Active Filter for the DESY III Dipole Circuit

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Abstract

The DESY III dipole circuit is now operated in a ramp mode cycle with 3.6 s repetition rate. Excitation is done by a 12-pulse thyristor converter, followed by a passive filter. The existing current control could be improved by addition of an active filter. The use of a more efficient passive filter reduces the size of the active filter and does not deteriorate the dynamic behaviour. The design of the control loops and the results of the simulation are presented.

Introduction

The ramping time of the DESY III proton synchrotron dipole magnets was determined to be about 1.5 s. With that and the time constant of the dipole circuit an excitation power of more than twice the I^2R-value or a total of 2.7 MW is necessary. A conventional 2-quadrant thyristor converter/inverter for 12-pulse operation is used as a main power supply, symmetrically controlled during the whole 3.6 s cycle time but operated in a gated freewheeling mode during the 100 % flat top and the 4.1 % injection flat bottom phases. In addition to this filtering of the output voltage, especially of its 600 Hz component, is needed. During the first stage a simple critical damped low-pass filter was provided to get a good dynamical behaviour. Later improvements of the synchrotron operation showed the necessity of a lower harmonics content. This can be attained by addition of an active filter, thus also improving the dynamical behaviour of the automatic control system. Figure 1 shows the equivalent circuit diagram.

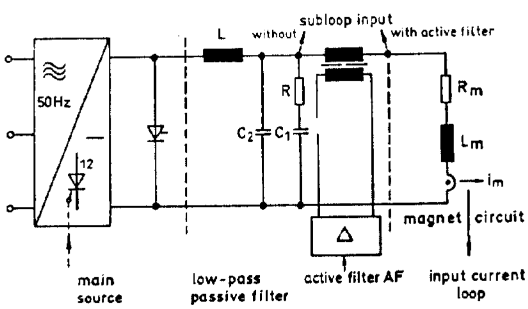

Fig.1: DESY III dipole excitation - Basic circuit diagram

System structure and equivalent block diagrams

Figure 2a represents the circuit containing all the elements of the multi-loop feedback system. The transfer functions of the single structure elements are listed below ($s = j\omega s^{-1}$).

F_{S1}: 2nd order rational approximation for the dead time T_z of the DC source. $T_z = 0.83$ ms. F_{S2}: Passive filter PF (series reactor without losses)

$$F_{S2} = \frac{1 + 2d \cdot s/\omega_0}{1 + 2d \cdot s/\omega_0 + (1+m)s^2/\omega_0^2 + 2md \cdot s^3/\omega_0^3} \quad (1)$$

$$m = \frac{C_2}{C_1}; d = \frac{R}{2\omega_0 L}; \omega_0^2 = \frac{1}{LC_1} \quad \text{(see Fig.1)}$$

F_{S3}: magnet circuit; 1st order delay network; $T_m = 1.7\,s$

$V_0 = \frac{U_G}{I_{mn}R_m}$ U_G: voltage of the DC source
I_{mn}: nominal rated magnet current

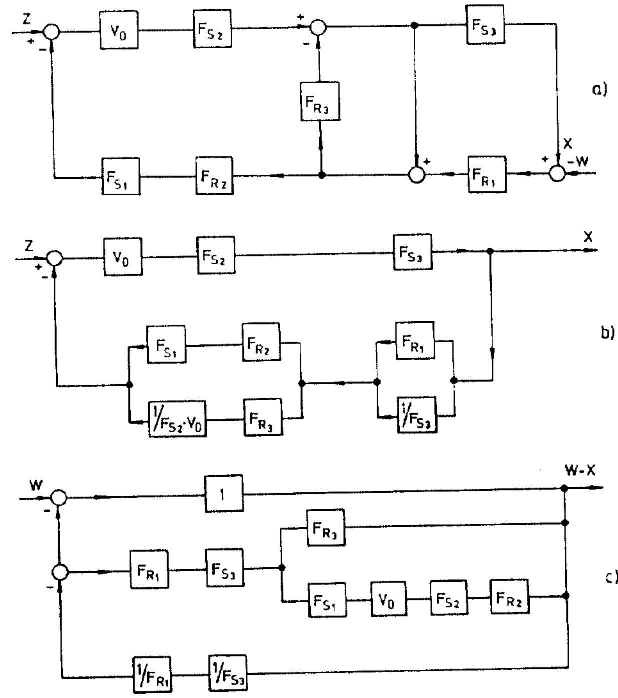

Fig.2: Multiloop control system -Block diagrams (see text)

