Nuclear Instruments and Methods in Physics Research A 747 (2014) 24–29

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Development of a magnet power supply with sub-ppm ripple performance for J-PARC with a novel common-mode rejection method with an NPC inverter

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ARTICLE INFO

Article history:
Received 15 January 2014
Received in revised form
5 February 2014
Accepted 11 February 2014
Available online 18 February 2014

Keywords:
Magnet
Power supply
Common-mode noise
NPC inverter

ABSTRACT

The mechanism that generates common-mode noise in inverter circuits, which are widely used in magnet power supplies, was evaluated by a circuit simulation. By following asymmetric operational sequences, pulsed voltage is applied to the parasitic capacitance of power cables that causes a common-mode current at each switching period of the semiconductor switches. Common-mode noise was also found to disturb the normal-mode excitation current by inducing higher frequency components in the applied voltage to the magnet. To eliminate the disturbing effect by the common-mode noise, a newly developed operational method that uses a neutral point clamped, NPC, inverter with reduced switching sequences was evaluated both by a circuit simulation and experimentally. The operational method for the NPC inverter could sufficiently reduce the common-mode noise. A high-power test operation performed using 16 bending magnets at the J-PARC facility achieved a ripple of less than 1 ppm in the excitation current.

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1. Introduction

One of the most important projects at the J-PARC [1] is the T2K experiment [2] in which the neutrino oscillation process is detected by using accelerator-driven high-intensity neutrino beams to produce extremely rare neutrino interactions. The physics of T2K includes the search for CP violation in the lepton sector. For this purpose, various research and development projects for future upgrades of the accelerator complex toward a multi-MW class beam power are underway. The synchrotron magnets must be excited by an extremely-high-precision current to avoid beam loss during multi-MW operations. Thus, a new magnet power supply with output current ripple of less than 2 ppm is required.

A measured frequency spectrum of the magnetic field deviation of a bending magnet of main ring synchrotron is depicted in Fig. 1. The measurement was performed using the existing power supply with the excitation current of 193 A, which corresponds to the injection energy of 3 GeV. The ripple component around 100 Hz is excited by the resonant coupling between the magnet inductance and a cable capacitance because the wiring between the synchrotron magnets and the power supplies at J-PARC is achieved by high-voltage power cables that have a coaxial electrostatic shield around the conductor. A rectification ripple by a converter circuit of the magnet power supply at 600 Hz and its harmonic components are also seen. It is reported that a common-mode noise current [3,4] is also generated in the magnet network due to a parasitic cable capacitance between the conductor and the ground potential. In order to achieve the ripple performance required for the future intensity upgrade of J-PARC, it is important to configure the magnet network, composed of the magnets and the power cables, in an electrically symmetrical manner to reduce the disturbing effect by the common-mode noise. Moreover, it is important to reduce the driving force of the common-mode noise in the magnet power supply because the perfect symmetry cannot be achieved due to the dispersion of electrical components in the magnet network. Although a filter circuit to reduce the normal-mode noise current is used in the magnet power supplies [5], no sufficient countermeasure is applied for the common-mode noise current. To achieve the precision required for the magnet power supplies for the future upgrade in J-PARC, effects from the common-mode noise must also be taken into account carefully.

Various filter circuitries have been developed and applied to reduce the common-mode noise in various applications. The common-mode transformer method uses a bifilar wound transformer at the output terminal to pick-up and to damp the common-mode current by a damping resistor at the secondary windings. In this method, power

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http://dx.doi.org/10.1016/j.nima.2014.02.025
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dissipation at the damping resistor, which is dependent on the load impedance, should be carefully estimated for a cooling system during design period. A wide-band frequency characteristic is also required for the transformer due to the higher frequency components generated by semiconductor switches. A by-pass capacitor method with a damping resistor in series is also effective to reduce the common-mode noise. But considerable attention should be paid to the design procedure to avoid a malfunction of surrounding electrical components by a higher-frequency by-pass current. In an active canceling method, a common-mode voltage or a current is detected. An opposite-phase voltage or current is applied by a transistor for the active cancelation of the common-mode noise. A wide-band frequency characteristic can be achieved when the transistor is activated in its linear region. A sufficient cooling system, which is required for the transistor to secure the stable operations, may cause an enlargement of the magnet power supply. Although each method can reduce common-mode noise to a certain extent, a careful consideration is required during the design period for the cooling system or the frequency response. Moreover, an enlargement of the power supply system may be the critical disadvantage for an existing accelerator complex such as J-PARC.

