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Improved Dynamic Filters for the Main Ring Magnet Power Supply of the KEK 12 GeV PS

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Summary

The dynamic filters of the KEK 12 GeV PS were improved in the voltage ripple detector, in the control system and in the power-up of the PWM and B-class amplifiers. Especially, a use of new developed voltage ripple detector was able to change from the former feed forward system to the feed back control system. As the results, the low frequency ripple voltage across the magnet coil ($\leq$ 300 Hz) could be reduced to less than - 26 db to the inputs in the B, Q_F and Q_D magnet power supply and the current ripple is considered to be about 8×10^{-5} at flat top current 2,850 A during extraction.

Introduction

The current for the main ring bending and quadrupole magnet are supplied from twelve phase rectifiers.[1)] A twelve phase rectifier consists of double six phase rectifiers connected in series. The ripple of the power supply theoretically contains 600 Hz and it's higher harmonic components. By reason of complicated patterns, one group of rectifiers for the bending power supply (BPS) generates 300 Hz ripple component and it's higher harmonics. However, in actual operation the uncharacteristic ripples of 50 Hz, 100 Hz and it's harmonics are considerably induced due to the fluctuation of ignition angle on the SCR rectifier and the three phase unbalance in commercial ac line.

These current ripples modulate the ejected proton beam spill during slow beam extraction. The ripples have to be decreased less than 10^{-5}. Passive filters were set up to reduce these ripples. They are consisted of a low pass filter and a resonance filter. The former has the cut-off frequency of 55 Hz and the response of - 12 db/oct. with under-damping and the latter has tuned frequency 100 Hz.

In the 12 GeV operation, the former dynamic filters[2)] could not reduce the lower frequency current ripples ($\lesssim$ 300 Hz) to a low level for desired beam spill at the flat top.

The voltage ripple detector and the control system are improved. Also the pulse wide modulation and the B-class audio amplifiers are powered up.

Basic considration of the system

The new dynamic filter has been improved by the negative feed back control system.[3)] Fig. 1 shows a schematic diagram of the magnet power supply (MPS) including dynamic filters. We consider that the ripple power is generated by the combination SCR rectifiers and the passive filter. The impedance of the ripple power source is estimated to be negligible because the impedance is designed nearly one percent of the magnet impedance.

Fig. 2 gives the equivalent circuit of a main power amplifier, Lp and magnet inductance converted into primary of a power reactor transformer (PRT). Where Lp is the primary inductance of the PRT. L_ℓ is the total inductance of the magnets. Np and Ns are number of the primary and secondary turns of single PRT respectively. n is the numbers of the PRT. The output power of single main amplifier, P_A, is denoted by

$$P_A = P_p + P_\ell$$
$$= [1 + (Np/Ns)^2(1/n)(L_\ell/Lp)]\ (P_{\ell t}/n) \quad ,$$

where Pp is the exciting power of the primary of a PRT. P_ℓ is the effective ripple power converted to primary of a PRT. $P_{\ell t}$ is the total ripple power for the magnet. The total output power of n amplifiers to decrease voltage ripple is given by

$$P_{At} = n\ P_A$$
$$= [(1 + (1/n)(L_\ell/Ls)]\ P_{\ell t}$$

where Ls is the secondary inductance of a PRT.

The phase of the amplifier output power has to be inversed to the ripple power on the magnet. The current ripples are able to reduce by suppressing the voltage ripples on the magnet.

Developed voltage ripple detector

A new developed voltage ripple detector is required to satisfy the following to improve the former feed forward into the feed back control system, and then a new detector has been developed.

(1) removing the multi-grounding the center of the main circuit voltage dividers for the MPS.

(2) obtaining the flat voltage gain from 50 Hz to 2 KHz.

(3) phase shift less than several degrees in the above frequency range.

(4) detecting only voltage ripples from output voltage of the MPS.

The new detector indicated in Fig. 3 consists of a low impedance resistive voltage divider with a detector reactor transformer (DRT), an equalizer and a high pass filter. The new detector satisfied the condition (1) by grounding only secondary of the DRT. The other conditions [(2) ∿ (4)] depend on the characteristics of the DRT, the equalizer etc.

