The HIMAC Very Low Ripple Synchrotron

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Abstract

We will report a performance of ripple content of a thyristor controlled power supply of the HIMAC twin synchrotron. The rms ripple content of dipole string is estimated to be about 10 ppm with a static low pass filter alone and that of Quadrupole is 2 ppm with an active filter.

1. INTRODUCTION

HIMAC synchrotron has been commissioned and begun clinical trial this summer[1]. We designed main power supply and magnet of the ring as an integrated system, and in particular put efforts to reduce ripples with concept of common and normal modes[2,3]. In the following, characteristic feature of the system and study on ripple component are described. In order to handle a vast amount of power for large synchrotron, SCR type polyphase rectifiers are used in many accelerator facilities. This type of power supply, however, is known to suffer from sub-harmonic ripple in addition to harmonic ripple. Besides the ripple, synchrotron also suffers from a transient oscillation due to a resonant property of a magnet string.

A number of ingenious ideas have been invented to over magnet string was a 6 terminal circuit rather than a conventional 4 terminal circuit. Full advantage of his 6 terminal model circuit, however, was not shed light until a conception of common mode and normal mode impedance is fully come ripple and transient spikes. It is Regenstreif at CERN in 1959 who first discovered that the magnet string must be treated as a ladder circuit[4]. His equivalent circuit of the CPS developed by the authors.

Many authors had studied to reduce current ripples. In Fig.1, a performance of the published data of the ripple magnitude is plotted for comparison of performance. Aknin of Saclay proposed a device which is able to feed a signal at the same frequency with the right amplitude and phase to compensate the ripple to improve the 70 Hz current ripple from 100 ppm to 7 ppm. Olsen of BNL developed "a high performance digital triggering system for phase controlled rectifiers" and achieved 10 ppm. McCarthy of Fermilab developed and achieved 10 ppm with a resistive load. It is to be mentioned, the active ground regulator is employed where common mode concept must be considered. Shafer revived Regenstreif's idea and reached the concept of common mode and normal mode[5].

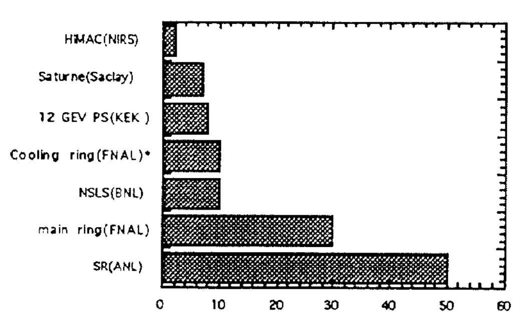

Fig.1 A comparison of the ripple performance(* indicates the ripple of resistive load). (HIMAC: present work, others taken from: Aknin et al., PAC79,3138; Baba et al., PAC81,3068; McCarthy et al., PAC85,3778; Olsen et al., PAC87,1408; Wolff et al., PAC81,3088; Praeg et al., PAC87,1526)

2. CHARACTERISTIC FEATURE OF HIMAC SYNCHROTRON

In the following, we show how we have achieved a low ripple magnet field with a SCR type synchrotron power supply in HIMAC.

2.1 The method of reducing common mode impedance.

It can be shown that it is possible to reduce the common mode inductance of the load by a proper combination of the coil; separate connection of the excitation coil due to the mutual coupling through iron yoke.

With an aid of common mode low pass filter, a reduction of inductance results in a reduction of ripple amplitude. In HIMAC, upper and lower coil of the dipoles are connected separately to reduce the common mode inductance. From a measurement of common mode and normal mode impedance, common mode inductance of the dipole string is estimated to be two order of magnitude lower than normal mode inductance. The common mode impedance of the quadrupole is 1/2 of the normal mode where separate connection was not optimally implemented.

2.2 Static Filter and Active Filter of common and normal mode

HIMAC power supplies are designed as 24 pulse SCR and their fundamental common mode exists at 600 Hz. We introduced static filters of both common and normal modes to power supplies. Our static filters are of Praeg type filter[6] whose cut off frequency is 70 Hz. Calculated common and normal current in a load magnet without the filter is shown in Fig.2(a). Fig.2(b) shows normal mode current. Comparing the curves, we observe that above 730 Hz, the common mode filter become effective to reduce current ripple when normalized by a ripple voltage.

In Fig. 3, typical example of a voltage ripple of common mode and normal mode is shown for the case of Focusing Quadrupole at flat top of 600 A (50% rating).

With further intricate adjustment of the circuit, we are recently able to improve the performance of the active filter by -20 dB; present reduction of 100 Hz ripple is -40 dB.

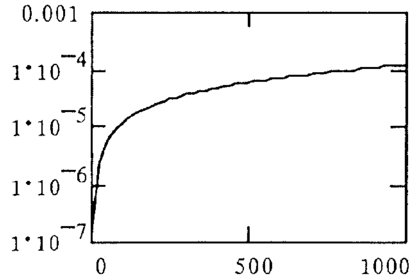

Fig.2 (a) Common mode magnet current vs. frequency without common mode filter .

