

POSSIBILITY OF WAVEFORM MANIPULATION OF THE MAGNET CURRENT IN A RESONANT NETWORK

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Abstract

In a rapid-cycling synchrotron (RCS), magnets are excited using a resonant network. If field saturation occurs, a sinusoidal waveform of the magnet current is deformed. Such an effect causes a tracking error when bending magnets and quadrupole magnets are excited separately with individual resonant networks (multi-network). Therefore, waveform deformation of the magnet current must be compensated in order to avoid a tracking error. This paper describes the possibility of waveform manipulation of the magnet current using a continuous AC power source.

1 INTRODUCTION

In Japan, a project aimed at an intense neutron source and a kaon factory is now in progress as the KEK/JAERI joint project for a high-intensity proton facility. The accelerator complex in this project comprises a 400-MeV Linac, a 3-GeV rapid-cycling synchrotron (RCS) and a 50-GeV Main synchrotron[1].

The 3-GeV RCS is a separated-function synchrotron, where magnets are excited with a repetition rate of 25 Hz using three or more resonant networks: one for bending magnets and the others for quadrupole magnets. Since each network is operated independently, magnetic-field tracking is necessary to perform stable acceleration of the proton beam. If the magnetic field is saturated, the waveform of the field is deformed and, therefore, the tracking between magnets fails. Since a tracking error causes serious beam loss in a high-intensity synchrotron, such a waveform deformation must be compensated.

So far, a pulse power supply has been used as an AC power source in many RCS's due to its simple configuration and reliability. However, it cannot compensate a waveform deformation. On the other hand, a continuous AC power supply has a possibility to perform waveform manipulation. Recently, a continuous AC power supply using an IGBT has been developed at BESSY II[2]. The IGBT is a fast-switching device, as compared with a thyristor and a GTO. Its switching frequency is so high that the output voltage easily follows the reference waveform. In addition, the size of the power supply is expected to be compact. Therefore, a power supply based on the IGBT was adopted as a continuous AC power source for the 3-GeV RCS magnet system.

In order to investigate the performance of the ac power supply using the IGBT, a model power supply has been constructed and various tests have been conducted. The most interesting issue is the possibility of waveform manipulation of a magnet current by controlling the continuous ac power supply. In the following sections, the results are described.

2 A MODEL POWER SUPPLY

2.1 Circuit Description

A model power supply is a PWM inverter with a chopper using the IGBT, as schematically shown in Fig. 1. The IGBT switching frequency is 16 kHz and the maximum output current is 6A. The waveform of the output voltage is controlled by a signal fed from a function generator.

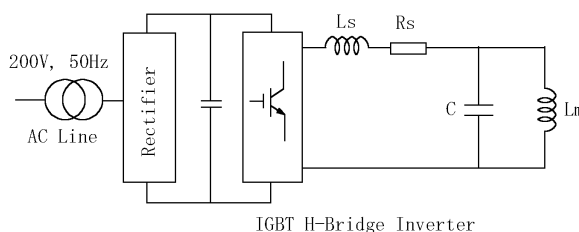


Figure 1: Block diagram of a model power supply and one-mesh resonant circuit.

The load is a one-mesh resonant circuit, which comprises a dummy magnet (L_m) and a resonant capacitor (C). Using these parameters, the resonance frequency is given by

$$\omega = 1/\sqrt{L_m \cdot C} \quad (1)$$

2.2 Frequency Response

For the purpose of waveform manipulation, it is convenient to deal with a magnet current as a Fourier series, since the frequency response of the power supply system must be taken into account. In order to evaluate the frequency response of our system, the model power supply and the resonant circuit is reduced into an equivalent circuit, as shown in Fig. 2. Here, the power supply is simply expressed by a voltage source (v_s), a filter inductance (L_s) and a resistor (R_s). The power loss

of the resonant circuit is considered by introducing resistors (R_c and R_m). i_s and i_m denote the source current and the magnet current, respectively.

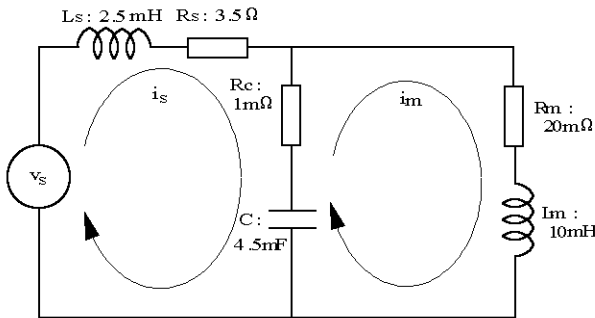


Figure 2: Equivalent circuit for evaluating the frequency response.

