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UPGRADING MAGNET POWER SUPPLY SYSTEM IN J-PARC MAIN RING

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Abstract

To increase the beam power of the main ring (MR) in the Japan Proton Accelerator Research Complex (J-PARC), the magnet power supply (PS) system for the MR was upgraded during the long-term shutdown period of the MR in FY2021. Therefore, a wide range of works were carried out, including the installation of new PSs, rearrangement of existing PSs, splitting of magnet families, and cable rewiring. The upgrade was successfully completed, and beam extractions to the experimental targets began.

INTRODUCTION

The repetition rate of the main ring (MR) cycle was increased from 2.48 s to 1.36 s to enhance the beam power of the MR. The beam power of the MR is scheduled to be upgraded up to 750 kW and above to satisfy the requirement from the T2K long-baseline neutrino experiment [1]. This can be achieved by shortening the acceleration period and the time interval between the beam bunch injection and extraction. The patterns of the excitation current for the bending magnet (BM) before and after high-repetition-rate operation are shown in Fig. 1.

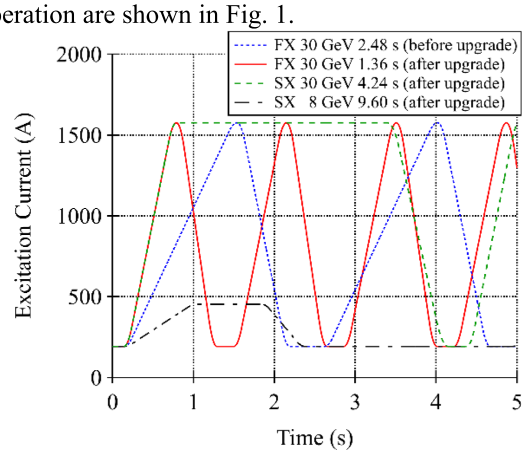

Figure 1: Patterns of the excitation current for BM before (2.48 s) and after (1.36 s) the upgrade. The patterns for the slow extractions (9.60 s and 4.24 s) are also shown.

The crucial point for the success of this scheme is the upgrade of the magnet power supply (PS) system, which involves two serious issues [2]. First, the output voltage increases by approximately twice that before the upgrade; consequently, the output voltage exceeds the rated voltage of the existing PS. Second, the power fluctuation in the electrical system, which is induced by the large energy transport between the magnets and electrical system in each MR cycle, is large. This study introduces a scheme to solve these issues, and reports the works done in FY2021 and the achievements of this upgrade.

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SCHEMES

The introduction of a PS with a high withstand voltage is a fundamental solution for increasing the output voltage. To suppress the power fluctuations in the electrical system, a capacitive energy storage system equipped with capacitor banks was employed. At least six BM PSs are required to be equipped with capacitor banks to avoid the power fluctuation exceeding the value before the upgrade. Three new buildings were constructed for the installation of six new BM PSs because of the shortage of space in existing buildings. Owing to limited budgets, new PSs were not assigned to all magnet families; instead, existing PSs were reused and rearranged for several magnet families.

New PS and Capacitor Bank

A schematic of the proposed PS is shown in Fig. 2. Six DC/DC converters with a rated voltage of 1650 V were connected in series to achieve a rated voltage ± 5.5 kV peak [3]. Most of the power is transferred between the capacitor banks and magnets in each MR cycle. Only resistive loss is supplied by the electrical system. The primary focus of the design of the capacitor bank was safety because the maximum stored energy reaches approximately 4 MJ for a single PS. A dry-type self-healing film capacitor was used to eliminate issues pertaining to gas pressure and flammability. A fuse was connected in series to the storage capacitors to prevent fault propagation. Schemes for energy concentration limitation and controlled energy dissipation were studied [4].

Reuse of Existing PS

Two approaches were adopted for using the existing PSs. First, the PS with a high withstand voltage that was used for the magnet family with high inductance was reassigned to that with low inductance. Second, the impedance of the magnet family was halved by reducing the number of magnets in a single PS. A summary of these rearrangements is provided in Table 1.

The large-scale PS that excited the magnet family with a high inductance was reused in the magnet family with a low inductance to realize the operation of a 1.36-s cycle involving the doubled output voltage. An example of a QFR magnet family is presented in Table 2. The rated output current and voltage were not the absolute criteria for this rearrangement. The large-scale PS mismatched the

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magnet family requiring a small output current at the flat-bottom period because controlling the output current with a small pulse width using a high-power switching device is difficult. The plan for the PS rearrangements was carefully prepared based on circuit simulations.