It is known that a magnet power supply which does not generate the driving force of the common-mode noise is the drastic solution for the problem. Therefore, a new operational method of a neutral point clamped, NPC, inverter to eliminate the common-mode noise in principle is developed and evaluated.

In this paper, the mechanism that generates common-mode noise current in conventional inverter circuits, which are widely used in accelerator magnet power supplies, is evaluated by a circuit simulation. Moreover, a newly developed operational method that uses an NPC inverter to eliminate the disturbing effects of common-mode noise current is reported. Successful high-power operation to evaluate the performance of the newly developed NPC inverter with bending magnets at J-PARC is also reported.

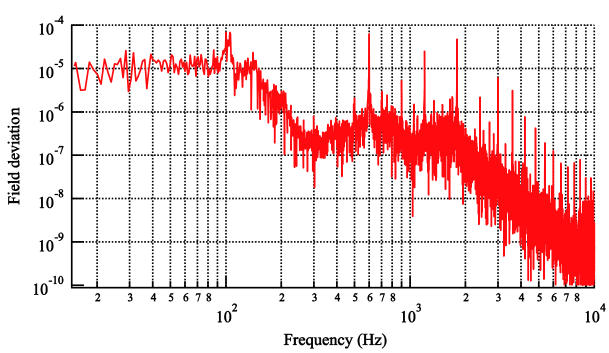

Fig. 1. Frequency spectrum of the measured magnetic field deviation of a bending magnet of J-PARC MR.

2. Common-mode noise

Magnet power supplies utilize a full-bridge circuit, also known as an inverter circuit, that uses insulated gate bipolar transistors (IGBTs) to precisely control the high-power output current. The high-frequency ripple current caused by switching of the IGBTs is suppressed by a low-pass filter. Conventionally, the low-pass filter is used to dump the normal-mode current ripple. No adequate method to reduce the common-mode ripple current is typically installed. In the development of a magnet power supply with the required extremely low output ripple, the effects of common-mode noise should be taken into account. In this section, the mechanism that generates common-mode noise current in a conventional inverter circuit is evaluated.

The schematic of an inverter circuit is shown in Fig. 2. Here, V_c is the voltage across a capacitor bank and S1–S4 are semiconductor switches such as IGBTs. P and N indicate the positive and the negative output terminals, respectively, which are connected to filter circuits and magnets. To generate a positive output voltage, the inverter circuit repeats the following two operational sequences at a particular switching frequency:

Sequence (a)
By triggering S1 and S4, the voltage of the P terminal with respect to the ground potential tends to V_c and the N terminal tends to 0 V. The positive voltage, V_c, across the output terminals induces a current flow to the magnet as indicated by the dashed line. In this operational sequence, S2 and S3 remain in the off state.
Sequence (b)
Immediately after turning off S4, S3 is triggered. The current loop changes as indicated by the dashed line. The inverter circuit therefore goes into a flywheel mode in which there is no voltage difference across the output terminals. During this operational sequence, the voltage of both output terminals is V_c with respect to the ground potential.

Conventionally, the wiring between magnets and power supplies consists of high-voltage power cables with a coaxial electrostatic shield. A parasitic capacitance thus exists between the conductor and the ground potential. Therefore, when the voltage of an output terminal with respect to the ground potential fluctuates, a common-mode noise current flows from the power supply to the ground potential to charge and discharge the parasitic cable capacitance. An equivalent circuit model of

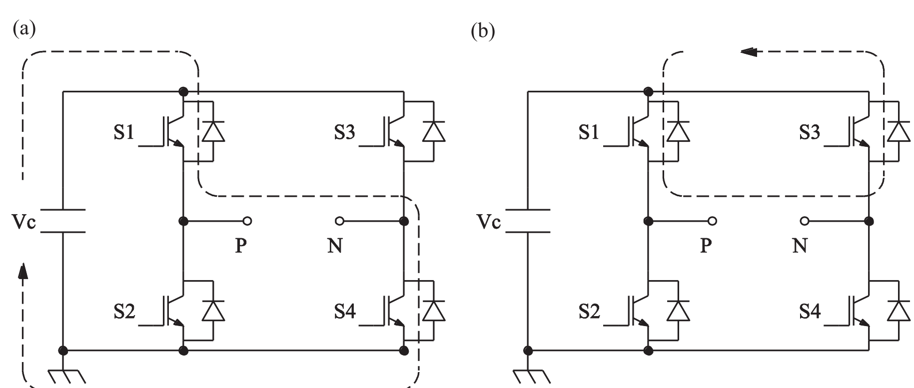

Fig. 2. Operational sequences of an inverter circuit with positive output voltage.

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