Design of the HIMAC Synchrotoron Power Supply

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Abstract

The design for lattice magnet power supplies of the HIMAC synchrotron is described. Characteristic feature includes separate neutral line, a configuration of separate coil of a magnet, an accurate description of load magnet and dynamic load analysis.

I. INTRODUCTION

HIMAC, the world first medical heavy ion accelerator complex dedicated to cancer treatment[1], is in the final construction stage. An initial beam test of the injector linac has been successful[2]. An alignment of machine components of the synchrotrons has started and preliminary tests of the synchrotrons without beam are expected to begin in this coming summer. The main accelerator comprises two separate synchrotrons where the slow extraction is based on the 3rd order resonance. Being medically dedicated, extraction energy, ion species, and intensity must be variable in a wide range, while a stable beam spill is required. Thus, tolerance for current stability, current ripples, and current spikes for lattice magnets is extremely tight in wide range of magnet current. In order to achieve high performances, we have carefully designed for power supplies from the point of view of the best combination of the power supply and the load magnets. Some parameters are given in Table 1.

We describe in this paper the design rationale of the system and an example of the analysis of the power supply and the magnets where 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.

II. DESIGN RATIONALE

In usual system configuration of a thyristor power supply and lattice magnets, a common mode component of coil current ripples and spikes are spatially distributed over whole load magnets and deteriorates the circulating beam as a closed orbit distortion and a tune shift which suggests an insufficient suppression of the common mode components in contrast to that of the normal mode. In order to suppress both modes simultaneously we separate magnet coils into upper and lower coils, we prepare the third neutral line, and we equip the common mode static filter for the power supply in addition to the normal mode static filter. As the lattice magnets are connected and excited in series by the power supplies, the parasitic resonance results like in a distributed circuit. In order to overcome this problem, bridging resistors are connected to each magnet coils: the resistor performs the damping of the resonance and bypasses the higher frequency components of the coil currents. From this viewpoint our thyristor power supply of 24 pulses is advantageous that that of conventional one. Lower frequency components as 50 Hz and 100Hz are suppressed by a technique of repetitive digital control developed at KEK. In order to achieve repetitive control of higher performance, we made much effort to increase an accuracy of the load parameter. To this end, a fractional polynomial fitting and an idea of effective inductance are developed. We adopted the VME and fast PDOS real time operating system to facilitate the control.

To get reproducible data for the repetitive control the sampling timing of a voltage and a current is synchronized to event clock signals which is phase-locked to a primary 50 Hz ac line voltage and an event generator, dual pattern memory for switching the spill pattern are developed.

The effect of the resonance is weakened by crossing-over cabling of the upper coil to lower coil from magnets to magnets. We carefully choose a standard cabling to reduce the lower frequency components of the spatially distributed coil currents.

Table 1 Main parameters of the power supplies and load.

Power supplies		
stability goal(ppm)	20	
repetition(Hz)	0.3- 1.5 at 600 MeV/u	
rise / flat top duration(s)(600MeV)	0.7/0.5 at 0.5 Hz	
rate of field change (T/s)	1.4	
Filter parameters	dipole	quadrupole
L_{static}(mH)	2.5	0.5
C1(mF)	0.4	2
C2(mF)	2	10
R(Ω)	2.2	0.44
$L_{dynamic}$(mH)	n.a.	0.5
Load	dipole	quadrupole
output power(MW)	5.13	0.538
voltage(kV)	2.27	0.32
current(kA)	2.26	1.35
total inductance(mH)	633.1	110.8
resistance(mΩ)	200.2	116.8

A. Configuration of power supplies and load magnets

The unique feature of the system of the power supply and load magnets is shown in Fig. 1. Three lines from the power supply, which are a positive, a negative and a neutral output, respectively, are connected to the load magnets. These three lines are connected to the upper coil, lower coil, and magnet yoke. The third line that performs as the neutral line of the power supply is introduced, for the first time, to separate the normal mode and the common mode more clearly. The neutral point of an upper half and a lower half of symmetric thyristor banks of the power supply are connected to the third line. In addition, low level electronics refers to this line.

In this viewpoint, the magnet coils comprise self inductance, mutual inductance, series resistance, capacitance between upper coil and lower coil, and capacitance to the magnet yoke. Consequently, **circuit of six terminals** is formed. It can be shown that the circuit is decoupled to a circuit of four terminals by the use of sum of upper coil current and lower coil current (normal mode), and by difference (common mode).