Fig. 4 gives the equivalent circuit of the low impedance resistive voltage divider with the DRT. Where R_1, R_2 and R_3 are the resistance of the voltage divider for the detector. L is the primary inductance of the DRT. r_1 and r_2 are internal resistance of the primary and secondary winding of the DRT respectively.

The ratio of output voltage, V_0, to input voltage, V_1, in the low frequency range is given by

$$V_0/V_1 = (R_3/A\omega)(LS/w)/(1 + LS/w)$$
$$F_\ell = R_3/A\omega \quad , \qquad \tau_\ell = L/w$$

where
$$A = (R_1 + R_2)/R_2$$
$$\omega = r_1 + r_2 + R_3 + R_1/A$$
$$w = (r_2 + R_3)(r_1 + R_1/A)/\omega$$

S is a differential operator. F_ℓ is the gain and τ_ℓ is the time constant.

The ratio of output to input voltage in the high frequency range is written by

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$$V_0/V_1 = (R_3/A\omega)/(1 + \ell S/\omega)$$

$$F_h = R_3/A\omega \quad , \qquad \tau_h = \ell/\omega \ ,$$

where ℓ is the total leakage inductance of the DRT. τ_h is time constant and F_h is the gain.

The new detector has phase shifts of the first order lead characteristic in the low frequency range and has the first order lag in the high frequency. Table indicates parameters of the new detector. Fig. 6-(a) shows the Bode's diagrams of the new detector and the detector satisfies the condition (2) and (3).

The voltage pattern has frequency components lower than 25 Hz and the ripple frequency is higher than 50 Hz. The signal from the DRT contains large amounts of pattern components. In order to remove this low frequency components, we design an equalizer to have a characteristic similar to the DRT for the low frequency range. The equalizer is given in Fig. 3. A difference ripple signal between the DRT and the equalizer output hed still very low frequency components at transient. An active high pass filter reduced the components.

Therefore, the new detector has satisfied the all proposed conditions. Fig. 5 shows operating signals of the new detector.

However, in the former, each divider had grounding points and then main error signals came from currents due to multi-grounding, and the other error signal came from the mismatching between the MPS and the equalizer. Especially, in the former divider, the phase of the output delayed by 20 degree from input signal at a typical frequency 300 Hz, since the former was made up by high impedance resistive divider. So, we operated the former system by the feed forward mode.

Amplifier system

The amplifier output power is desgined to reduce the measured ripples except for transient of the magnet power supply (MPS) when the magnet saturates at flat top. The power is fed into main circuit through the PRT by the pulse wide modulation (PWM) and the B-calss audio amplifier system with appropriate phase compensation. The PWM system with the carrier frequency 40 KHz has the effective range from 50 Hz to 2 KHz, and consists of 22 water-cooled power modules with 4 high power switching transistors (2SC1471 selected). The module has a demodulating low pass filter to eliminate the switching noise.

In the former, a capacitor was connected into the main circuit to reudce the switching noise. The capacitor was removed from the present system because a parasitic oscillation was excited in the negative feed back control loop by the capacitor.

The maximum output power of a module is 3.4 KW (r.m.s.). For the low frequency less than 73 Hz in bending (B) and 75 Hz in quadrupole (Q), the effective power reduce to keep within the rated current of power transistor.

Two groups of the 9 modules serve for the B MPS and the other two groups of the 2 modules for the Q_F and Q_D magnet power supply respectively.

Every module is connected to a PRT. The PWM output power increased by about ten times the former system by raising dc voltage of the amplifier from 110 V to 300 V.

The B-class audio main amplifier system covers frequency from 70 Hz to 2 KHz, and has the 20 water-cooled modules. One module consists of 8 transistors (2SD465) connected in parallel. The rated output power of a module is 2.3 KW (r.m.s.). The system is made by push-pull circuit with two groups connected in parallel the three and two modules for the B and Q MPS, respectively. Every system is connected to a PRT. The output power increases about 4.5 times the former.

The calculated Bode's diagrams are given by the solid lines in Fig. 6-(b ∿ d) for the both amplifier systems.

Results

After above improvements, the current ripples have been estimated at 8.4×10^{-6} or less on the flat top current of 2,850 A for the bending MPS, and 7.9×10^{-6} or less on the flat top current of 1,500 A for the quadrupole MPS.

