RAPID-CYCLING POWER SUPPLIES FOR THE J-PARC RCS SEXTUPOLE MAGNETS

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Abstract

In the J-PARC 3-GeV synchrotron, the sextupole magnets were excited with DC-biased 25Hz sinusoidal waveform. Direct excitation for the rapid-cycling magnets causes large reactive power and voltage fluctuation in DC-link.

This paper proposes design of the smoothing circuit for direct excitation of the rapid-cycling magnets. Especially, theoretical power-flow analysis shows a relationship between required DC-capacitance and voltage fluctuation in DC-link. Experimental results obtained from practical power-supply agree with analytical results.

INTRODUCTION

The Japan Proton Accelerator Research Complex (J-PARC) is a high-intensity proton accelerator facility designed to produce at MW-class output beam power. The J-PARC accelerator complex consists of a 181-MeV linac, a 3-GeV rapid cycling synchrotron (RCS), a 50-GeV synchrotron, and several experimental facilities. The 3-GeV RCS accelerates a 181-MeV proton beam from the linac up to 3-GeV at a repetition rate of 25 Hz. The 3-GeV RCS requires 18 sextupole magnets with three families for the chromaticity correction [1]. One family consists of six focusing sextupole magnets, and other two families consist of six defocusing sextupole magnets. An individual power supply excited for each family and the current pattern is a DC-biased sinusoidal of a frequency of 25 Hz as shown in figure 1.

In general, excitation of the rapid-cycling magnets were used a resonant circuit to reduce a power-supply rating. The resonant circuit, which is tuned for operation frequency, consists of chokes and capacitors, and it's connected between power supply and magnet. However, in case of the sextupole magnet power supply in the J-PARC RCS, we select direct excitation not resonant excitation because the power-supply rating and total cost were acceptable comparison with the resonant excitation.

In the sextupole magnet power supply, peak rating were 1100 V and 750 A, respectively. Peak power of the power supply is 825 kVA, but average power is slightly 31 kW. In other words, direct excitation for the rapid-cycling magnets causes large reactive power and voltage fluctuation in DC-link. To keep current control accuracy, voltage fluctuation in DC-link should be suppressed. Smoothing circuit, which is composed of DC capacitance and DC inductance, is an important role to suppress voltage fluctuation in DC-link and to absorb reactive power.

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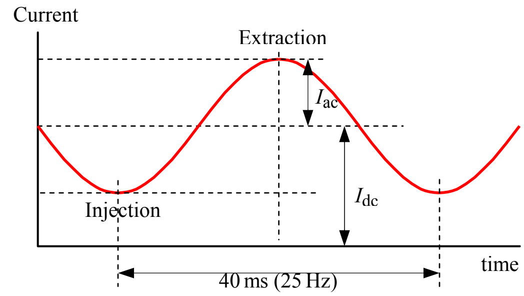

Figure 1: Waveform pattern of the sextupole magnet current.

This paper proposes design of the smoothing circuit for direct excitation of the rapid-cycling magnets. Especially, theoretical analysis shows a relationship between required DC-capacitance and voltage fluctuation in DC link from power-flow analysis.

SYSTEM CONFIGURATION

Figure 2 and table 1 show a main circuit and a parameter of the sextupole magnet power supply, respectively. The power supply is connected in series to six magnets chain. The power supply is composed of a twelve-pulse diode rectifier, a smoothing circuit, a voltage fed H-bridge inverter, and a passive filter. The output terminals in each H-bridge inverter are connected in two-series and in four-parallel, and the neutral point of the output terminal is grounded to reduce a line-to-ground voltage. The switching element of the H-bridge inverter uses IGBT of 1400V-600A, and the switching frequency of all IGBT is 20 kHz.

DESIGN OF A SMOOTHING CIRCUIT

DC Capacitance

To design the required DC-capacitance in the smoothing circuits, it is necessary to know the power flowing from the power supply.

The output current of the sextupole magnet power supply, $i(t)$ is given by

$$i(t) = I_{dc} - I_{ac} \cos \omega t , \qquad (1)$$

$$\omega = 2\pi f = 2\pi / T ,$$

where I_{dc} and I_{ac} are dc and 25 Hz amplitude of the output current, respectively. f is the excitation cycle, so it is 25 Hz. Output voltage of the power supply $v(t)$ is