It should be emphasized that a conventional configuration of the power supply and its load should also be treated as 6 terminal-circuit. An advantage of introducing this neutral line is to clarify and visualize a circuit of an unpredictable leakage capacitance among an excitation cable, coil and a ground line of which location is also quite unpredictable. In our new scheme this ghost ground line is replaced by the physical neutral line.

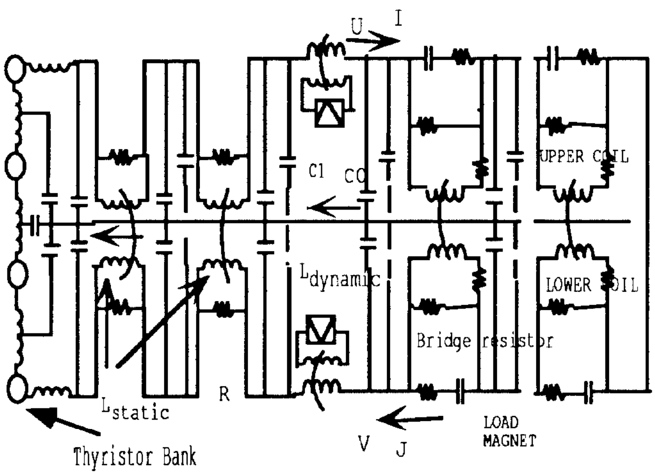

Fig.1 Equivalent circuit of the power supply system

B. Analysis

Frequency characteristic of voltage difference, U-V, current difference I-J, voltage sum U+V, current sum I+J of the unit magnet with leakage capacitance are able to be calculated by multiplying transfer matrix. Neglecting the resistance that bridges the coil inductance in order to damp the resonance and to by-pass the coil current, we get the six-terminal transfer matrix for each magnet:

$$\begin{pmatrix} 1 & -(pL+R) & 0 & 0 \\ -pC0 & 1+pC0(pL+R) & 0 & 0 \\ 0 & 0 & 1 & -(pL+R) \\ 0 & 0 & -pC & 1+pC(pL+R) \end{pmatrix}$$

with C=C0+2C1, p=jω. As is seen, the difference and the sum components are decoupled. Multiplying the matrix of a number of magnets and terminating the end coils depending upon the short or open connection, we can calculate the electrical characteristics of the system. Numerical computing of the resonant frequency shows a dispersive nature as shown in Fig. 2. Although above expression is for the simple case, it can be shown that any complicated circuit could be decoupled by decomposing into simpler circuit. Fig. 2 shows resonance characteristic of the current sum of quadrupole load where angular frequency ω_0 is normalized by the resonant frequency ω_0, which is given by the load inductance and leakage capacitance. In this case, the number of resonance is 10 for 12 units of quadrupole magnets. Note the appearance of lower frequency, lower than that of the resonance frequency of the unit cell of the magnet. Beyond $\omega / \omega_0 = 2$, which corresponds the cutoff frequency, the resonance is suppressed.

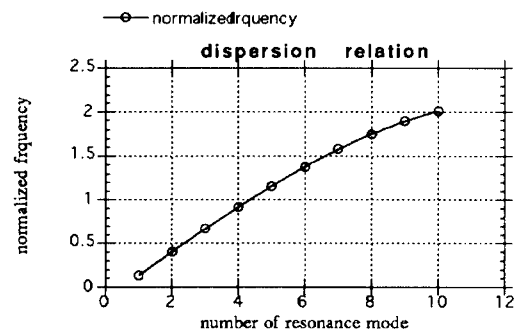

Fig.2 Dispersion relation of the sum current of quadrupoles

Analytic expression of the difference of the upper coil and lower coil current is obtained as

$$\frac{I_m - J_m}{U_i - V_i} = Z_0 \left(\sinh m\zeta - \frac{Z_0 \sinh m\zeta + Z\cosh m\zeta}{Z_0 \sinh N\zeta + Z\cosh N\zeta}\sinh N\zeta\right)$$

with $\tanh N\zeta = -\frac{Z_0}{Z}$, where 2 Z is an impedance of a unit magnet treated as an element of the ladder circuit and Z_0 is usual characteristic impedance. This expression suggests the effectiveness of the bridging damping resistor.

In Fig. 3, a typical example of the spatial distribution of the resonance is shown. As shown, the mode is characterized by (2n-1)/4 wave length where the fundamental mode, ω/ω_0=0.127, is a quarter wave length. This mode must be carefully avoided. This pattern is universal regardless of various parameters .

C. Shuffling of magnets by cabling

Due to a property of a ladder circuit of the load magnet and cable, a resonated current has a cosine shaped spatial distribution along the magnet. The inhomogeneity caused by the effect of the particular resonance is minimized by a proper pattern of combinations of reversing the direction of the magnetic field among unit magnets, by cable shuffling.