The voltage ripples have been reduced less than - 26 db in the frequency from 100 Hz to 500 Hz by the dynamic filter system. Also the voltage gain was - 18 db at 50 Hz, and - 12 db at 2 KHz. Dots given in Fig. 6-(d) indicate the measured voltage ripple ratio of output to input.

For the typical bending MPS, Fig. 7 shows the analysed spectra of the voltage ripple on the input and output voltage detector pointed out in Fig. 1. Fig. 8 (photo.) gives the input (top) and output (bottom) voltage ripple wave with the above condition. The similar results have been obtained for the Q_F and Q_D magnet power supply.

Acknowledgements

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2) H. Sato et al., KEK-76-20.
3) H. Baba et al., Proc. 3rd Symp. on Accelerator Sci. and Tech., Osaka, 1980, p.191.

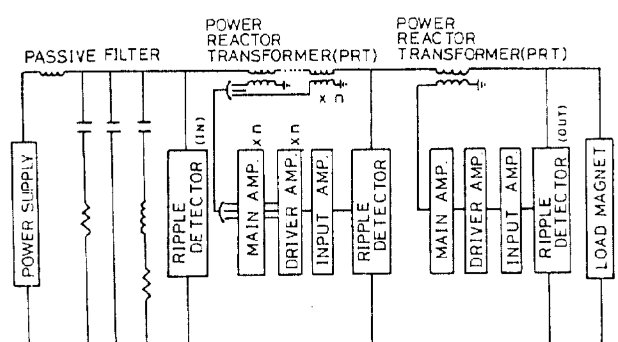


Fig. 1 Schematic diagram of magnet power supply.

	n
Bmag.1	9
Bmag.2	9
Q_F	2
Q_D	2

Table Parameters of the new ripple detectors

	R_1	R_2	R_3	$r_1=r_2$	L	ℓ	θlead	θlag
B-MPS	60 kΩ	30 Ω	150 Ω	10 Ω	2.0 H	1.0 mH	3.0°	3.6°
Q-MPS	800 Ω	16 Ω	150 Ω	10 Ω	2.0 H	1.0 mH	2.0°	3.9°

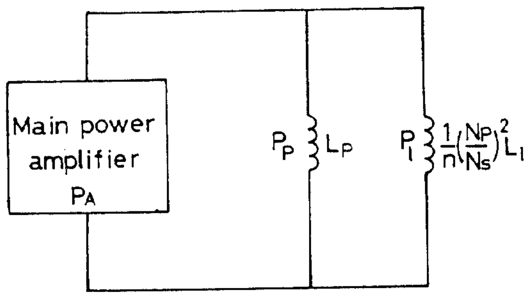


Fig. 2 Simplified equivalent circuit of the dynamic filter.

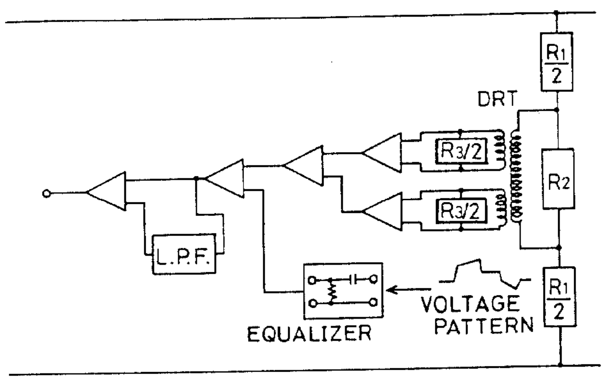
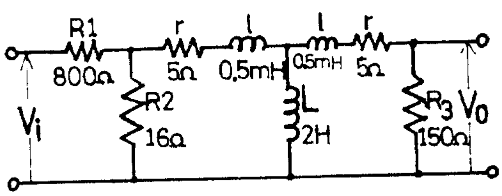


Fig. 3 New voltage ripple detector.



$$G(s) = \frac{T_1 S}{1 + T_1 S} \quad (f \ll 100)$$
$$= \frac{1}{1 + T_2 S} \quad (f \gg 200)$$

Fig. 4 Equivalent circuit of new detector.

