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Development of the 320 kA pulsed magnetic horn power supply with a novel energy recovery system for the T2K experiment

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ABSTRACT

The 320 kA pulsed magnetic horn power supply with a novel magnetic energy recovery system for the T2K experiment has been developed. The magnetic energy once stored in the horn system during an excitation period by a pulsed current of 320 kA is recovered by a full-bridge circuit to the energy storage capacitors. Four switching arms by high-power thyristors in the full-bridge circuit are actively controlled for an efficient energy recovery process. Operational principle of the energy recovery system was proved by both the simulation study and the high-voltage test operation. Successful operations of the newly developed pulsed magnetic horn power supply were also confirmed by high-voltage test operations.

1. Introduction

The long baseline neutrino oscillation experiment, T2K [1], had been started in 2010. A proton beam accelerated up to 30 GeV by the main ring synchrotron of J-PARC [2] is extracted by kicker magnets [3] and transported to the neutrino beamline. At the end of the beamline, charged pions are produced by collisions with graphite target. Muon neutrinos as decay products travel to the Super-Kamiokande detector [4], which is located 295 km away from the J-PARC site. The primary goals of the T2K experiment include the search for the last unknown mixing angle, θ_{13}, in the lepton sector.

One of the most important aspects for the T2K experiment is the intensity of the neutrino beams to a particular direction, because the interaction of neutrino in the far detector, Super-Kamiokande, is an extremely rare process. For this purpose, magnetic horns [5] are used to forwardly focus the charged pions. By an extremely large excitation current generated at the inner and the outer conductor of the horn, a toroidal magnetic field is produced and used for the focusing. The magnetic horn system for the T2K experiment [6] is required to generate integrated magnetic field of 1.3 Tm to focus pions with the typical transverse momentum of 0.4 GeV/c. Thus the pulsed power supply for the magnetic horn is required to generate pulsed excitation currents of 320 kA. Required parameters of the pulsed magnetic horn system for the T2K experiment are summarized in Table 1.

The pulsed power supply for the magnetic horn is equipped with an energy storage capacitor. By a resonant coupling between the energy storage capacitor and the inductance of the magnetic horn, sharp excitation currents in the time range of few milli-seconds are generated. The required field uniformity is less than 1% for eight proton beams of which the time duration is 1.1 μs. In order to secure the requirement, the pulse width of few hundred of microseconds is sufficient. In this case, the voltage of the energy storage capacitor of more than few tens of kilovolts is required. From the availability of the energy storage capacitor, the pulse width is designed to 4.5 ms. In this short period of time, the magnetic energy of about 150 kJ is transmitted to the magnetic horn from the pulsed power supply. During the falling period of the excitation current, the energy once stored in the magnetic horn should be managed. Conventionally, returned energy from the horn is dissipated by a damping resistor in the pulsed power supply [7,8]. Otherwise, serious disturbances such as flicker or frequency modulation may happen if the magnetic energy is sent back to the AC main grid. The T2K experiment aims to increase its repetition cycle from the current value of 0.5 Hz to increase the neutrino intensity in the future. In that case, hundreds of kW of electrical power should be dissipated at the damping resistor. The thermal stress may influence the reliability in long term operation. Thus, an efficient energy management system for the pulsed magnetic horn power supply should be developed.

In this article, design strategies of the newly developed pulsed magnetic horn power supply for the T2K experiment is comprehensively reported. Results from the successfully conducted test operations are also reviewed.

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Table 1
Electrical parameters of the magnetic horn system for the T2K experiment.

Peak current	320 kA
Pulse width	4.5 ms
Waveform	Sinusoidal
Inductance of the horn	1.5 μH
Inductance of the wiring	1.5 μH
Total resistance	400 μΩ
Energy deposition	200 kJ
Magnetic energy	154 kJ
Repetition rate	0.5 Hz

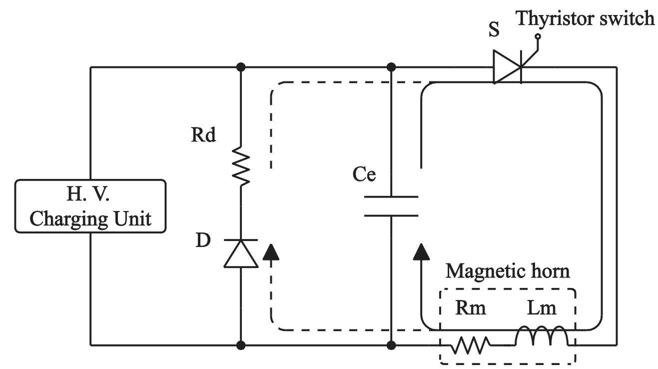

Fig. 1. Conceptual circuit schematic of a conventional pulsed power supply with a damping resistor and a crowbar diode.

