, a separation of common and normal mode and a separation of magnet coil is particularly emphasized. In this article we present more detailed study of a static filter, an impedance , an admittance , a voltage, and current of the load magnets, in presence of parallel resistors.

In our design rationale, we have introduced an idea of the difference and the sum of the current and voltage. In this article we call those components common mode and normal mode respectively and corresponding impedance and admittance are defined accordingly.

Common mode filter of the HIMAC is the world first trial to high power synchrotron magnet. An idea of damping transient spikes by bypass resistor across the magnet by one of the author, K. Sato, has been circulated among an accelerator community and its effectiveness is confirmed in KEK PS and INS TARN II. In this article , the effect of the bypass resistor is analyzed and is shown to be effective as experimentally and intuitively expected. By separating the excitation coil of the dipole magnet into upper and lower we are able to shift the resonant frequency of the common mode to higher region where filtering effect by common mode filter is more effective. The separation of the coils also enables us to transpose the coils among the magnet strings [1],[2].

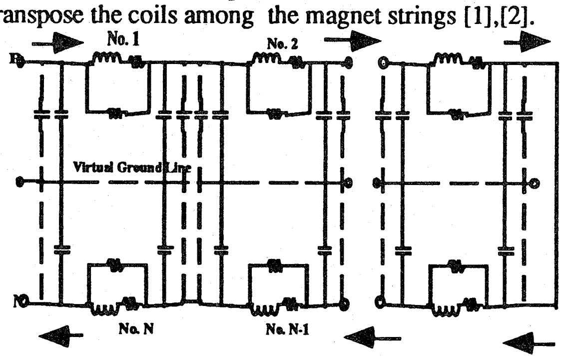

Fig.1 a An equivalent circuit of a conventional load

II. CIRCUIT MODEL

In order to understand a characteristic feature of our 6 terminal circuit with neutral line, simplified equivalent circuits of a conventional one and ours are compared in Fig.1 a and b. In either case of the equivalent circuit a leakage capacitor has to be included for a study of resonant characteristics of the magnet strings. In conventional circuit, leakage current through the leakage capacitor flows into a virtual ground line. With the virtual ground line, the equivalent circuit forms the 6 terminal circuit even in the conventional circuit. In most conventional cases, seen from a power supply side, when we number the magnet from 1 to N, the nearest magnet is 1 and N. With the presence of the leakage capacitor, ac coupling between the number 1 and N is inevitable. This ac coupling causes an imbalance of current between the magnet n and magnet N-n. In addition due to the cascade connection of the magnet, which we call magnet strings, a magnitude and a phase of the current also depend upon a position n of the cell. Thus one must solve the 6 terminal equivalent circuit. Due to an ambiguity of the ground line, however, the validity of any model of the conventional configuration is unfounded. On the other hand, in our circuit where we have added the actual third neutral line to both the power supply circuit and the load magnet strings, the validity of our 6 terminal model depicted in Fig.1 b is more reliable. The nearest magnet to the power supply side in this scheme is the upper coil and the lower coil of magnet number N. With a combination of the common mode lowpass filter and the separation of upper and lower excitation coil, ripple component and transient spikes are expected to be suppressed.

To make a discussion simple without a loss of generality, we assume that the upper half and the lower half of the 6 terminal circuit is symmetrically made. In this case, it can be shown that the 6 terminal circuit is decoupled to two independent 4 terminal circuit of common and normal mode circuit.

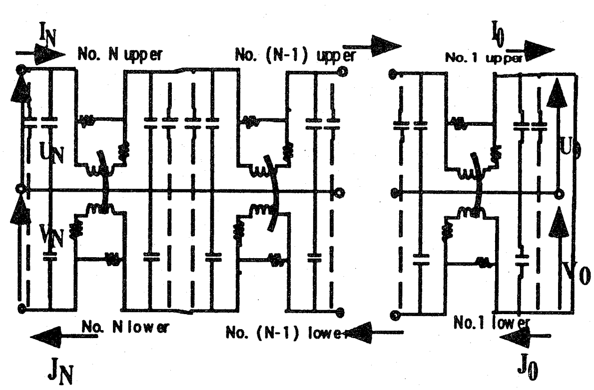

Fig.1 b An equivalent circuit of HIMAC dipole load

In the following , an analysis is performed for decoupled common and normal mode circuit.