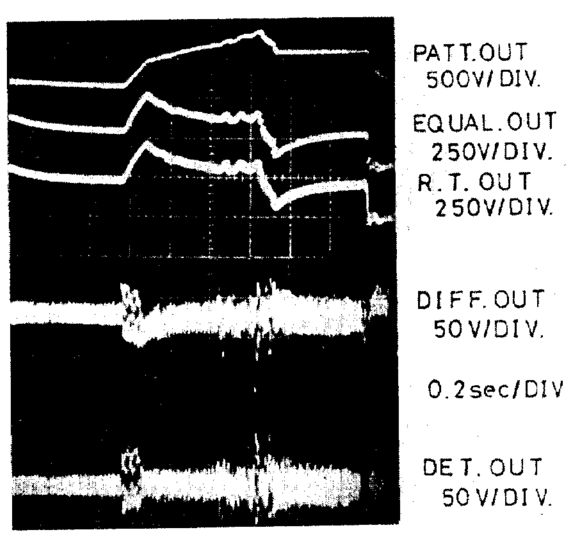


Fig. 5 Operating signals of the new detector.

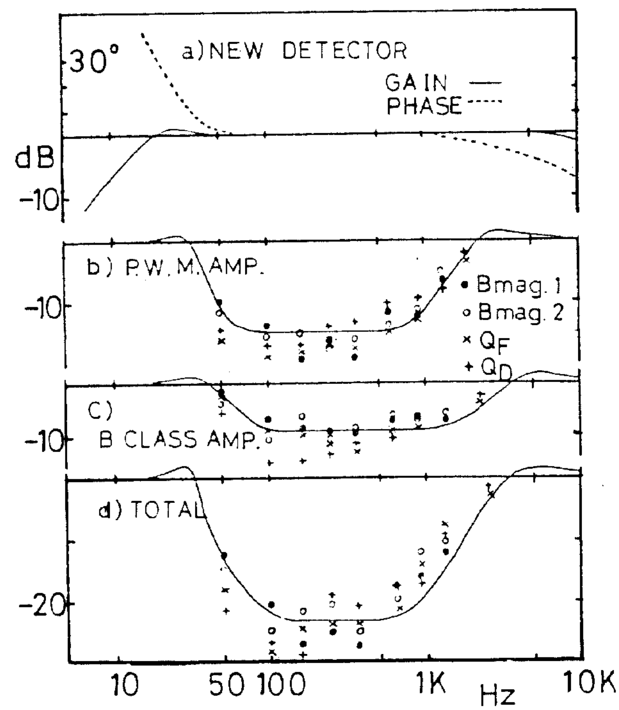


Fig. 6 Bode's diagrams of the dynamic filter.

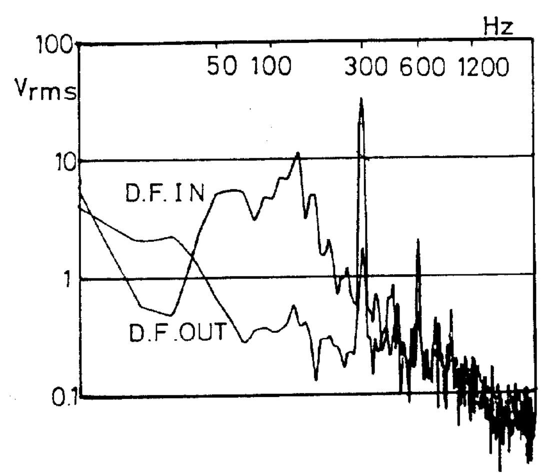


Fig. 7 Analysed spectra of the voltage ripple.

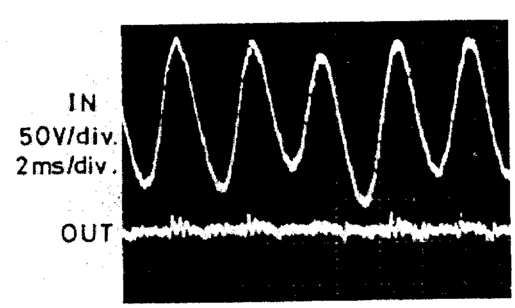


Fig. 8 Wave forms of the voltage ripple.