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DEVELOPMENT OF HIGH-CURRENT CORRECTION MAGNET POWER SUPPLY FOR TPS FACILITIES

B. S. Wang, K. B. Liu, and Y. S. Wong
NSRRC, Hsinchu 300092, Taiwan

Abstract

In this paper, the focus is on the development of a bipolar high-current correction magnet power supply for the future TPS-II permanent magnet corrector coil. The maximum output current of the prototype is specified as 20 A, operating at a voltage of 48 V. This configuration enhances the amplitude of the trim magnetic core correction magnetic field, thereby providing greater flexibility in manufacturing the permanent magnet corrector coil. The Danisense DP50-IP-B DCCT is the current feedback component to design a power supply with high current and stability. MOSFETs are configured in a full bridge setup serving as power switches. The driving frequency is set at 40 kHz. Analogue modulation control circuitry and protection circuits ensure precise current control loop modulation. Finally, a hardware prototype circuit is constructed in the power supply laboratory with an input voltage of 48 V, an output current of 20 A, a maximum power of 960 W, and the current ripple component maintained within 400 μA. This validates the control loop design of the prototype, demonstrating the capability to achieve rapid and stable output current performance. The small-signal bandwidth tested using a 1V input reference signal shows a -3 dB bandwidth of 8.51 kHz. Long-term current stability is within ±10 ppm, and the interface is compatible with existing TPS correction magnet power supply interfaces, allowing for direct operation within the current system.

INTRODUCTION

Over the past decade, maintenance personnel at the Taiwan Photon Source (TPS) have been continuously engaged in improvement and enhancement efforts to optimise beam quality and facility performance [1]. In the foreseeable future, TPS is poised to transform energy efficiency. For instance, replacing the existing iron core magnet structures with a permanent dipole, quadrupole, and sextupole magnets is considered within the storage ring. The anticipated benefits of this transformation include a significant reduction in component power dependency, thereby achieving substantial energy savings.

However, this shift necessitates larger trim coils for fine-tuning and correcting the magnetic field deviations of permanent magnets. To meet the requirements of internal correction coils for permanent magnets, a 20-ampere high-current correction magnet power supply has been designed [2]. The increased current capacity provides greater flexibility in magnetic field adjustments while producing permanent magnets and satisfying the requirements of the TPS Fast Orbit Feedback (FOFB) system. FOFB plays a crucial role in maintaining stability in particle beam trajectories by rapidly correcting any deviations caused by external disturbances or system fluctuations.

By incorporating FOFB requirements into the design, the enhanced power bandwidth aims to improve beam stability and reproducibility within the TPS. The primary objective of this study is to address these challenges by adopting a bipolar, high-bandwidth, cost-effective, and compact Danisense DC Current Transformer (DCCT) as the current feedback component for the TPS corrector magnet power supply. This DCCT seamlessly integrates into the new version of the corrector magnet power supply board while retaining the existing TPS correction magnet power supply system interface and protection logic, ensuring maximum compatibility [3].

The High-Current Correction Magnet Power Supply (HCCMPS) development brings numerous advantages, providing a high output current capacity, repeatability, and stability. The performance and reliability of this power supply prototype have been validated through various experiments. However, due to the HCCMPS output power capacity being twice that of the CMPS version, a thorough assessment and update of the Buck power are necessary.

POWER STAGE AND PWM ALGORITHM

The overall configuration of the HCCMPS, as depicted in Fig. 1, comprises the power stage, buck power supply, current feedback circuit, and protection circuit. In the power stage, a full-bridge converter is chosen as the DC-DC power converter for its advantages, primarily its ease of polarity switching and modulation mode operation. This selection results in excellent zero-current crossing characteristics in the output current, generating bipolar voltage and current outputs. The analogue current error signal is processed through a PI compensator and compared with a triangular carrier to develop a 40 kHz pulse-width modulation (PWM) frequency. In PWM modulation mode, two UC3525N components generate positive and negative current PWM signals and a slight bias to enhance control performance at low currents. This configuration aids in low-current control and response speed during zero-crossings. It introduces switching losses in the metal-oxide-semiconductor field-effect transistors (MOSFETs) but simultaneously increases the duty cycle during low currents, enhancing resolution at low currents. The HIP4081A full-bridge driver IC drives four MOSFETs to produce a pulse-modulated voltage waveform. Following this modulation process, the output signal passes through an L-C low-pass filter consisting of two parallel 200 μH output inductors, six 0.82 μF output capacitors, and a damping load. This arrangement effectively eliminates harmonic voltages generated by high-frequency switching, thus correcting the magnet load and achieving the desired output current setting.