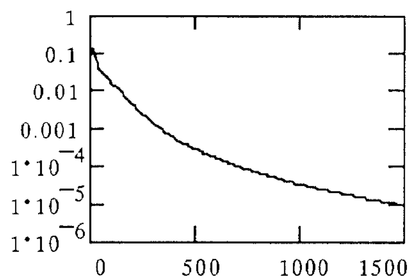

Fig.2 (b) Normal mode magnet current vs. frequency. with normal mode filter

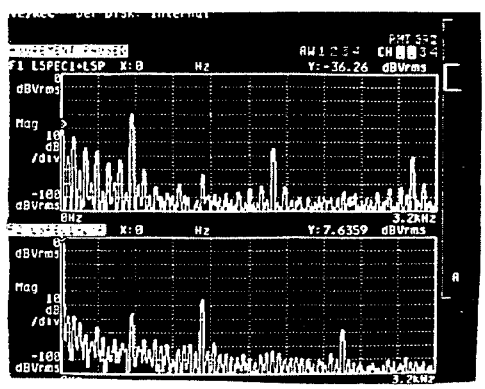

Fig. 3 A voltage ripple of common mode (upper race) and normal mode (lower trace).

For economic reasons, the active filter of the dipole is omitted. But it is confirmed that the rms ripple is small enough, about 10 ppm at flat top.

2.3 Implementation of a grounded neutral line to power supply and magnet string

Stray capacitance is inevitable when we consider frequency characteristics of the ripple and transient spikes. A voltage develops between excitation cables and a virtual ground line. The best way to localize this effect is to physically implement the grounded neutral line which is extended from the neutral point of the thyristor rectifier up to the furthest magnet coil all along the synchrotron ring. Magnet yoke is connected to the grounded neutral line. With this configuration, the model circuit for analysis become more reliable and it is shown that a transfer function of the lowpass filter become simpler whereas that of floating power supply is complicated. Addition of this grounded neutral line is advantageous to eliminate number of practical problems such as isolation of the yoke, elimination of the specially ordered bus duct between the AC transformer and the rectifier transformer, an elimination of the isolation amplifier for a low level control circuit.

2.4 Bypass(damping) resistor

A bypass resistor connected in parallel to the magnet coil is originally proposed by Regenstreif[4] to reduce the normal mode transient exponential decay caused by an abrupt change of voltage. Using this bypass resistor is very economic and effective. It is especially effective for suppressing the transient spike. It can be shown that it is also possible to suppress both the common and normal resonance of the magnet string. The resistance of 50 ohm and 100 ohm was chosen for Quadrupole and Dipole, respectively.

2.5 PLL based timing system and ripple basher

All power supplies with trapezoidal field pattern refers to the 1.2 kHz timing clock. This event signal is phase locked to the primary three phase AC line voltage and consists of 16 bit data. Jitters of the PLL is less than 2 μs. Pattern error due to this error is as small as 2 ppm. Small jitters ensures the reproducibility of the ripple pattern. Based on this reproducibility, external sinusoidal signal is applied to minor AVR (Automatic Voltage Regulator) to cancel out the ripple voltage sensed in a regulator circuit. This phase locked signal generator, which we dubbed as "ripple basher", reduced the ripple amplitude to a great extent, namely -15 dBV in a 50 Hz ripple of Focusing Quadrupole. With this apparatus temporarily installed, sub-ppm ripple ampiitude is realized.

The 50 Hz main ripple of the dipole is also reduced by -10 dB with temporal ripple basher. 3 to 4 ppm rms ripple of dipole magnet string is thus possible without active filter. Further test and a possibility of installation to the power supply system is under study.

2.6 Static Var Compensator (SVC)

SVC is a device to suppress the variation of the AC line voltage by a reactive compensation. Compensation is done by a 12 pulse thyristor controlled reactor (5MVA) in collaboration with lead capacitors and higher harmonic filters; the 3rd (1.5 MVA), 5th (1.5 MVA), 11th (3.5MVA), 13th (3.5MVA) with high impedance 6.6 kV transformer (5MVA). SVC's performance to improve the voltage imbalance is excellent: Voltage unbalance without SVC, is 3.6 %, and with SVC it is reduced to less than 0.1 %.

3. RIPPLE PERFORMANCE

In the following, three methods of performance test are described in chronological order.

3.1 Magnetic field ripple estimated from one turn coil

In early stage of the power supply improvement the performance of the ripple component of the power supply of the Dipole, Focusing Quadrupole and Defocusing Quadrupole is detected via one turn coil. The signal of the induced voltage of the one turn coil is observed by Advantest R9211 FFT Servo analyzer and HEWLETT PACKARD HP 35670A FFT analyzer both in time domain and frequency domain. Typical excitation level was set to that of the kinetic energy of 230

MeV/u and 600 MeV/u (48 % and 83 % of the full excitation, respectively).