III. ANALYSIS

A. STATIC FILTER

Static filter comprises of two stage common mode and normal mode filter. In a conventional filter, only a normal mode (summed) component is filtered; a transfer function of output to input voltage of normal mode is , without a load,

$$\frac{U_2+V_2}{U_1+V_1}=\frac{1}{1+ZY},$$

whereas transfer function of common mode is

$$\frac{U_2-V_2}{U_1-V_1}=1-\frac{ZY}{1+ZY}\frac{U_1+V_1}{U_1-V_1}.$$

In a common mode filter, this is expressed by

$$\frac{U_2-V_2}{U_1-V_1}=\frac{1}{1+YZ-kpLY}\approx\frac{1}{1+2pLY},$$

$$\frac{U_2+V_2}{U_1+V_1}=\frac{1}{1+YZ+kpLY}\approx 1.$$

The filter has to be evaluated with its load connected. Our common mode filter has a bridge resistor between the center tap and the end of the inductor. The decoupled 4 teminal transfer matrix for common and normal mode component is,

$$\begin{pmatrix}U_2-V_2\\ I_2-J_2\end{pmatrix}=\begin{pmatrix}1+Z_cY_f\left(1+\frac{1}{1+\frac{Z_n}{Z_d}}\right)+Z_nY_f\left(1+\frac{1}{1+\frac{Z_c}{Z_d}}\right) & Z_c\left(1+\frac{1}{1+\frac{Z_n}{Z_d}}\right)+Z_n\left(1+\frac{1}{1+\frac{Z_c}{Z_d}}\right)\\ Y_f & 1\end{pmatrix}\begin{pmatrix}U_1-V_1\\ I_1-J_1\end{pmatrix}$$

and

$$\begin{pmatrix}U_2+V_2\\ I_2+J_2\end{pmatrix}=\begin{pmatrix}1+Z_nY_{sum}\left(1+\frac{1}{1+\frac{Z_c}{Z_d}}\right)+Z_cY_{sum}\left(1+\frac{1}{1+\frac{Z_n}{Z_d}}\right) & Z_n\left(1+\frac{1}{1+\frac{Z_c}{Z_d}}\right)+Z_c\left(1+\frac{1}{1+\frac{Z_n}{Z_d}}\right)\\ Y_{sum} & 1\end{pmatrix}\begin{pmatrix}U_1+V_1\\ I_1+J_1\end{pmatrix},$$

respectively where Z_c, Z_n is a common mode and normal mode impedance of the corresponding filter, Z_d is a bridge resistor of the filter, Y_f is an admittance between the cable and neutral line, Y_{sum} is a total admittance of the filter.

B. MAGNET STRINGS

For simplified symmetric π type model as in Fig.1 b, the transfer matrix for normal (sum) and common (difference) mode is expressed by

$$\begin{pmatrix}U_2\pm V_2\\ I_2\pm J_2\end{pmatrix}\equiv M\begin{pmatrix}U_1\pm V_1\\ I_1\pm J_1\end{pmatrix}$$
$$=\begin{pmatrix}1+Z_{n,c} & Z_{n,c}\\ (2+Z_{n,c}Y_c)Z_{n,c}Y_c & 1+Z_{n,c}Y_c\end{pmatrix}\begin{pmatrix}U_1\pm V_1\\ I_1\pm J_1\end{pmatrix}$$
$$=\begin{pmatrix}X_{n,c} & Z_{n,c}\\ Z_{n,c}^{-1}(1+X_{n,c})(1-X_{n,c}) & X_{n,c}\end{pmatrix}\begin{pmatrix}U_1\pm V_1\\ I_1\pm J_1\end{pmatrix}$$

where $X_{n,c}\equiv 1+\dfrac{Z_{n,c}Y_{n,c}}{1+\frac{Z_{n,c}}{Z_d}}$ is a convenient parameter to express a measure of deviation from a resonant frequency of a unit π cell and to manipulate the multiplied matrix simple. It is also convenient to express the cell of the matrix by a hyperbolic sinusoidal function,

$$M=\begin{pmatrix}\cosh\varsigma & Zo\sinh\varsigma\\ \sinh\varsigma/Zo & \cosh\varsigma\end{pmatrix},$$

with $\sinh\zeta_n=\sqrt{(X_{n,c}+1)(X_{n,c}-1)}$, $\cosh n\zeta_{n,c}=X_{nc,}$

$$Z_{on,c}=\frac{Z_{n,c}}{\sqrt{(X_{n,c}+1)(X_{n,c}-1)}}.$$

A condition of I − J = 0 and U + V = 0 at the end of magnet strings leads to following equations for a voltage, current, admittance, impedance at n-th cell,