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Adjustments to the wire diameter of the output inductor L may be necessary depending on the current output specifications.

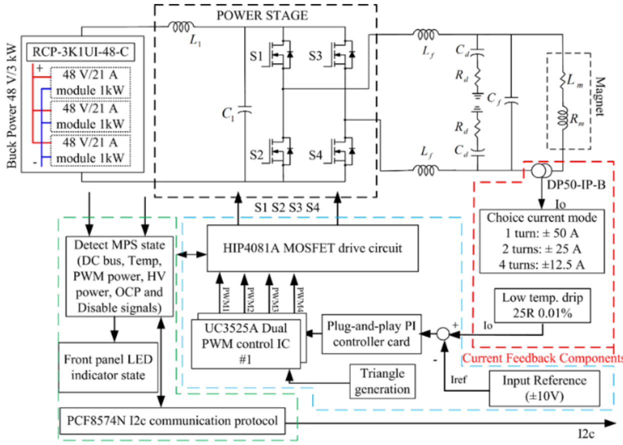

Figure 1: System architecture diagram.

CURRENT FEEDBACK COMPONENT

This version's current feedback component is the Danisense DP50IP-B, known for its high stability and precision in DCCT technology. The key specifications include the ability to measure a maximum current of up to 72 amperes for short durations on the PCB board, linear accuracy within ten ppm, utilisation of zero-flux detection technology, a PCB mount configuration, three selectable current ratings (12.5 A, 25 A, 50 A), a high bandwidth of 300 kHz, and a compact form factor. Its physical appearance is depicted in Fig. 2. The DP50IP-B outputs in current mode and converts this to a voltage signal through an exact, low-temperature coefficient (25R, 0.01 %, VFR B1214) resistor before entering the current feedback control loop for modulation. Regarding cost, the DP50IP-B is notably more cost-effective than the continuously rising prices of LEM DCCT and Shunt versions. A single unit of the Isabellenhutte RUG-Z-R100-0.1-TK1, a 100 mΩ shunt resistor, costs approximately 500 USD. In contrast, the Danisense DP50IP-B comes in at around 250 USD. It offers a cost advantage and boasts a measurement range of up to 25 amperes, making it the primary choice for the current feedback component in the HCCMPS system.

Figure 2: DP50IP-B component.

PCB LAYOUT DESIGN OF HCCMPS

The replacement of the Isabellenhütte RUG-Z-R100-0.1-TK1 component with the Danisense DP50IP-B and the reconfiguration of the output inductor pose initial challenges in designing a structure within limited space to accommodate multiple output inductors and allow for current mode selection with DP50IP-B. Several key considerations are outlined below:

1. Component Layout: Effectively ensuring space for parallel output inductors to handle existing applications of 25A and 50A is crucial when integrating DP50IP-B into the magnetic flux correction design.
2. Current Switching Modes: DP50IP-B offers three current switching modes, enabling jumpers and customised copper plates based on current requirements to ensure sufficient current-carrying capacity.
3. Enhanced Ground Protection: Strengthening the ground area on the PCB's upper and lower layers enhances signal integrity and reduces noise interference. This step ensures improved output current characteristics for HCCMPS.

In Fig. 3., a hardware photo of the completed HCCMPS prototype in our laboratory is displayed. It demonstrates compatibility with the control interface and the current TPS CMPS version. The integration of DP50IP-B and the reconfigured output inductor successfully addresses the challenges posed by the space constraints, and the enhancements in current switching modes and ground protection contribute to the improved performance of HCCMPS in achieving enhanced output current characteristics.