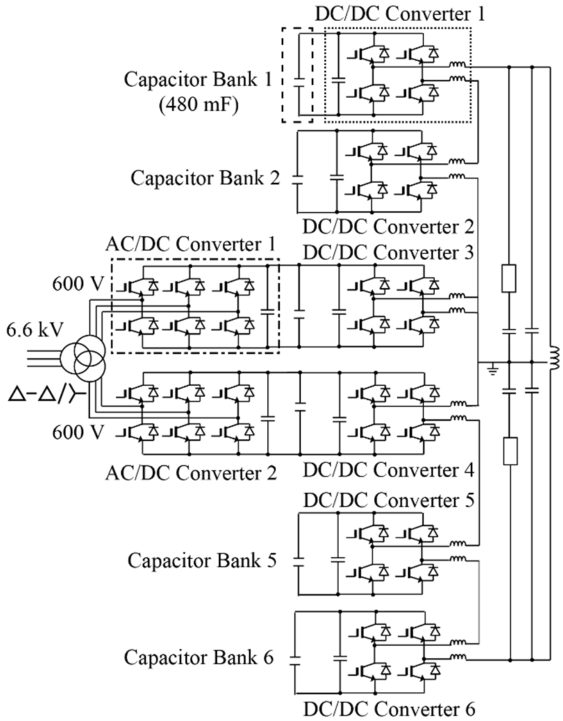

Figure 2: Circuit schematic of new BM PS.

Table 1: Summary of Upgrade

Family - 2021	Family 2022 -	Assignment of PS
BM1-6	BM1-6	new PS with C-BANK
QDN	QDN	new PS with C-BANK
QFN	QFN	new PS with C-BANK
QDX	QDX1	former BM5 PS
	QDX2	former BM6 PS
QFX	QFX1	former BM1 PS
	QFX2	former BM2 PS
QFP	QFP	former QFR PS
QDR	QDR	new PS without C-BANK
QFR	QFR	former QDX PS
QDT	QDT	new PS without C-BANK
QFT	QFT1	former QFT PS
	QFT2	former QDT PS
QDS	QDS1	former QDS PS
	QDS2	former QDR PS
QFS	QFS1	former QFS PS
	QFS2	former QFP PS
SDA SDB	SD	new PS without C-BANK, family integration
SFA	SFA	new PS without C-BANK

Table 2: Example of PS Replacement (QFR)

	Previous	New
Rated output current	1038 A	1037 A
Rated output voltage	800 V	2100 V
Output power (peak)	0.81 MW	2.07 MW

Some magnet families were split into two, and the peak output voltage of a single PS was expected to be acceptable even after the upgrade. To realize this method, a wide range of wiring works was performed in the PS buildings, MR tunnel, and sub-tunnels that connect the PS buildings and MR tunnel. An example of a family split is shown in Fig. 3, where the large and small rectangles represent PSs and magnets, respectively. The connections of the power cables that originally traced all six QDS magnets in the MR tunnel were rewired. Subsequently, two QDS families with identical numbers of magnets were created. Although this new topology breaks the optical symmetry, the total cable length is minimal, which contributes to cost reduction. In addition to the family split, some existing power cables were replaced to satisfy the voltages required after the upgrade.

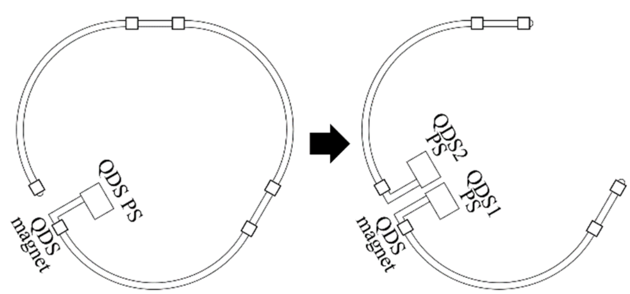

Figure 3: Family split of QDS.

WORKS

The PS system was upgraded during the shutdown period, from July 2021 to March 2022.

Some existing PSs that were no longer in use were removed, and newly delivered PSs were installed. Important parts were disassembled from the removed PSs and kept as spare parts.

As mentioned in the previous section, a wide range of wiring work was performed. The total lengths of the power and control cables were 35 km and 12 km, respectively. The wiring in the high-dose area was carefully planned to minimize the radiation doses to the workers. After wiring was completed, a continuity check of the wired cables and impedance measurements of the magnet families were performed. Wiring failures were corrected immediately upon discovery. However, these confirmation schemes cannot identify the magnetic polarity faults. Even if the power cables for the positive and negative terminals are swapped, the impedance of the magnet family remains normal. Hence, no signs of failure were observed during PS operation. Therefore, magnetic field measurements were conducted for the magnets that underwent rewiring. The target

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magnet family was excited using a small amplifier. The output current was limited to 12 A to avoid serious damages in the case of wiring failure. The magnetic fields generated were measured using a portable gaussmeter. The measured values were approximately 10-20 mT. These values are sufficiently larger than the residual magnetic field of approximately 3 mT. Owing to the magnetic field measurements, polarity failures were found in the three magnet families before the PS commissioning started.