Supposing that the time dependent factor is $e^{j\omega t}$, the circuit performance is described by the following equation:

$$\begin{pmatrix} I_s \\ I_m \end{pmatrix} = M^{-1} \begin{pmatrix} V_s \\ 0 \end{pmatrix}, \quad (2)$$

where

$$\begin{aligned} i_s &= I_s e^{j\omega t}, \\ i_m &= I_m e^{j\omega t}, \\ v_s &= V_s e^{j\omega t}, \end{aligned}$$

and

$$M = \begin{pmatrix} R_s + R_c + j\omega L_s + \frac{1}{j\omega C} & -R_c - \frac{1}{j\omega C} \\ -R_c - \frac{1}{j\omega C} & R_c + R_m + j\omega L_m + \frac{1}{j\omega C} \end{pmatrix}. \quad (3)$$

Here, the transfer impedance is defined by

$$Z \equiv \frac{V_s}{I_m} = \frac{1}{(M^{-1})_{21}} \equiv \zeta \cdot e^{-j\vartheta}. \quad (4)$$

3 EXPERIMENT

3.1 Measurement of the Transfer Impedance

The frequency dependence of the normalized transfer impedance was measured by exciting the resonant circuit with various frequencies. Here, the resonance frequency of this circuit was tuned to be 25 Hz. Fig. 3 shows the transfer impedance, where the open circle and the solid line denote the measured modulus and the evaluated one, respectively. The square and the dashed line denote the measured phase and the evaluation, respectively. The

normalizing factor (ζ_1) is the modulus of the transfer impedance at the resonance frequency. The numerical results of the transfer impedance at each harmonic up to the fifth order are summarized in Table 1.

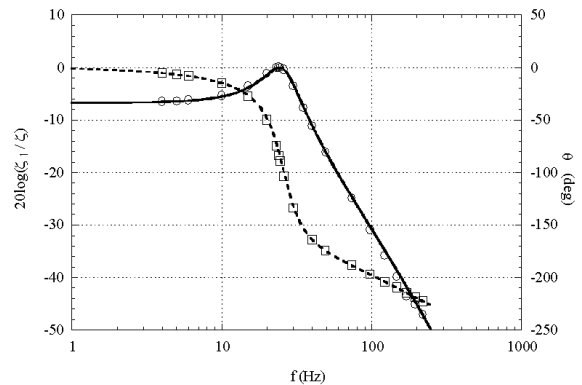


Figure 3: Frequency dependence of the normalized transfer impedance.

Table 1: Transfer impedance at each harmonic.

| n | f (Hz) | ζ_n / ζ_1 | θ_n (deg) |
|-----|----------|---------------------|------------------|
| 1 | 24.48 | 1 | -90.0 |
| 2 | 48.96 | 6.40 | -174.3 |
| 3 | 73.44 | 17.52 | -188.3 |
| 4 | 97.92 | 35.04 | -196.9 |
| 5 | 122.40 | 60.94 | -203.8 |

3.2 Waveform Manipulation

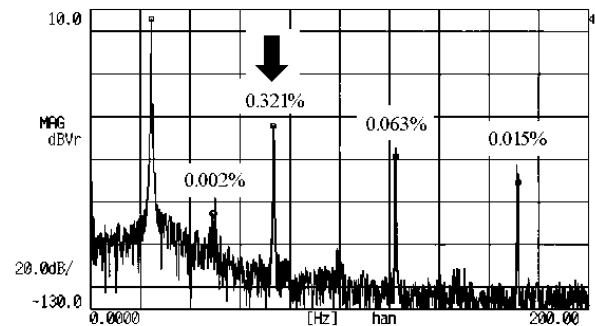


Figure 4: Typical spectrum of the magnet current.

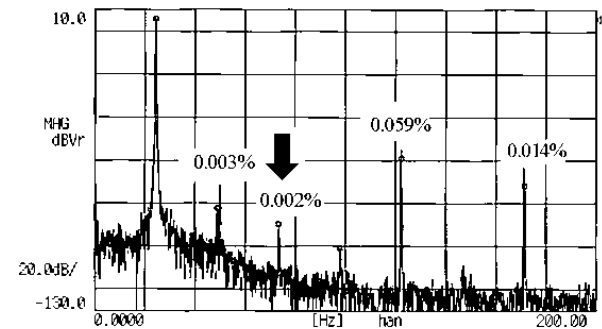


Figure 5: Spectrum of the magnet current after a harmonic correction.

