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Study of wave form compensation at CSNS/RCS magnets

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ABSTRACT

A method of wave form compensation for magnets of the Rapid Cycling Synchrotron (RCS), which is based on transfer function between magnetic field and exciting current, was investigated on the magnets of RCS of Chinese Spallation Neutron Source (CSNS). By performing wave form compensation, the magnetic field ramping function for RCS magnets can be accurately controlled to the given wave form, which is not limited to sine function. The method of wave form compensation introduced in this paper can be used to reduce the magnetic field tracking errors, and can also be used to accurately control the betatron tune for RCS.

1. Introduction

The Chinese Spallation Neutron Source (CSNS) is an accelerator-based science facility. CSNS is designed to accelerate proton beam pulses to 1.6 GeV kinetic energy, striking a solid metal target to produce spallation neutrons. CSNS has two major accelerator systems, a linear accelerator (80 MeV Linac) and a rapid cycling synchrotron (RCS). The function of the RCS accelerator is to accumulate and accelerate protons from the energy of 80 MeV to the design energy of 1.6 GeV at a repetition rate of 25 Hz [1,2]. The magnetic field tracking is an important issue for CSNS/RCS. The magnetic field tracking errors between the quadrupoles and dipoles can induce tune shift. If the tune shift induced by magnetic field tracking errors is large enough to pass through the resonance line, emittance growth as well as beam losses will occur [3–5]. The accurate tracking of quadrupoles and dipoles (accuracy requirements: 0.1%) is necessary.

Because of the magnetic saturation and the eddy current effects, there may be magnetic field tracking errors between different magnets of CSNS/RCS. For the magnets of RCS, which are powered by resonant circuits [6,7], the exciting current and magnetic field is unable to be controlled step by step during ramping. For this type of magnets, the feed-back system is unable be used to accurately control the magnetic field ramping wave form [8,9]. The accurate magnetic field tracking was achieved by performing harmonic field correction at J-PARC/RCS [10]. To reduce the magnetic field tracking errors for CSNS/RCS, a method of wave form compensation for RCS magnets was investigated. By performing wave form compensation, the magnetic field ramping function for RCS magnets can be accurately controlled to the given wave form, which is not limited to sine function.

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2. Introduction of the method of wave form compensation

The method of wave form compensation is based on transfer function between magnetic field and exciting current of the magnets of RCS. Higher order time harmonics of exciting current, which are computed based on transfer function, are injected into resonant circuits to modify the power supply ramping function, and the magnetic field ramping wave form can be accurately controlled.

The method of wave form compensation for magnets of RCS was tested on one type of quadrupole of CSNS/RCS named 253Q. By performing wave form compensation, the magnetic field ramping function $GL(t)$ of 253Q was accurately compensated to the same wave form as the dipole of CSNS/RCS, named 160B. In other words, all the normalized time harmonics of 253Q were compensated to the same as 160B. Table 1 shows the measurement results of magnetic field time harmonics of 253Q and 160B with no wave form compensation. Higher order time harmonics of magnetic field for both 160B and 253Q are large, and the normalized time harmonics are absolutely different between 253Q and 160B. The magnetic field ramping function $GL(t)$ with the same wave form as 160B can be expressed as:

$$\begin{aligned} GL(t) = & GL_0 + A_1 \cdot GL_0 \sin(2\pi f_0 t - \frac{\pi}{2}) \\ & + A_2 \cdot GL_0 \sin(4\pi f_0 t - \frac{\pi}{2} + \varphi_2) \\ & + A_3 \cdot GL_0 \sin(6\pi f_0 t - \frac{\pi}{2} + \varphi_3) \\ & + A_4 \cdot GL_0 \sin(8\pi f_0 t - \frac{\pi}{2} + \varphi_4) + \cdots \end{aligned} \tag{1}$$

Table 1
Time harmonics of the exciting current and magnetic field of 253Q and 160B before wave form compensation, the phases mean phase deviation from fundamental harmonic, and the amplitude of time harmonics of magnetic field is normalized value.

