DEVELOPMENT OF A FEEDBACK CONTROL SYSTEM FOR RESONANT POWER SUPPLIES IN THE J-PARC 3-GeV SYNCHROTRON

Y.Watanabe#, N.Tani, J-PARC/JAEA, Tokai, Ibaraki, JAPAN

Abstract

In the J-PARC RCS (Rapid Cycling Synchrotron), dipole and quadrupole magnets are excited using resonant circuits. This paper proposed a feedback control to improve the amplitude and phase stability, especially against variation of capacitance caused by temperature characteristics in the resonant circuit. The control system has been successfully demonstrated and achieved amplitude and phase stability under ±0.005% and ±0.5 uS, respectively.

INTRODUCTION

The main magnet of the J-PARC RCS consists of 24 dipole magnets and 60 quadrupole magnets. Dipole magnets are excited from one resonant circuit, and quadrupole magnets are excited from individual seven resonant circuits. Their current pattern is DC-biased 25-Hz sinusoidal waveform. In case of the resonant circuits, a disturbance factor for the current stability is mainly capacitance variation. Insulation material of the capacitor is oil-cooled polypropylene film which has temperature characteristics of −0.05%／℃. In the J-PARC RCS, the capacitors in the resonant circuit are installed outdoors, therefore variation of outdoors air temperature directly influences to the capacitor. To stabilize the magnet current against capacitance variation, it is possible to be increased feedback gain of the power supply; however, its may causes to be unstable control.

This paper proposes a control method for stabilization of the resonant power supply. The method focuses on capacitance variation affect only fundamental component, performs to feedback fundamental amplitude and phase component obtained from FFT in the magnet current waveform. The control system has been demonstrated by the QFN power supply which is the most large-scale in the quadrupole family.

REQENCY CHARACTERISTICS

Figure 1 shows a resonant circuit of the QFN magnet power supply. The QFN resonant circuit consists of twelve magnets, one choke-transformer, seven capacitor-banks and one power supply. Magnet inductance L_m, choke-transformer inductance L_{ch} and capacitor-bank capacitance C are following equation.

$$\omega = \frac{1}{2\pi\sqrt{LC}} = 25Hz \cdot \quad (1)$$

$$L = \frac{L_m \cdot L_{ch}}{L_m + L_{ch}} \cdot \quad (2)$$

#yasuhiro.watanabe@j-parc.jp

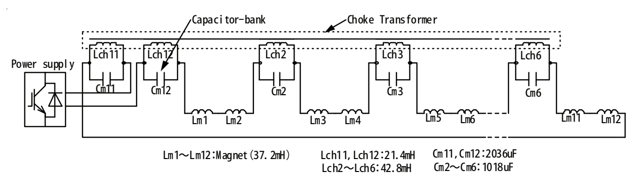

Figure 1: Resonant network of the QFN.

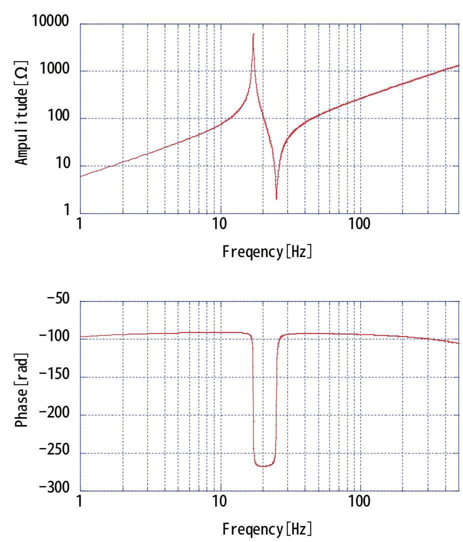

Figure 2: Frequency characteristics of the QFN impedance.

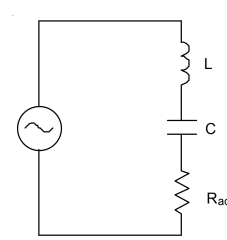

Figure 3: Equivalent circuit of the resonant circuit.

Figure 2 shows frequency characteristics of the impedance in the QFN resonant circuit. The minimum impedance is 1.3 Ω at the resonant frequency 25 Hz. Peak of the impedance at the frequency 17 Hz is anti-resonance due to the resonance between choke transformer and the capacitor. More than 30 Hz can be regarded as an inductance because phase lag is about 90 degrees. Therefore, it is sufficient to consider only the fundamental component of the capacitance variation.