2. Energy recovery system

The magnetic horn system for the T2K experiment is excited by a pulsed current of 320 kA. With this extremely large excitation current, total energy deposition at the load system: the magnetic horn, strip lines and high-voltage power cables, is as large as 200 kJ. Total energy of about 350 kJ including the magnetic energy should be managed by the pulsed power supply. Conventionally, magnetic energy returned from the magnetic horn during the falling period is dissipated by a damping resistor to avoid an unacceptable effect in the AC main grid. But the long term reliability of the resistor is one of the serious concerns in the development. On the other hand, there is a method to recover the magnetic energy to the energy storage capacitor again by a crowbar diode. In this method, the recovered energy can be used for the next operational cycle. Thus an efficient operation can be achieved. But for a system with extremely large current, a choke reactor to decrease the peak amplitude of current should be used to reduce the power dissipation at the crowbar diode [9,10]. In this case, energy deposition due to a joule loss and an eddy current loss at the reactor may be serious.

Thus a system which does not require a damping resistor nor choke reactor is developed and employed for the pulsed magnetic horn power supply for the T2K experiment. In this chapter, operational principles of both the conventional system and the newly developed energy recovery method are described.

2.1. Pulsed power supply with damping resistor

Circuit schematic of a conventional pulsed power supply equipped with a damping resistor is depicted in Fig. 1. After the initial charge up to the energy storage capacitor, Ce, by the high-voltage charging unit, a trigger signal is transmitted to the gate terminal of the thyristor switch, S. At this timing, excitation current starts to flow as depicted by the solid line. The discharging process from the energy storage capacitor ends when the voltage across the capacitor drops to zero voltage. As a result, the excitation current reaches the maximum value. During the falling period of the excitation current, negative voltage is induced at the inductive magnetic horn, thus the forward voltage is applied to the crowbar diode. This initiates the conduction of the crowbar diode and the energy deposition at the damping resistor as shown by the dashed line. Results from a simulation study for these processes are shown in Fig. 2(a) and (b) indicate the currents to the magnetic horn and the damping resistor, respectively. (c) shows the voltage change at the energy storage capacitor.

The simple circuit configuration is the main advantage of this method. This method is conventionally used in many applications. Because the energy in the storage capacitor is lost completely after an excitation to the magnetic horn, it is required for the high-voltage charging unit to recharge up the capacitor from zero voltage to the rated voltage again for the next operational cycle. Thus the high-voltage charging unit is required to have a larger output electrical power in a high repetition rate operation. It is

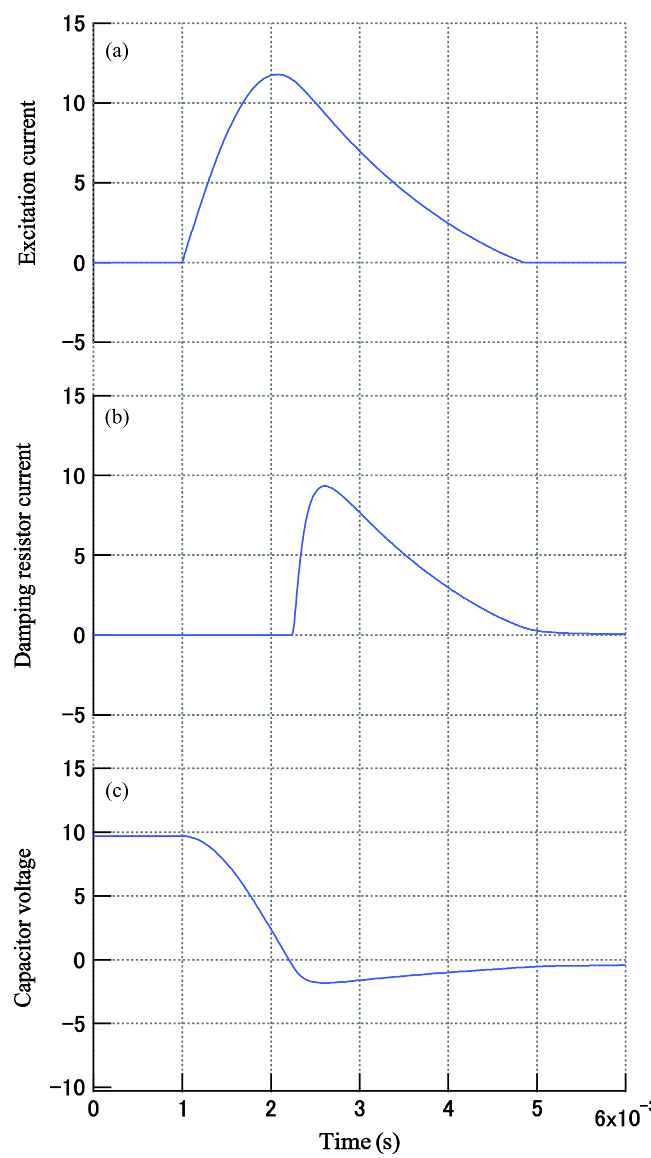

Fig. 2. Simulated excitation current to the magnetic horn (a), the current to the damping resistor (b) and the voltage of the energy storage capacitor (c). During the falling period of the excitation current, the energy stored in the magnetic horn is returned to the pulsed power supply and dissipated at the damping resistor.

also required for an extremely high current application such as for the T2K experiment to develop a damping resistor with sufficiently long life time. Current concentration to tiny area of the