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A Study of a Low-Ripple Power Supply for Electromagnets with a Demountable Common Mode Filter

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Abstract

It is noticed recently that common mode components of both voltage and current of power supplies deteriorate the ripple and noise performance of a normal mode output connected with a magnet coil. The appearance of common mode components in addition to normal mode components supposedly comes from a mixing of two modes due to a symmetry breaking in circuit element configuration of upper and lower halves referring to a grounding line. In order to investigate an origin of common mode components and such a mixing together with the effectiveness of a common mode filter, a 3kA-210V power supply of twelve-pulses thyristor-rectifier type with both of a demountable common mode filter and a demountable grounding terminal was constructed. A mixing of two modes was observed at a normal mode output but common mode components were suppressed with a common mode filter effectively. In order to formulate the performance of a power supply circuit which causes the mixing, a six-terminal circuit consisting of three inputs and three outputs is expressed by a 4x4 transfer matrix of a sympletic matrix based on a reciprocity theorem. A symmetry breaking causes a sympletic rotation and thus mixes two modes.

1 Introduction

A power supply for electromagnets is one of the most important elements for accelerators because its stability and noise level have been found out to be essential for a high-performance operation of accelerators.

At HIMAC(Heavy Ion Medical Accelerator in Chiba) synchrotrons, the power supply is equipped with not only a normal mode filter, which is usually installed in power supplies, but also a common mode filter. The achieved current noise is very low below 1 ppm leading to a high-performance operation of the accelerators. It is pointed out theoretically that this very low ripple is indebted to a common mode filter[1] because common mode components are suppressed very much. More theoretical and experimental studies, however, are needed because of no direct measurements of the effectiveness of a common mode filter and no explanation of mechanism of an origin of common mode components.

Preliminary tests on the 3kA-210V power supply show the importance of the common mode filter. The common mode components appeared to the normal mode output as odd-integer multiples of 360Hz when the filter was bypassed. When the filter was brought into action, such components are very much suppressed.

This fact implies that a mixing of both components of common mode and normal mode occurs due to a symmetry breaking which comes from a difference of a circuit element configuration between upper and lower halves referring to a grounding line. Because we take accout of a current flow on a grounding line, we have to consider a six-terminal circuit consisting of three inputs and three outputs.

2 Theoretical investigation

2.1 Sympletic rotation

In the present study of power supplies, it is essential to introduce a current flow on a grounding line. Before we take account of a six-terminal circuit, we consider an eight-terminal-pair circuit. A voltage and a current for each terminal-pair are defined appropriately so that four voltages and four currents form row vectors, respectively, as

$$\mathbf{V} = \begin{pmatrix} V_0 \\ U_0 \\ V_1 \\ U_1 \end{pmatrix} \quad and \quad \mathbf{I} = \begin{pmatrix} I_0 \\ J_0 \\ I_1 \\ J_1 \end{pmatrix}. \tag{1}$$

If a circuit does not include active power sources, a reciprocity theorem becomes valid. When a working state varies from a combination of $\mathbf{V}$ and $\mathbf{I}$ to that of $\mathbf{V}'$ and $\mathbf{I}'$, the theorem provides a scalar product relation of

$${}^t\mathbf{I}'\mathbf{V} = {}^t\mathbf{V}'\mathbf{I} \tag{2}$$

where ${}^t\mathbf{V}'$ and ${}^t\mathbf{I}'$ are transposed vectors, respectively, being line vectors.

We then devide eight-terminal-pairs to two of four-terminal-pair for input and output each. In addition, in order to form a common line for grounding, we connect two terminals of two inputs and two terminals of two outputs to form three input terminals and three output terminals. A resultant circuit with six terminals is shown in Fig. 1 which corresponds to a circuit of a power supply and its load.

From the original voltages and currents, two new row vectors, $\mathbf{X_0}$ and $\mathbf{X_1}$, for input and output are defined, respectively, as

$$\mathbf{X_0} = \begin{pmatrix} V_0 + U_0 \\ I_0 + J_0 \\ V_0 - U_0 \\ I_0 - J_0 \end{pmatrix} \quad and \quad \mathbf{X_1} = \begin{pmatrix} V_1 + U_1 \\ I_1 + J_1 \\ V_1 - U_1 \\ I_1 - J_1 \end{pmatrix}. \tag{3}$$

We call components of summation-type and difference-type as normal mode and common mode, respectively.

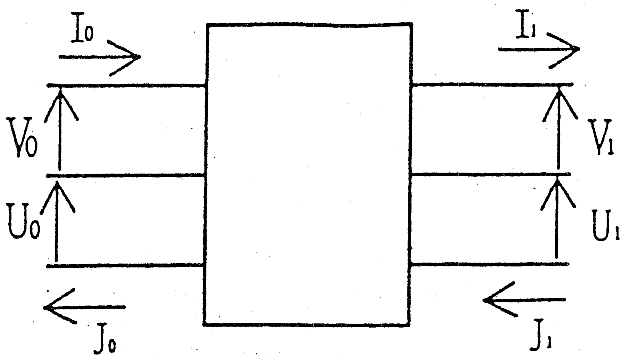

Figure 1: A six-terminal circuit and definition of symbols of voltage and current.