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INCREASING THE IMPEDANCE CAUSED BY CAPACITANCE VARIATION

Figure 3 shows an equivalent circuit of the resonant circuit. In case of the capacitance is changed to C + ΔC from C, increase ratio of the impedance, $|Z_1|/|Z_0|$ is as follows.

$$\frac{|Z_1|}{|Z_0|} = \frac{\sqrt{R_{ac}^2 + (\omega L - 1/\omega(C+\Delta C))^2}}{\sqrt{R_{ac}^2 + (\omega L - 1/\omega C)^2}} . \quad (3)$$

R_{ac} is AC resistance. The Q factor in the resonant circuit is as follows.

$$Q = \frac{1}{\omega C R_{ac}} . \quad (4)$$

Substituting Eq. (1) and Eq. (4) into Eq. (3) yields

$$\frac{|Z_1|}{|Z_0|} = \sqrt{1 + Q^2\left(\frac{\Delta C}{1+\Delta C}\right)^2} . \quad (5)$$

Δ C is small, Eq. (5) can be approximated as follows.

$$\frac{|Z_1|}{|Z_0|} = \sqrt{1 + Q^2 \Delta C^2} . \quad (6)$$

It is assumed that variation of outdoors air temperature is equal to the variation of the inside capacitor temperature. In case of variation range of the outdoor air temperature is defined as ±20 degrees, the capacitance changes ±1%. The Q factor of the QFN is 98. From Eq. (6), increase ratio of the impedance is 1.4.

PROPOSED CONTROL SYSTEM

Figure 4 shows a system configuration of the control system for the main magnet power supplies. This system comprises of timing unit, VME crate, 16-bit ADC and 16-bit DAC, and control PC. To synchronize 12 MHz J-PARC master clock for all power supplies, the timing unit makes 100 kHz clock from the 12 MHz, and distributes 100 kHz clock and trigger 25 Hz for all ADC, DAC and DO (Digital Output). The VME crate includes one CPU board with Ethernet controller and nine 16-bit DO boards. One-cycle (40ms) current pattern data (16-bit, 4000 points) were written by the PC via Ethernet, the DO board outputs current reference pattern synchronized 100 kHz clock. The ADC includes two channel 16-bit 100 kHz

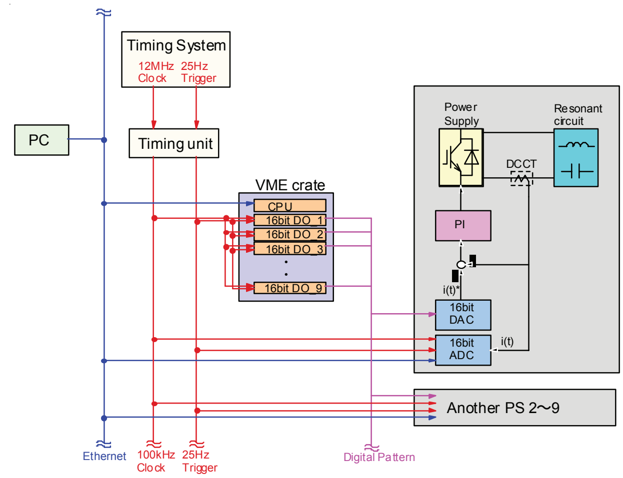

Figure 4: System configuration of the power supply control.

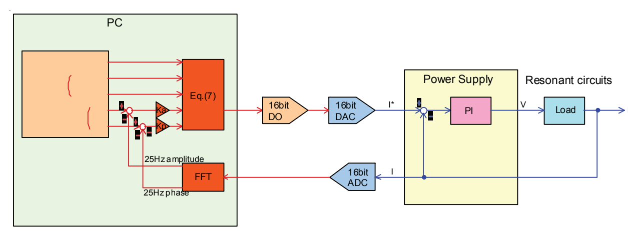

Figure 5: Block diagram of the proposed control.

ADC, and records the output current and the output voltage waveforms synchronized 100 kHz.

Figure 5 shows a proposed control block for magnet power supply. Control sequence is below. Feedback cycle of the control is about 30 seconds.

(1) The ADC digitizes the current waveform measured by the DCCT during one second (25-cycles).

(2) The PC takes data from the ADC via the Ethernet and to FFT analysis.