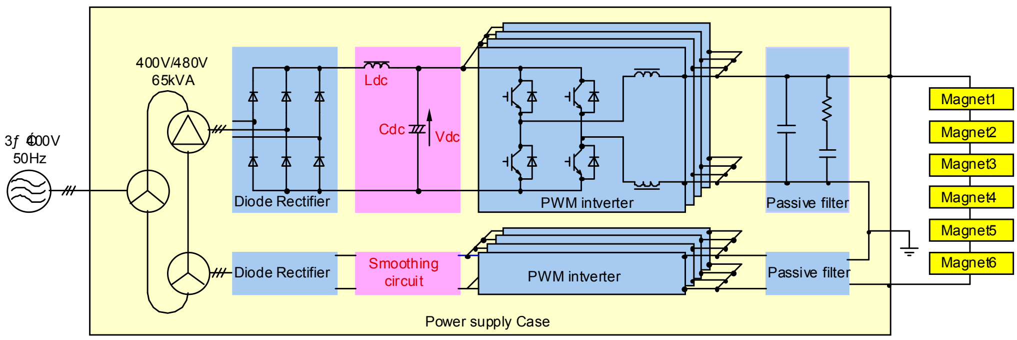

Figure 2: System configuration of the sextupole magnet power supply.

Table I: Parameter of the Sexpole Magnet Power Supply

Parameter		Value
Peak output voltage	V_{max}	1100 V
Peak output current	I_{max}	750 A
Output current (DC component)	I_{dc}	433 A
Output current (AC component)	I_{ac}	317 A
Reputation rate	f	25 Hz
Peak output power	P_p	825 kVA
Average output power	P_a	31 kW
Magnet resistance (Total)	R_m	132 mΩ
Magnet inductance (Total)	L_m	19.3 mH
DC-link voltage	V_{dc}	600 V
DC inductance	L_{dc}	10 mH
DC capacitance (Total)	C_{dc}	264 mF

$$v(t) = R_m i(t) + L_m \frac{di(t)}{dt}, \quad (2)$$

where R_m and L_m are magnet resistance and inductance, respectively. The instantaneous output power of the power supply $p(t)$ is given by

$$\begin{aligned} p(t) &= v(t)i(t) \\ &= R_m\left(I_{dc}^2 + 1/2\, I_{ac}^2\right) \\ &\quad + \sqrt{4R_m^2 + (\omega L_m)^2}\, I_{dc} I_{ac} \cos(\omega t - \alpha) \\ &\quad + \omega L_m I_{ac}^2 \cos(2\omega t - \beta), \end{aligned} \quad (3)$$

where

$$\alpha = \cos^{-1}\left(-2R_m \Big/ \sqrt{4R_m^2 + (\omega L_m)^2}\right),$$
$$\beta = \cos^{-1}\left(R_m \Big/ \sqrt{R_m^2 + (\omega L_m)^2}\right).$$

Here, R_m is negligible because $\omega L_m >> R_m$, therefore Eq. 3 is

$$\begin{aligned} p(t) &= R_m\left(I_{dc}^2 + 1/2\, I_{ac}^2\right) + \omega L_m I_{dc} I_{ac} \sin(\omega t) \\ &\quad + \omega L_m I_{ac}^2 \sin(2\omega t) \end{aligned} \quad (4)$$

The first term in Eq. 4 represents an active power, and the amplitude is 31kW. The active power receives from power line through the twelve-pulse diode rectifier. The second and third term in Eq. 4 represent reactive power and amplitude of the second and third terms are 418 kW and 152 kW, respectively. The reactive power circulates between the smoothing circuits and magnet inductance. Therefore, DC-link voltage is fluctuation with ω (25 Hz) and 2ω (50 Hz). The output energy ΔE_{out} from the power supply calculates integration of the second and third term in Eq. 4 from t=0 to t=T/2. Thus, the output energy ΔE_{out} is given by

$$\begin{aligned} \Delta E_{out} &= \int_0^{T/2} \left[\omega L_m I_{dc} I_{ac} \sin(\omega t) + \omega L_m I_{ac}^2 \sin(2\omega t)\right] dt \\ &= 2 L_m I_{dc} I_{ac}\,. \end{aligned} \quad (5)$$

The output energy ΔE_{out} is provided by the smoothing circuits. Energy storage element in the smoothing circuits is DC capacitance and DC inductance. In this section, DC inductance is negligible because stored energy capacity in inductance is very small rather than capacitance. Therefore, the output energy ΔE_{out} is equal to released energy from the DC capacitance. Here, DC-link average voltage and its fluctuation amplitude are defined as V_{dc} and is ΔV_{dc}, respectively. In case of DC-link voltage drops from $V_{dc} + \Delta V_{dc}$ to $V_{dc} - \Delta V_{dc}$, released energy from the DC capacitance is given by

$$\begin{aligned} \Delta E_{out} &= \frac{1}{2} C_{dc}(V_{dc} + \Delta V_{dc}) - \frac{1}{2} C_{dc}(V_{dc} - \Delta V_{dc}) \\ &= 2 C_{dc} \Delta V_{dc} V_{dc} \end{aligned} \quad (6)$$