We then adopt Equation (2) to these vectors and obtain a relation of

$$ {}^t\mathbf{X}_0'\mathbf{S}\mathbf{X}_0 = {}^t\mathbf{X}_1\mathbf{S}\mathbf{X}_1' \tag{4}$$

where **S** stands for a 4x4 version of a unit sympletic matrix defined as

$$\mathbf{S} = \begin{pmatrix} 0 & 1 & 0 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -1 & 0 \end{pmatrix} \tag{5}$$

We introduce a 4x4 transfer matrix τ for input and output vectors, $\mathbf{X}_0$ and $\mathbf{X}_1$ as

$$\mathbf{X}_0 = \tau\mathbf{X}_1 \tag{6}$$

Here we set $\mathbf{X}_0' = \mathbf{X}_0$ and $\mathbf{X}_1' = \mathbf{X}_1$ for Equation (4) and obtain

$$ {}^t\mathbf{X}_1{}^t\tau\,\mathbf{S}\,\tau\mathbf{X}_1 = {}^t\mathbf{X}_1\mathbf{S}\mathbf{X}_1 = \mathbf{O} \tag{7}$$

and thus obtain a sympletic condition for a transfer matrix as

$$ {}^t\tau\,\mathbf{S}\,\tau = \mathbf{S} \tag{8}$$

In studies of linear coupling motion in periodic system for accelerators, the sympletic condition has been parameterized in a form of a sympletic rotation[2] as

$$\tau = \begin{pmatrix} \mathbf{I}\cos\phi & \mathbf{D}^{-1}\sin\phi \\ -\mathbf{D}\sin\phi & \mathbf{I}\cos\phi \end{pmatrix} \begin{pmatrix} \mathbf{A} & \mathbf{O} \\ \mathbf{O} & \mathbf{B} \end{pmatrix} \times \begin{pmatrix} \mathbf{I}\cos\phi & -\mathbf{D}^{-1}\sin\phi \\ \mathbf{D}\sin\phi & \mathbf{I}\cos\phi \end{pmatrix} \tag{9}$$

or

$$\tau = \mathbf{RUR}^{-1} \tag{10}$$

where **I** is a 2x2 unit matrix, **A**, **B** and **D** are 2x2 version of unit sympletic matrix, and **R** is a 4x4 sympletic rotation matrix.

2.2 Symmetry breaking

When a circuit element configuration is in symmetry for upper and lower halves referring to a grounding line, a normal mode and a common mode are separated independtly of each other. In this case, Equation (9) becomes as

$$\tau = \begin{pmatrix} \mathbf{A}_0 & \mathbf{O} \\ \mathbf{O} & \mathbf{B}_0 \end{pmatrix} \tag{11}$$

In order to show that a symmetry breaking causes a mixing of components of a normal mode and a common mode, we suppose a configuration shown in Fig. 2 for the simplicity.

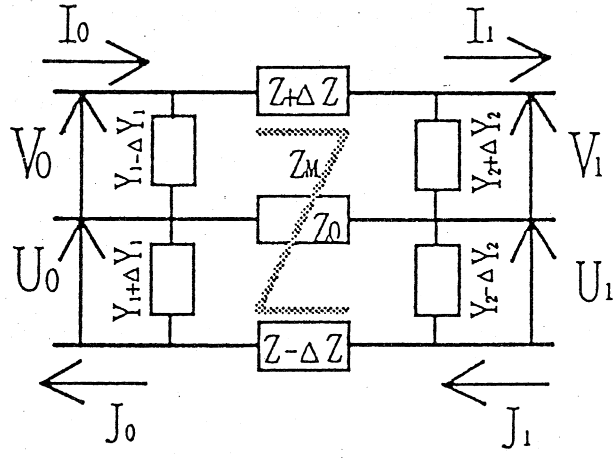

Figure 2: A configuration in a symmetry breaking.

For the further simplicity, we assume relations

$$Z_0 = 0,\ Y_1 = Y_2 = Y,\ \text{and}\ \Delta Y_1 = \Delta Y_2 = \Delta Y \tag{12}$$

For the first order approximation, we then obtain

$$\tan 2\phi = \Delta Z/Z_M \tag{13}$$

and

$$\mathbf{D} = \begin{pmatrix} -1 & 0 \\ 2\Delta Y Z_M/\Delta Z & -1 \end{pmatrix} \tag{14}$$

but **A** and **B** are identical to matrices of Equation (11), $\mathbf{A}_0$ and $\mathbf{B}_0$, for a symmetric configuration but need not be detailed here.

It is known from Equations (13) and (14) that a sympletic rotation occurs due to such a symmetry breaking as ΔZ and ΔY, and thus causes a mixing of a normal mode and a common mode.