F_{R1}: magnet current regulator

$$F_{R1} = \frac{V_I \cdot (1 + sT_m)}{sT_m} \qquad PI-characteristic \quad (2)$$

$$F_{R1} = \frac{V_I \cdot (1 + sT_m)(1 + sT_2)}{s^2 T_m T_2} \qquad PI^2-characteristic \quad (3)$$

F_{R2}: voltage regulator; $F_{R2} = F_{R21} \cdot F_c$

$$F_{R21} = \frac{V_{II} \cdot (1 + sT_2)}{sT_2} \qquad PI-characteristic \quad (4)$$

F_C: compensating element ("phase shifter")

$$F_C = \frac{1 + sT_3}{1 + sT_4} \cdot \frac{1 + sT_3}{(1 + sT_5)(1 + sT_6)} \quad (5)$$

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F_{R3}: active filter AF

$$F_{R3} = V_{III} \frac{T_7 \cdot T_8 \cdot s^2}{(1+sT_7)(1+sT_8)(1+sT_9)^2} \qquad (6)$$

$$T_7 = 10\,ms;\; T_8 = 4.6\,ms;\; T_9 = 0.32\,ms;\; V_{III} = 8$$

The representation of Fig. 2a requires that no or only negligible reaction occurs between structure elements opposite to the arrow direction. Figure 2b shows the monoloop block diagram which is equivalent to Fig. 2a for the effect of the most important disturbance variable ΔU_{line} and also for the open-loop response. The use of line diagram Fig. 2c leads to the simulation of the normalized following error. The simulations were carried out with the aid of the Hewlett Packard "Linsys" method.

Dynamic characteristics

The layout of the elements of the automatic control system was done with the aim to get a minimum tracking error. For that, the following measures were taken into account:

- high gain of the current loop at the expense of the subloop gain. In the case of the AF circuit a compromise must be found because the size of the AF depends on the reciprocal of the subloop gain;
- compensating networks F_C in case of the structure with only PF to enlarge the open-loop bandwidth. Having a suitable layout, F_C acts mainly as phase shifter with little influence on the magnitude. See also Ref. [1];
- double integration in the current path. In this case, the voltage subloop may not have an integral element to ensure the stability of the whole system.

The following error was analyzed for the first transition period of the magnet current between the DC injection level and the beginning of the linear ramp. Its duration is 0, 1 s and during this time the control input w obeys to the equation

$$w = a \cdot t^3 + b \cdot t^4 \qquad (7)$$

a and b have to be determined such that at the end of the transition period $\dot{w}$ is equal to the ramp gradient and $\ddot{w} = 0$.

Circuits with passive filter only

We compare the circuits having 2 different low-pass passive LC-filters

a)
critical damped; $\omega_0 = 2\pi \cdot 37\,s^{-1}$
according to the a.m. transfer function F_{S3}: $d = 1$; $m = 0$
Damping of the 600 Hz component: 18 dB

b)
third order; $\omega_0 = 2\pi \cdot 26\,s^{-1}$; $m = 0.1$; $d = 0.4$
Damping of the 600 Hz voltage component: 35 dB

a)
current loop: PI-characteristic: $V_I = 1500$
voltage loop: PI-characteristic: $V_{II} = 2$; $T_2 = 0.05\,s$
$T_3 = 3\,ms$; $T_4 = 15\,ms$; $T_5 = T_6 = 0.2\,ms$

b)
current loop: PI-characteristic: $V_I = 900$
voltage loop: PI-characteristic: $V_{II} = 2$; $T_2 = 0.005\,s$
$T_3 = 6\,ms$; $T_4 = 3\,ms$; $T_5 = T_6 = 0.4\,ms$

Figure 3 shows the open-loop responses for these two cases with the following parameters of the feedback amplifiers:

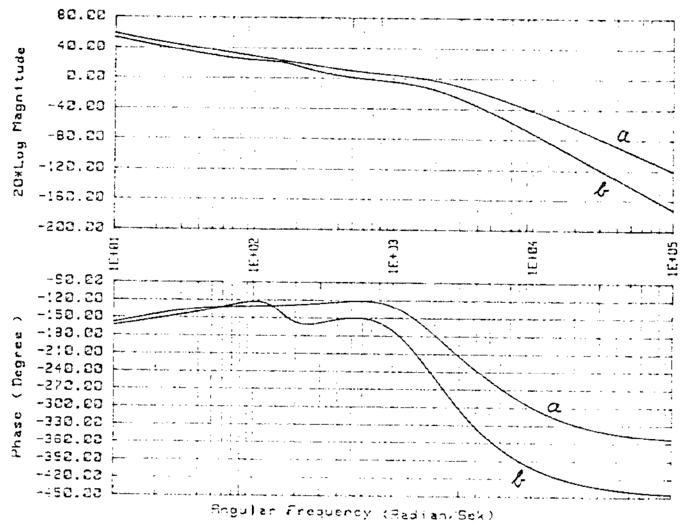

Fig.3: Circuit with passive filter only - Open loop frequency responses (see text)

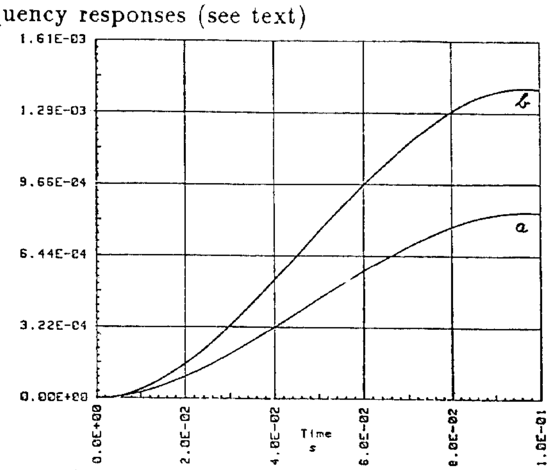

Fig. 4: Circuit with PF only - Tracking error (see text)

In Fig. 4 the tracking error of the magnet current, related to the nominal rated current is represented with a maximum at the end of the transition period due to the single integration of the current loop. This value is kept during the ramp phase.

Circuits with passive and active filters

The active filter has a transfer function as described above. The other system parameters are

passive filter: third order; $\omega_0 = 2\pi \cdot 27.5\,s^{-1}$; $m = 0.1$; $d = 1$
current loop: $V_I = 1000$; 2000; 4000; PI or PI^2 characteristic
voltage loop: $V_{II} = 3.74$; PI or P-characteristic; $T_2 = 15\,ms$

Figure 5 shows the frequency responses of the active filter

(b) and the open voltage loop (a) and Fig. 6 the open-loop Bode Diagrams for the whole system.

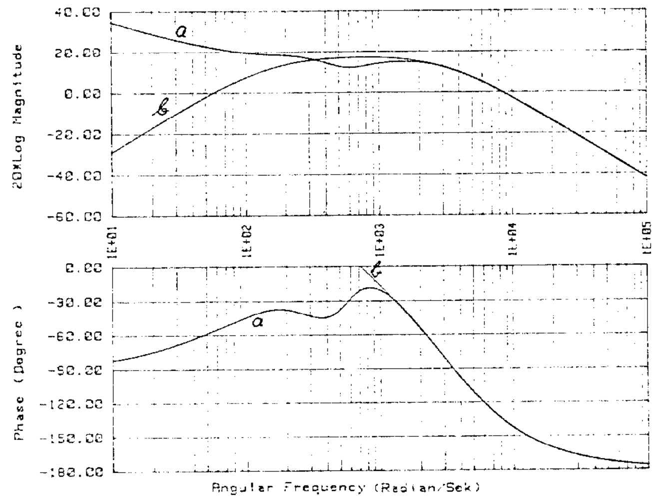

Fig.5: Circuit with passive and active filter – Bode Diagrams of the open voltage loop (a) and the AF (b)