Waveform manipulation of the magnet current has been tried by mixing the harmonic contents with the fundamental one in a reference signal for the power supply. Here, the dummy magnet was excited up to the limit of the power supply in order to saturate the magnet core as much as possible. The magnet current was measured by a current transformer, and was fed into a spectrum analyser. The results are shown in Figs. 4 and 5.

Fig. 4 is the spectrum of the magnet current without a harmonic correction. As shown, peaks with odd order are dominant due to saturation of the dummy magnet. A harmonic correction aiming at the peak of the third harmonic was performed. As shown in Fig. 5, the target peak, indicated by an arrow, was successfully reduced from 0.321% to 0.002%, while other harmonics were not affected. Here, the amplitude and the delay time of the third harmonic were adjusted to be 5.8% of the fundamental amplitude and 2.23ms, respectively. Similarly, the peak of the fifth harmonic was also successfully cancelled by adjusting the amplitude of 4.0% and delay of 0.77ms.

4 DISCUSSION

As mentioned above, harmonic manipulation was successfully demonstrated. Using eqs. (4), the voltage waveform of the n th harmonic is obtained in terms of the n th harmonic of the magnet current, as follows:

$$v_n = \pm \zeta_n \cdot (a_n \cos(n\omega t - \vartheta_n) + b_n \sin(n\omega t - \vartheta_n)) \quad (5)$$

Here, a_n and b_n are the usual n th Fourier amplitudes of the magnet current, i.e., $|I_n|^2 = a_n^2 + b_n^2$. The negative sign is needed for waveform cancellation. Otherwise, the positive sign is used. The above equation can be simplified to the following expression:

$$v_n = \zeta_n \cdot |I_n| \sin(n\omega t - \delta_n) \quad (6)$$

Here, v_n is the n th harmonic of output voltage, and δ_n is given by

$$\delta_n = \frac{\pi}{2\omega} \left(1 - \frac{1}{n}\right) + \frac{\vartheta_n + \phi_n[\pm\pi]}{n\omega} - \frac{\vartheta_1 + \phi_1}{\omega} \quad (7)$$

ϕ_n is defined by: $\phi_n = \tan^{-1}(b_n/a_n)$. Either $+\pi$ or $-\pi$, enclosed by square brackets, on the right-hand side is needed to negate the sign of the amplitude to cancel the n th peak. On the other hand, this term must be omitted in the case of waveform formation. Finally, the following relation between the n th harmonic and the fundamental one is obtained:

$$\left| \frac{V_n}{V_1} \right| = \left| \frac{I_n}{I_1} \right| \cdot \left| \frac{Z_n}{Z_1} \right| = \left| \frac{I_n}{I_1} \right| \cdot \frac{\zeta_n}{\zeta_1} \quad (8)$$

In our case, the required voltages for harmonic manipulation of the magnet current are summarized in Table 2. In this way, waveform manipulation of the magnet current can be performed. As shown in the table, both the estimated amplitude and the phase for

cancellation of the third and fifth harmonics are consistent with the actually adjusted values within a few percent.

Table 2: Required voltage for harmonic cancellation.

| n | ϕ_n (deg) | $ I_n/I_1 $ | $ V_n/V_1 $ | δ_n (ms) |
|-----|----------------|-------------|-------------|-----------------|
| 1 | 33.6 | 1.0 | 1.0 | 20.42 |
| 2 | -136.4 | 0.00002 | 0.000128 | 4.1 |
| 3 | 95.2 | 0.00321 | 0.0562 | 2.9 |
| 4 | - | $<10^{-5}$ | - | - |
| 5 | 164.3 | 0.00063 | 0.0384 | 1.4 |

The compensation of field saturation is one of applications of waveform manipulation. A flat-bottom formation and so-called dual-frequency operation are other applications in the RCS. These possibilities have been already demonstrated by introducing a switching device to the resonant network[3,4]. The disadvantage of this method is that a switching device is needed in each mesh. Therefore, it becomes difficult to synchronize the switching timing as the number of mesh becomes large. Harmonic manipulation may be an alternative method to achieve such waveforms without any modification of the resonant network. However, this method requires a large reactive power to the ac power supply, while the resonance condition is almost satisfied in the switching method so that the reactive power can be reduced. This is one reason to adopt a resonant network in the RCS. Harmonic manipulation is expected to be useful in order to perform a slight modification of the current waveform. However, it seems not to be practical to apply this method to large-waveform modification.

5 CONCLUSION

Waveform manipulation of the magnet current, aiming at a specific harmonic content, has been successfully demonstrated. The adjusted voltage and the phase of the reference signal were consistent with the estimation using a transfer impedance of the model system. In this way, harmonic manipulation is expected to be useful for a slight modification of the waveform of the magnet current in the resonant network.

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