	253Q	160B
I_{DC} − Amp.(A)	745.1	1223.0
$I_{25\text{ Hz}}$ − Amp.(A)/Phase(°)	538.5/0	877/0
$I_{50\text{ Hz}}$ − Amp.(A)/Phase(°)	7.02/50.2	6.16/40.0
$I_{75\text{ Hz}}$ − Amp.(A)/Phase(°)	2.94/36.7	3.26/27.5
$I_{100\text{ Hz}}$ − Amp.(A)/Phase(°)	1.14/26.7	1.46/21.8
$I_{125\text{ Hz}}$ − Amp.(A)/Phase(°)	0.50/26.3	0.73/11.4
$GL(BL)_{DC}$ − Amp.	100%	100%
$GL(BL)_{25\text{ Hz}}$ − Amp./Phase(°)	0.715243/0	0.712699/0
$GL(BL)_{50\text{ Hz}}$ − Amp./Phase(°)	5.77E−3/104.7	2.66E−3/80.6
$GL(BL)_{75\text{ Hz}}$ − Amp./Phase(°)	1.57E−3/117.4	8.55E−4/76.8
$GL(BL)_{100\text{ Hz}}$ − Amp./Phase(°)	4.06E−4/122.8	2.73E−4/74.5
$GL(BL)_{125\text{ Hz}}$ − Amp./Phase(°)	1.85E−4/98.2	1.08E−4/72.6

where GL_0 is DC offset of the integration of the magnetic field gradient of 253Q, f_0 is the frequency of the fundamental time harmonic, the normalized amplitude A_1, A_2, A_3, A_4 and phases φ_2, φ_3, φ_4 are the same as 160B.

The flow process for the wave form compensation is shown in Fig. 1. For a start, higher order time harmonics of exciting current for 253Q were set to zero for the sake of simplicity. Because higher order time harmonics of exciting current is at open-loop control for CSNS/RCS magnets, the output higher order time harmonics of power supply were not zero, as shown in Table 1. The magnetic field and exciting current at different time during the exciting current ramping were measured offline by using the harmonic coil measurement system [11,12]. The measurement coil rotates with an angular velocity ω in the magnetic field and $\theta = \delta$ is the angular position at time $t = 0$, then, $\theta = \omega t + \delta$ and integral field changing with time is obtained at every rotating phase θ in space. The magnetic field at different time during the exciting current ramping was measured and the fit of the transfer function was made in order to reduce the effect of measurement noise. Comparing different fitting model, fitting model of Fourier series function for the relation of I - GL has the minimum fitting error, which was less than 1.5E−4. Fig. 2 shows the measured results of the relation of I - GL and the fitting functions, expressed as:

$$I = F_{Upward}(GL) = a_0 + a_1\cos(\omega GL) + b_1\sin(\omega GL) + a_2\cos(2\omega GL) + b_2\sin(2\omega GL) + \cdots \tag{2}$$

$$I = F_{Downward}(GL) = c_0 + c_1\cos(kGL) + d_1\sin(kGL) + c_2\cos(2kGL) + d_2\sin(2kGL) + \cdots \tag{3}$$

where I is the exciting current, the a_0, a_1, a_2, b_1, b_2, c_0, c_1, c_2, d_1, d_2, ω, k are fit coefficients. $I = F_{Upward}(GL)$ and $I = F_{Downward}(GL)$ are the transfer functions for the exciting current ramping upward and downward respectively. Based on the transfer function, expressed as formula (2), (3), the exciting current pattern $I(t)$ corresponding to the given magnetic field wave form $GL(t)$, expressed as formula 1, was calculated. By performing FFT to the calculated exciting current pattern $I(t)$, the DC offset and time harmonics of current were obtained. By inputting the obtained DC offset and time harmonics of the current into the resonant circuits, the magnetic field ramping function of 253Q was accurately compensated to the wave form $GL(t)$. The calculated time harmonics of the exciting current and the measurement results of the magnetic field after wave form compensation are shown in Table 2. The normalized amplitude and phases for all the time harmonics of 253Q were compensated to almost the same as 160B, besides 100 Hz and 125 Hz harmonics. Because the components of 100 Hz and 125 Hz harmonics are very small, the difference of the phases of 100 Hz and 125 Hz harmonics between 253Q and 160B after wave form compensation may be induced by the measurement noise. Because of the small components, the effects of the difference of the phases of 100 Hz and 125 Hz harmonics on the magnetic field wave form are small. By performing wave form compensation, magnetic field ramping function of 253Q was compensated to the same wave form as 160B, and the magnetic field tracking error between 253Q and 160B was effectively reduced, as shown in Fig. 3. The maximum magnetic field tracking error between 253Q and 160B was reduced from 0.45% to 0.049%. The tests on 253Q of CSNS/RCS show that, by performing wave form compensation, the magnetic field as a function of time for RCS magnets can be accurately controlled to the given type of function, which is not limited to sine function.