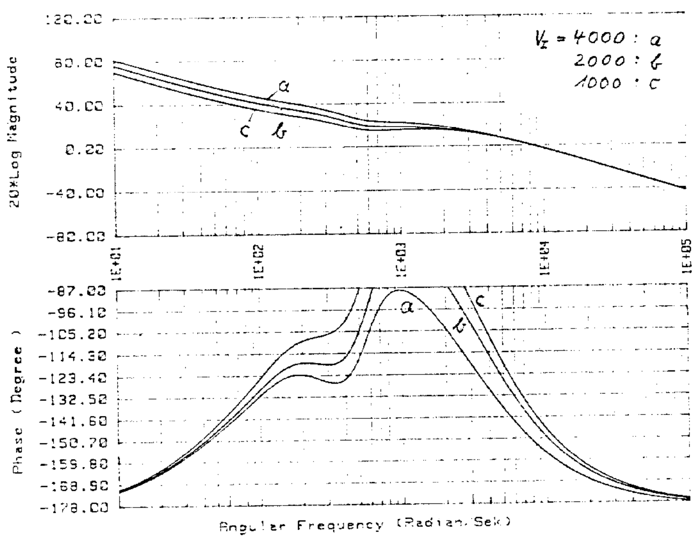

Fig.6: Circuit with passive filter and active filter – Bode Diagrams of the whole open-loop system

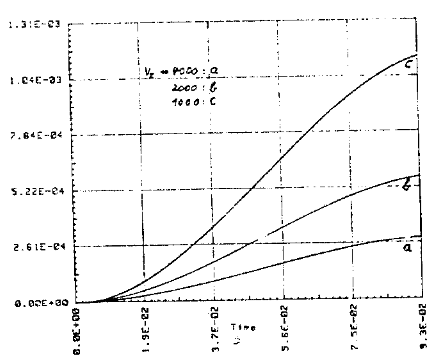

Fig.7: Circuit with passive and active filter – Tracking error for mono-integrating current loop

For these no conspicuous difference was found for the two different current loop characteristics.

Figure 7 and 8 are graphics of the tracking error for the two different current loop modes. In the continuation in time of Fig. 8, the following error decays to zero during the linear ramp. Figure 9 shows the frequency response: magnet current to passive filter output with (b) and without (a) AF thus showing the damping of the 600 Hz component.

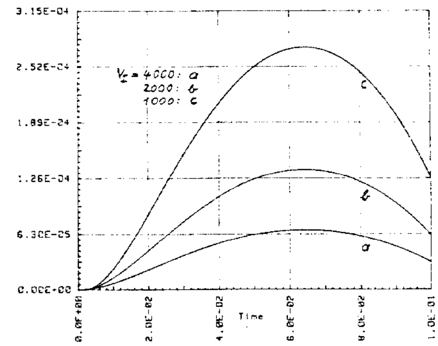

Fig.8: Circuit with passive and active filter – Tracking error for dual-integrating current loop

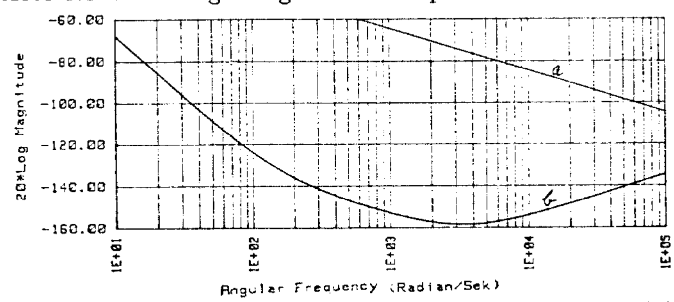

Fig.9. Harmonics attenuation without (a) and with (b) active filter. (see text)

Results

The graphs of the following error show a strong dependence on the current loop gain, which may be enlarged considerably by the use of an active filter. A more effective passive filter ensures that the remaining amount of harmonics voltage to be absorbed by the active filter remains small. – The input of the voltage subloop after the AF has nearly no harmonics content – 115 dB for 600 Hz or 0.7 mV – and therefore offers much better conditions than in usual installations with PF only. In the optimum case of Fig. 8, the maximum of the tracking error of the magnet current related to its actual value is $1.3 \cdot 10^{-3}$. Compensation by introduction of the second derivative of the reference value as described in [1] would minimize this value during the transition period strongly. The remaining tracking error at the start of the linear ramp can not be compensated by this methods but its value, related to the actual magnet current value, is only 4×10^{-4} and decays rapidly.

References

1. W. BOTHE, *"Magnet circuits for DELTA"*
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