$V_c(n) = V_c(0)\cosh n\zeta_c$ $\quad$ $I_c(n) = Y_{c0}\, V_c(0)\sinh n\zeta_c$
$Y_c(n) = Y_{c0}\tanh n\zeta_c$ $\quad$ $Z_c(n) = Z_{c0}\,\mathrm{cotanh}\, n\zeta_c$

$V_n(n) = Z_{n0}\, I_{n0}(0)\sinh n\zeta_n$ $\quad$ $I_n(n) = I_{n0}(0)\cosh n\zeta_n$
$Y_n(n) = Y_{n0}\,\mathrm{cotanh}\, n\zeta_n$ $\quad$ $Z_n(n) = Z_{n0}\tanh n\zeta_n$

where we have used suffixes of c and n for common and normal instead of the expression I − J , I + J, U − J , U + J.

The number of cells N is 13 for Dipole and 12 for Quadrupole respectively.

For n=12 and 13 cell, matrix elements are, in terms of X,

$$\cosh 12\zeta = (1-8X^2+8X^4)(1-64X^2+320X^4-512X^6+256X^8)$$

$$Zo\sinh 12\zeta = -4j\,X(1+2X)(1-2X)(3-4X^2)(1-2X^2)(1-16X^2+16X^4)$$

$$Zo^{-1}\sinh 12\zeta = -4j\,X(1-2X)(1-X)(1+X)(1+2X)(3-4X^2)(1-2X^2)(1-16X^2+16X^4)$$

$$\cosh 13\zeta = X(13-364X^2+2912X^4-9984X^6+16640X^8-13312X^{10}+4096X^{12})$$

$$Zo\sinh 13\zeta = j(1-6X-24X^2+32X^3+80X^4-32X^5-64X^6)(1+6X-24X^2-32X^3+80X^4+32X^5-64X^6)$$

$$Zo^{-1}\sinh 13\zeta = j(-1+85X^2-1204X^4+6496X^6-16896X^8+22784X^{10}-15360X^{12}+4096X^{14})$$

In order to evaluate the effect of the bypass resistor r, we introduce a k parameter defined as $k = \omega_0 L_m / r$ where ω_0 is a resonant angular frequency of a unit cell.

The calculated common mode admittance for different k-parameter are shown in Figs.2 a,b,c,d and 3 a,b where k parameters varies from 10^{-6} to 0.5. Note that the admittance is normalized by a characteristic admittance. Note also that the characteristic admittance and the resonant angular frequency differ for common and normal mode, Vertical axis is a logarithm of absolute value of the admittance and horizontal axis is angular frequency normalized by ω_0,. With high impedance as in Fig.1 a (n=13), the lowest resonant frequency of the common mode appears at $x= \omega / \omega_0 =$ 0.1. This is in contrast to the normal mode admittance where it does at x=0.2 shown in Fig.3 a (n=13). These figures indicate that in conventional load, the lowest significant mode at the entrance of the load is the common mode.

There is a difference of peak position near x=1 between that of n=13 and n=12 as shown in Fig.2 a and b. The pattern of the admittance changes as the cell number becomes smaller with decreasing number of zero's and pole's. This indicates a transient response is dependent upon the cell location.

The effect of the bypass resistor is evident from Fig. 2c, d and Fig. 3 b. As is seen an amplitude of the admittance is greatly reduced. In HIMAC , k parameter is expected to be around 0.1 and 0.5 for common and normal mode.

Finally, we estimate a current flowing through the magnet which is given below.

$$\frac{V_{cm}(n)}{V_0(0)} = \cosh n\varsigma_c\{1-\frac{Z_c(n-1)}{Z_c(n)}\cosh\varsigma_c+\frac{Z_c(n-1)}{Z_c(n)}\sinh\varsigma_c\}$$

$$\frac{I_{nm}(n)}{I_0(0)} = Z_{n0}\sinh n\varsigma_n\{1-\frac{Z_n(n-1)}{Z_n(n)}\cosh\varsigma_n+\frac{Z_n(n-1)}{Z_n(n)}\sinh\varsigma_n\}$$

Common mode magnet voltage, and normal mode magnet current has more poles and zeros than that of the admittance and shows very interesting pattern.