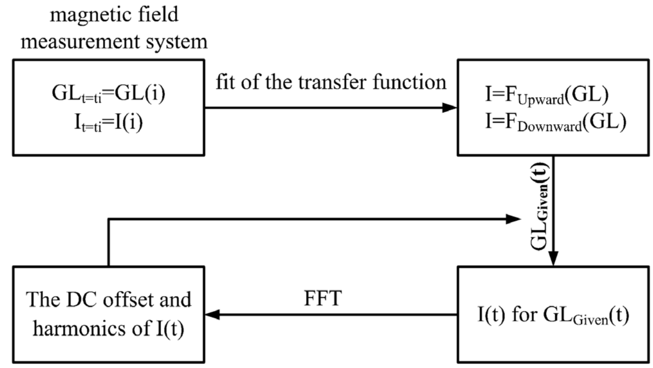

Fig. 1. The flow process diagram for the wave form compensation.

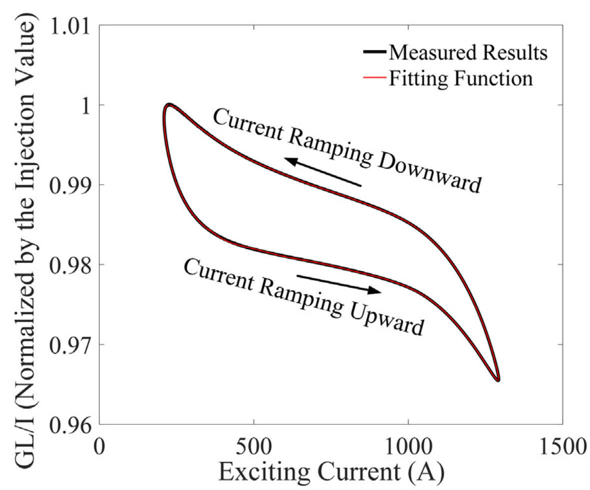

Fig. 2. The measured results of the relation of I - GL and the fitting functions.

Table 2
The calculated time harmonics of current of 253Q and the measurement results of the magnetic field after wave form compensation, time harmonics of the exciting current are the power supply output values.

	253Q	160B
I_{DC} − Amp.(A)	746.8	1223.0
$I_{25\text{ Hz}}$ − Amp.(A)/Phase(°)	537.7/0	877/0
$I_{50\text{ Hz}}$ − Amp.(A)/Phase(°)	6.46/27.0	6.16/40.0
$I_{75\text{ Hz}}$ − Amp.(A)/Phase(°)	3.29/20.7	3.26/27.5
$I_{100\text{ Hz}}$ − Amp.(A)/Phase(°)	1.38/14.8	1.46/21.8
$I_{125\text{ Hz}}$ − Amp.(A)/Phase(°)	0.57/11.7	0.73/11.4
$GL(BL)_{DC}$ − Amp.	100%	100%
$GL(BL)_{25\text{ Hz}}$ − Amp./Phase(°)	0.712649/0	0.712699/0
$GL(BL)_{50\text{ Hz}}$ − Amp./Phase(°)	2.56E−3/78.8	2.66E−3/80.6
$GL(BL)_{75\text{ Hz}}$ − Amp./Phase(°)	7.77E−4/71.5	8.55E−4/76.8
$GL(BL)_{100\text{ Hz}}$ − Amp./Phase(°)	2.24E−4/61.1	2.73E−4/74.5
$GL(BL)_{125\text{ Hz}}$ − Amp./Phase(°)	9.41E−5/58.2	1.08E−4/72.6