The relative magnitude of the rms ripple from the FFT analyzer is calculated from the following simple relation;

$$\text{Relative ripple} = \omega B_{rms}(\omega) / (dB/dT)$$

where dT is an averaged acceleration period. Typically dT = 0.625 sec. The ripple of the magnetic field was calculated and is plotted in Fig. 5.

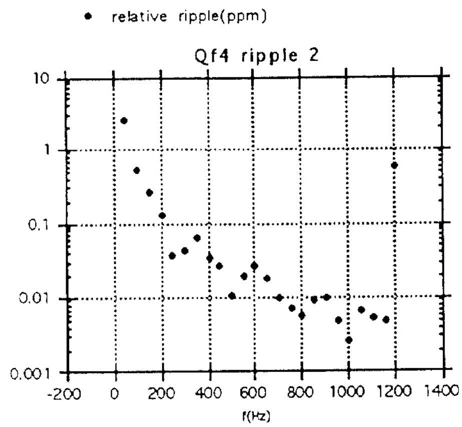

Fig.5 Magnetic field ripple content of the Focusing Quadrupole at an early stage of an improvement (unit in ppm)

3.2 Voltage ripple

In Fig. 6, we present a recently improved normal mode voltage ripple of the Quadrupole power supply output. Estimated rms current ripple of the largest component of 50 Hz is 1.9 ppm in this case.

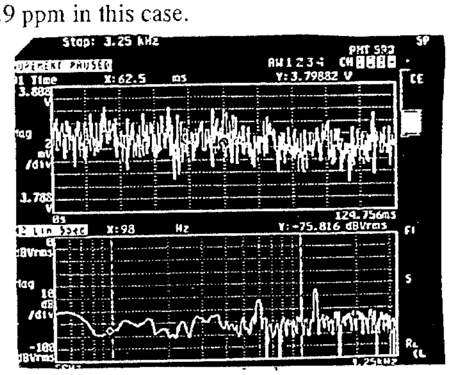

Fig.6 Improved voltage ripple (lower trace) and DCCT signal(upper trace).

3.3 Estimation from the beam spill

As a most sensitive detector of the ripple is the beam spill, we will estimate the magnitude of the ripple from the beam spill. Suppose the beam spill is proportional to the time derivative of the triangular separatrix. In our extraction process, the flat top level of the Focusing Quadrupole is monotonically decreased while the strength of the extraction sextupole is held constant. For simplicity of discussion, we assume the beam spill fluctuation is mainly caused by Focusing Quadrupole.

$$\text{Spill} = \alpha\, d((\nu(t)-11/3)^2/dt$$

where α is a proportional constant and $\nu(t)$ is a betatron tune. Assume the tune varies linearly expressed as $a\,t+b$ and the ripple component expressed as $\varepsilon_n \sin(\omega_n t+\delta_n)$. Recalling the fact that the tune shift in HIMAC lattice is expressed as follows;

$$\Delta\nu_x = 4.91\,\delta_F - 0.46\,\delta_D$$

$$\Delta\nu_y = -0.46\,\delta_F + 5.33\,\delta_D$$

and neglecting the effect of Defocusing Quadrupole,

$$\text{Spill} = 2\,\alpha\{a\,t+b-11/3+5\,\Sigma\,\varepsilon_n \sin(\omega_n t+\delta_n)\}$$

$$\{a+5\,\Sigma\,\omega_n\,\varepsilon_n \cos(\omega_n t+\delta_n)\}$$

An evaluation of the second term for n=1 (50 Hz) leads to,

$$\varepsilon_1 < |a| / (5\,\omega_1).$$

Here coefficient a divided by a duration period of beam spill is defined as a stopband.

It is known that the width of the stopband of the third order resonance is an order of magnitude narrower than that of half integer resonance: Width of stopband for HIMAC it is 0.0033. Substitution of relevant values yield for critical ripple ε_1 = 3 ppm. This is roughly consistent with that obtained from one turn coil.

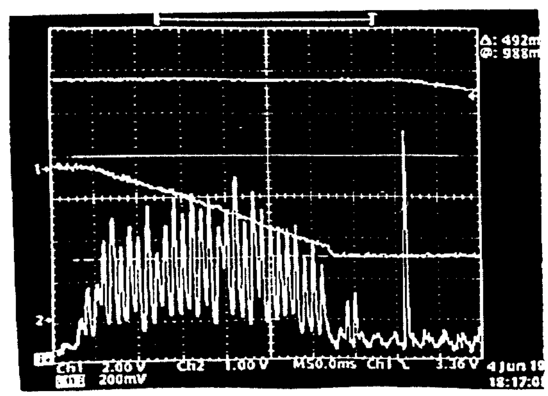

Fig. 7 Typical beam spill (lower trace) and beam intensity (upper trace).

4. CONCLUSION

Low ripple content power supply was completed at NIRS. Third order slow resonant extraction where better than a few ppm ripple is required was successfully done at an excitation level of 30 % to 80 % of the full rating without resorting to other means of spill feedback system.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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