3 Experimental investigation

3.1 Power supply and magnet load

As shown in Fig. 3, a 3kA-210V power supply of twelve-pulses thyristor-rectifier type with both of a demountable common mode filter and demountable grounding terminals was constructed. A common mode reactor transformer(CMRT) can be bypassed by a switch and grounding lines can be detached by switches, SW1, SW2, SW3, and SW4. A load consists of four synchrotron long bending magnets which were dismantled from TRISTAN of KEK.

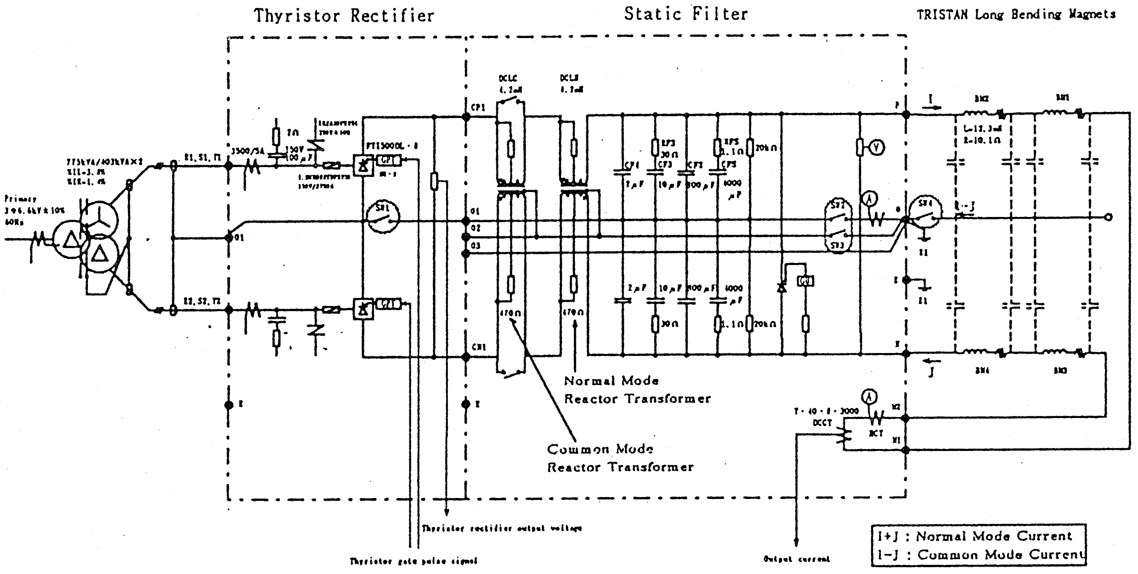

Figure 3: Circuit diagram of a power supply and a magnet load.

3.2 Brief summary of observations

Most of the present observation was based on combinations of on/off states of switches SW1, SW2 and CMRT. But a combination of SW1 on, SW2 on, and CMRT off was not succeeded because something occured and was wrong with the power supply. Therefore we could not observe the effectiveness of the common mode filter directly contrary to expectation because SW1 should be switched off necessarily when CMRT was bypassed.

We observed amplitude and/or frequency spectrum of voltages between positive and negative lines before and after the filters. We observed a stability of dc current by DCCT and a frequency spectrum of a primary ac line voltage, too.

Observations around 1.5kA dc showed that a ripple amount was about 50 ppm and a dc stability was about plus/minus 2 ppm which were quite well despite the fact that no active filter was installed.

It is considered that normal mode components appear at frequencies of 720n Hz where n=1,2,3,— although common mode components appear at 360(2n-1) Hz where n=1,2,3,—.

It should be pointed out from the observation that a continuous background of a frequency spectrum was decreased by 5-10 dB at a frequency above 750 Hz when SW1, SW2, and CMRT all are in action.

Components of proper frequencies of normal mode and common mode before and after the filters are attenuated reasonably by filters; so that a mixing of common mode components, namely some symmetry breaking is considered to occur before the filters.

Grounding seems to play an important role to suppress ripple and noise. When SW1 is switched on or off but SW2 is switched on and CMRT is in action, SW1 off resulted in an increase of proper freqeuncy components of common mode by a factor of about 4 but resulted in no change for normal mode components.

4 Summary

We formulated a mixing of normal mode components and common mode components due to a symmetry breaking of circuit element configuration. The expression is based on symletic rotation due to an appropriate parametrization of a transfer matrix based on a general reciprocity theorem. This expression suggests that a system configuration should have symmetry referring to a grounding line with the help of a common mode filter.

It was difficult for a direct measurement of effectiveness of the common mode filter because something was wrong with the power supply in the case of absence of a common mode filter contrary to expectation. The best performance was achievable when the grounding was tight and the common mode filter was in action. However, we did not succeeded to make an origin of common mode components and a mixing mechanism clear. Further investigation is needed although a necessity itself of the common mode filter is clear.

Acknowledgement

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References

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[2] D. A. Edwards and L. C. Teng, Parametrization of Linear Coupled Motion in Periodic System, IEEE Trans. on Nucl. Sci. NS-20(1973)885