(3) Time-domain setting-current pattern, $i(t)^*$ is produced by following equation.

$$i^*(t) = I_0^* + K_a(I_1^* - I_1)\cos\left(\omega t + K_p\left(\alpha_1^* - \alpha_1\right)\right) + \sum_{n=2}^{10} I_n \cdot \cos\left(n\omega t + \alpha_n\right) . \quad (7)$$

I_0, I_1 and α_1 are DC, 25-Hz amplitude and 25-Hz phase of the measured current, respectively. I_0^*, I_1^* and α_1^* are DC, 25-Hz amplitude and 25-Hz phase of the setting current, respectively. K_a and K_p are amplitude and phase feedback gain, respectively. To force sinusoidal

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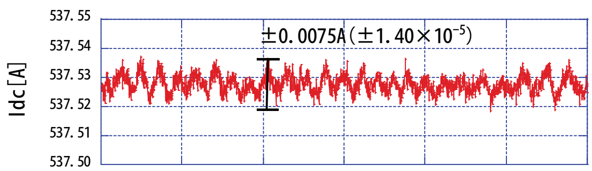
magnetic field, the current reference pattern is mixed with harmonic component as shown the third term of Eq. (7). As mentioned above, feedback control for the DC and the harmonic component is not necessary because the capacitance variation is not affect DC and the harmonic component.

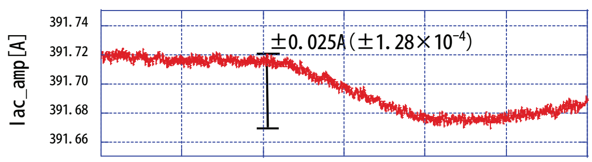
(4) Calculated current reference pattern data are translated for CPU board and it gives the DAC through the DO.

EXPERIMENTAL RESULTS

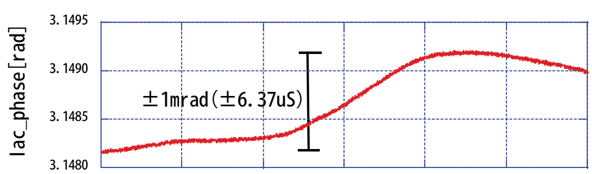
Figure 6 and Figure 7 show long-term stability of the QFN power supply without and with proposed control, respectively. In case of without feedback control, DC component I_0 is stable, however, 25Hz amplitude I_1 and phase α_1 drift according to the outdoor air temperature. In case of with feedback control, 25Hz amplitude and phase stability under ±0.00255% and ±0.32 uS, respectively.



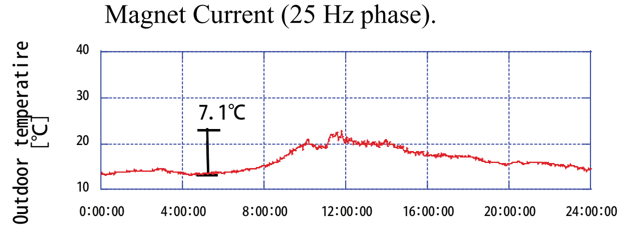
Magnet Current (DC component).



Magnet Current (25 Hz amplitude).



Magnet Current (25 Hz phase).

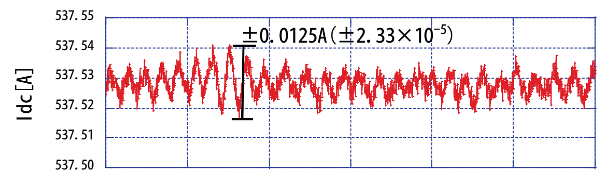


Outdoors air temperature.

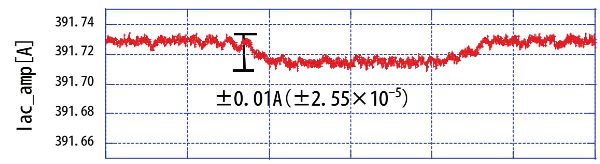
Figure 6: Long-term stability the QFN power supply without proposed control during 24-hours.

CONCLUSION

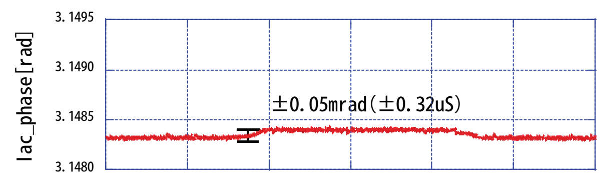
The feedback control system has been developed for the resonant power supply in J-PARC RCS. Stability of the all power supplies have been achieved amplitude and phase stability under ±0.005% and ±0.5 uS, respectively.



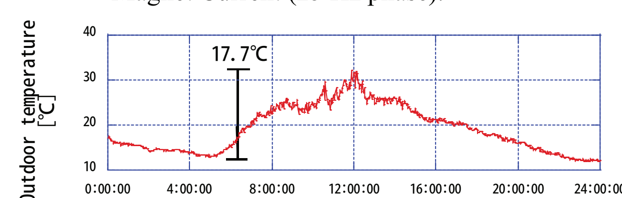
Magnet Current (DC component).



Magnet Current (25 Hz amplitude).



Magnet Current (25 Hz phase).



Outdoors air temperature.

Figure 7: Long-term stability the QFN power supply without proposed control during 24-hours.