The output currents of the PSs were calibrated [5]. The output current of each PS was measured using an identical current sensor. The accuracy of this portable current-measurement system was less than 1 mA. The output currents before and after the upgrade were measured, and the obtained calibration factor was applied to the software for current pattern generation. Consequently, the difference between the output currents before and after the upgrade was reduced to less than 10 mA. This value is sufficiently smaller than the output current deviation of approximately 100 mA.

PS COMMISSIONING

The PSs were tuned for stable operation with three types of excitation current patterns, depending on the beam destinations. The first is the fast extraction (FX) mode, which has already been described. The second and third were slow extraction (SX) modes of 30 GeV and 8 GeV, respectively, which were used for the hadron experiments. An example of excitation current pattern of a BM PS is shown in Fig. 1.

Here, the control method of the new BM PS (Fig. 2) is introduced. DC/DC converters 1, 2, 5, and 6 were commanded to drive the inductive components of the magnets with feedforward control. The reference patterns of the output voltages of these four converters are determined in such a way that the energy balance during one cycle is equal to zero to drive pure inductance. The difference between the measured and reference output voltages is automatically compensated for by DC/DC converters 3 and 4, which are controlled by the feedback control of the output current. Herein, the sharing ratio of the output voltage between the sets of DC/DC converters 1, 2, 5, and 6 and DC/DC converters 3 and 4 was tuned to make the maximum voltage of each DC/DC converters balanced. Note that the DC/DC converters 1, 2, 5, and 6 should remain active during the flat-top period in the SX 30 GeV mode, although the inductive effect can be ignored in this DC state. This behavior suppresses the input power below the rated power of the transformer, whereas capacitor banks 1, 2, 5, and 6 are forced to discharge during the flat-top period. Thus, sufficient time for recharging these four capacitor banks must be saved in the period of current ramp-down [6]. Additionally, the tracking errors of the output current that appear at the beginning and end of the current ramp-up were successfully compensated for by the learning control scheme [7, 8].

The input power of the MR in the FX mode was effectively suppressed compared with that without capacitor banks. The measured input and output power of a single BM PS are shown in Fig. 4. The fluctuation range of the input power was approximately 1/7 that of the output power. Note that if the energy storage system is not equipped, the curve of the input power should be almost identical to that of the output power.

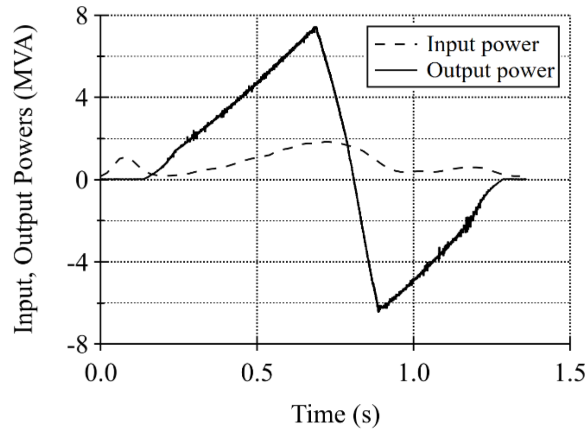

Figure 4: Input and output powers of a single BM PS during a single cycle of 1.36 s. The output power is derived by multiplying the output current and voltage. The input power is obtained by multiplying the root-mean-squares of the input current and voltage.

BEAM TEST

The first beam was extracted smoothly after stable 2000 turns in July 2022, owing to careful confirmations of the wiring.

The horizontal beam ripple in the flat-bottom period in the FX mode was measured using beam position monitors (BPMs) at high-dispersion positions. As shown in Fig. 5, the beam ripple under 200 Hz was improved compared with that before the upgrade. This result is consistent with the Fourier spectra of the measured current ripples of the old and new BM PSs [3].

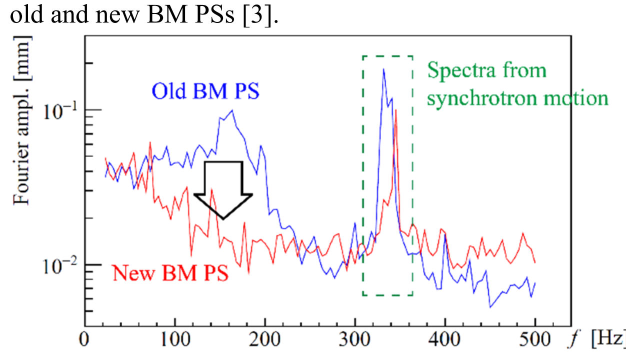

Figure 5: Fourier spectra of horizontal beam positions obtained every 1 ms by BPMs at high-dispersion positions. The blue and red lines represent the results before and after the upgrade, respectively [9].

The beam study of FX 1.36 s with a 30-GeV acceleration began in April 2023. Finally, a beam power of 760 kW was obtained (only in a single cycle mode). This result suggests the continuous beam power of the MR above its original design value of 750 kW is promising [9]. Furthermore, the SX 9.60 s mode was successfully operated and used for a hadron experiment from February to March 2023.

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