From Eq. 5 and Eq. 6, DC capacitance C_{dc} is obtained as

$$C_{dc} = \frac{L_m I_{dc} I_{ac}}{\Delta V_{dc} V_{dc}}. \qquad (7)$$

In case of the voltage fluctuation in DC-link is under is under 3%, so ΔV_{dc} is 18 V in case of V_{dc} is 600 V, the required DC-capacitance is given by

$$C_{dc} = \frac{19.3\times10^{-3}\times433\times317}{18\times600} = 245 \text{ mF.}$$

In this paper, DC capacitance C_{dc} is set to 264 mF.

DC inductance

DC inductance in the smoothing circuits acts to suppress amplitude fluctuation of the AC-line current. DC-inductance is defined by simulated results as shown Figure 3. In this paper, amplitude fluctuation of the AC-line current is under about 50 % in case of the rated operation, the DC inductance is set to 10 mH.

EXPERIMENTAL RESULTS

Figure 4 shows the experimental waveforms in case of rated operation, which is the DC component I_{dc}=433 A and AC component I_{ac}=317 A. The data acquisition of the each waveform is 16 bit ADC with 50 kHz of sampling clock. The output voltage leads by 90 degree with respect to the output current because of inductive load at 25 Hz. Waveform of the DC-link voltage is fluctuation with 25 Hz and 50Hz. Fluctuation amplitude of the DC-link voltage is ±11V, which is 2 % of the DC-link average voltage 546 V, under 3 % of the design value. Amplitude fluctuation of the AC-line current is smaller than simulated results.

Table 2 shows the FFT analysis of the output current from dc to 5th order. All components are under 0.01% of the peak current which is 750 A. Therefore, the output current is no influence from voltage fluctuation in DC-link.

SUMMERY

This paper has proposed design of the smoothing circuit for direct excitation of rapid-cycling magnet. The practical power supply has been demonstrated consistency in proposed design.

REFERENCES

[1] S. Igarashi, et al, "Eddy Current Effects of the J-PARC RCS Sextupole Magnets", IEEE Transactions on Applied superconductivity, Vol.18, No.2, pp.289-292, 2008.

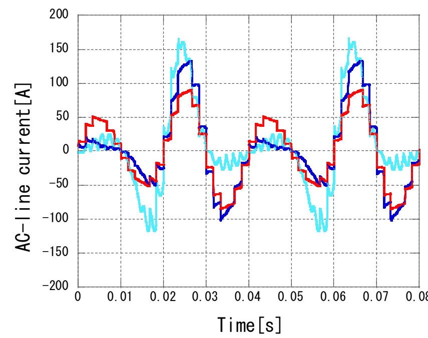

Figure 3: Simulated results of the AC-line current in case of the rated operation. (DC inductance 500uH: light blue, 4 mH : blue , 10 mH : red)

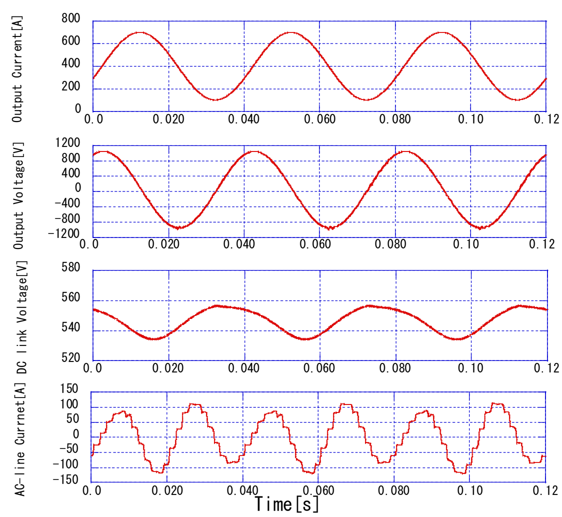

Figure 4: Experimental results of the rated operation. (I_{dc}=433 A, I_{ac}=317 A).

Table II: FFT Analysis of the Magnet Current Focus on Low Freqency Region

	Frequency	Amplitude	Ratio against Peak current
0	DC	433.149 A	-
1st	25 Hz	318.555 A	-
2nd	50 Hz	0.040 A	0.0053 [%]
3rd	75 Hz	0.033 A	0.0044 [%]
4th	100 Hz	0.049 A	0.0065 [%]
5th	125 Hz	0.077 A	0.0100 [%]