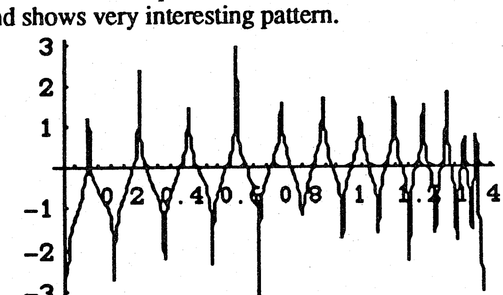

Fig.2 a Common mode admittance n=13, k=10^{-6}

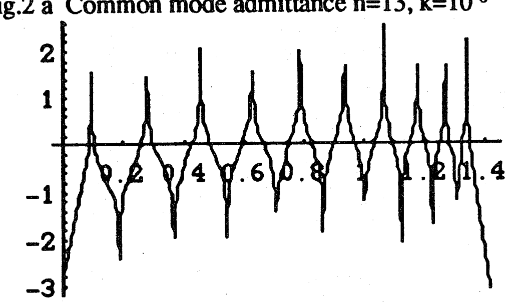

Fig.2 b Common mode admittance n=12, k=10^{-6}

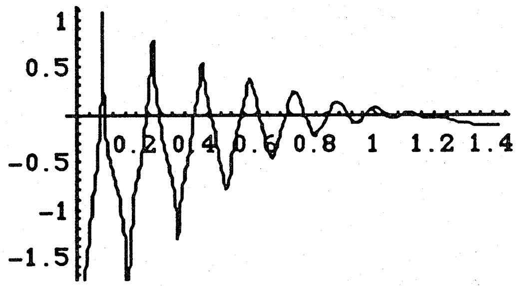

Fig.2 c Common mode admittance n=13, k=0.1

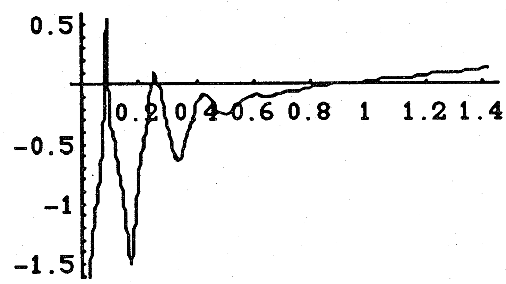

Fig.2 d Common mode admittance n=13, k=0.5

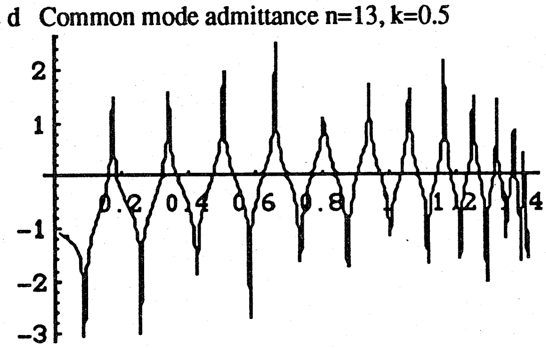

Fig.3 a Normal mode admittance n=13, k=10^{-6}

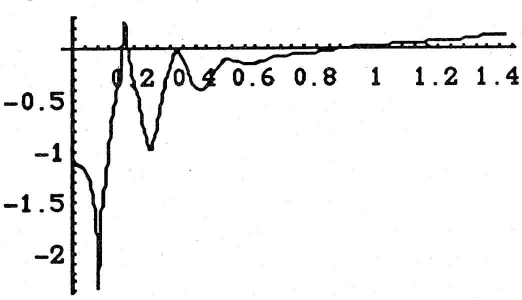

Fig.3 b Normal mode admittance n=13, k=0.5

V. ACKNOWLEDGEMENTS

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V. REFERENCES

[1] M. Kumada et al., 8th Symp. Accel. Sci & Tech., 1991, RIKEN

[2] M. Kumada et al., in the proceedings of PAC 93, Washington, D.C, USA.