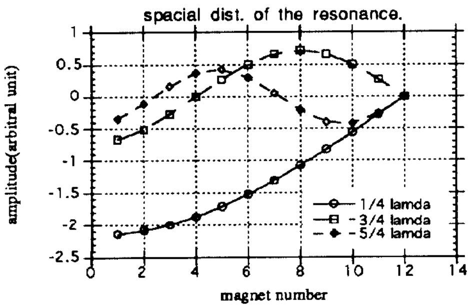

Fig.3 Typical example of the spacial distribution

For the case of dipole magnets, we have studied closed orbit displacement of third and fourth order components of every possible amplitude of the resonant frequency. The result tells no transposable (standard cabling) is the best for the fundamental mode for our operational tune. At design stage, it is difficult to predict the mode of the most dominant resonance. And the choice of shuffling may subject to change depending upon the actual mode of resonance.

D. Electrical characteristics by a fractional polynomial fitting

To express a magnetic field strength B by the excitation current I or voltage V or vice versa, instead of polynomial expansion, a fractional polynomial equation is proposed:

$$B(I) = \frac{a_0}{1+b_1I+b_2I^2} + a_1(1-\frac{c_0}{1+c_1I+c_2I^2+c_3I^3+c_4I^4})I$$

where a_0 is proportional to H_c, a_1 ampere turn and $1/c_0$ permeability of an iron core. This equation is a natural extension of Ampere's law and is able to express three distinct regions of an excitation level: low field where remanent field dominates, medium field of high permeability, high field where saturation effects dominate. In an actual digital repetitive feedback algorithm, more sophisticated expression is used corresponding to a hysteresis effect.

E. Effective Inductance

Time derivative of magnetic flux is an induced voltage. In the case of time dependent field strength, an effective inductance L_{eff} that is viewed from the power supply, should be defined by a usual inductance L_0 and its time derivative.

$$L_{eff}=L_0+I\ dL_0/dt = S\ dB/dI$$

where S is an effective area of the flux density.

An excitation dependence of the inductance is calculated from a test data of a power supply with following equation;

$$L_{eff} = \frac{V-IR}{\frac{dI}{dt}}$$

where a resistance is appropriately calculated at flat-base and flat-top periods. As shown in Fig. 4., the effective inductance depending on the excitation current shows a strong saturation effect due to the effect of the derivative of the field strength with respect to the current by an order of magnitude compared to the saturation of the field strength itself. For this reason, fitting equation in the proceeded section is used and its derivative is taken. Accurate calibration of the absolute inductance is now required. This is done by an analog integrator system developed for the magnetic field measurement. With this method the inductance and the resistance of the load is precisely determined, where decoupling of the resistance and the inductance is possible with two different timing conditions.

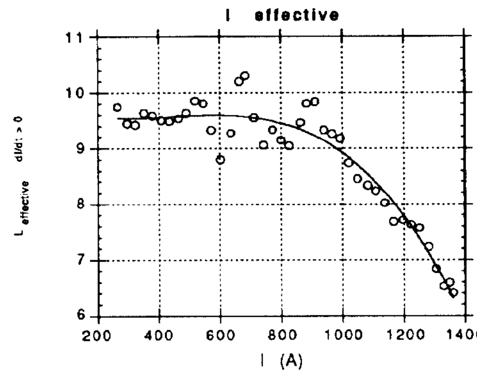

Fig.4 Excitation dependence of Quadrupole Inductance

III. DISCUSSION

Performance of the power supply was checked at the factory with dummy load. Ripple current calculated (division by the nominal inductance) from ripple voltage is at a level of design goal although it must be checked with actual current. This is because even a small amount of a spurious ripple generated by the transient spike could enhance the ripple current under resonance condition. In the preceding argument, a description about the SVC (Static Var Compensator) which will help to improve ac power line is omitted because of the limited space. With a help of the SVC, actual neutral line with full load magnet, moreover with a full set of damping resistor, the better performance of the power supply is expected in an operation scheduled this summer.

IV. ACKNOWLEDGEMENTS

We gratefully acknowledge the support of all the other member of the division of accelerator physics and engineering, research center of heavy charged particle therapy, NIRS.

V. REFERENCES

[1] Y. Hirao et al., NIRS-M-89, HIMAC-001 (1992).
[2] T. Murakami et al., this conference.
[3] M. Kumada et al., 8th Symp. Accel. Sci & Tech., 1991, RIKEN