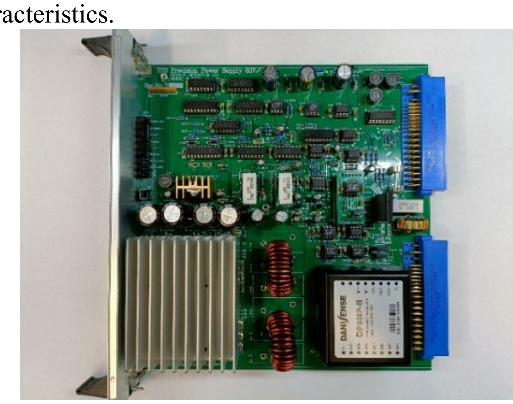
Figure 3: Hardware of HCCMPS converter.

EXPERIMENTAL AND ANALYSIS RESULTS

Several experiments were conducted to validate the current output performance of HCCMPS. These experiments encompassed output current ripple, long-term output current stability, and small-signal bandwidth of the output current. To ensure the accuracy and reliability of the test results, high-precision and high-resolution instruments were employed to measure external output current and stability. The Dynamic Signal Analyzer (DSA) and Ultrastab Saturn Current Sensor (USCT) played pivotal roles in analysing and measuring the output current spectrum.

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Output Current Ripple

Using the HP35670A DSA, output current spectrum analysis was performed within the frequency range of 10 to 6.4 kHz with a high resolution of 1600 points sampling. When the DP50IP-B provides a 20-ampere current, FFT analysis was conducted on the output current, as shown in Fig. 4. The main harmonic power component is at 120 Hz with 58.46 uA, while the total output current ripple remains within 0.4 mA.

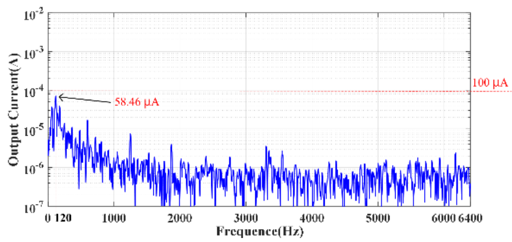

Figure 4: Spectrum of HCCMPS converter.

Stability

We served as recording instruments in the long-term output current stability measurement of HCCMPS, the USCT, and an 8 1/2 high-resolution digital voltmeter (DVM). The stability of ±20 A output current was tested using a quadrupole magnet. Fig. 5 illustrates the measured output current stability of HCCMPS. The output current was set at ±20 A, sampled every 10 seconds, and recorded over an eight-hour duration. The variation in output current remained within 400 µA, indicating a current stability of approximately ±10 ppm.

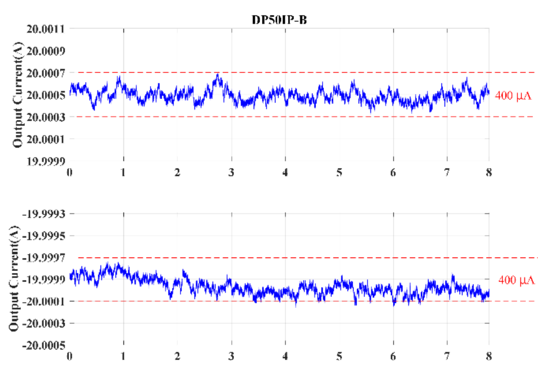

Figure 5: Stability of HCCMPS converter.

Bandwidth

To measure the frequency response of HCCMPS output current using small-signal current perturbation, we primarily utilised the HP 35670A DSA with a frequency sweep sine wave mode. The source function was configured to set DC offset and scaling levels. Fig. 6 depicts the frequency response of the DP50IP-B magnet power supply system when subjected to a 1-ampere signal disturbance. The gain at -3 dB yields a bandwidth of 8.51 kHz, while the phase at -45° occurs at 3.25 kHz. Additionally, Fig. 7 illustrates output current gain and phase curves when perturbed at different voltage levels (1-10 A). It is noteworthy that as the perturbing current increases, the bandwidth decreases. However, the performance remains impressive, especially at 10A output current, where the gain reaches 2.576 kHz, and the phase is at 1.68 kHz. These results suggest that HCCMPS is well-suited for fast correction magnet applications.

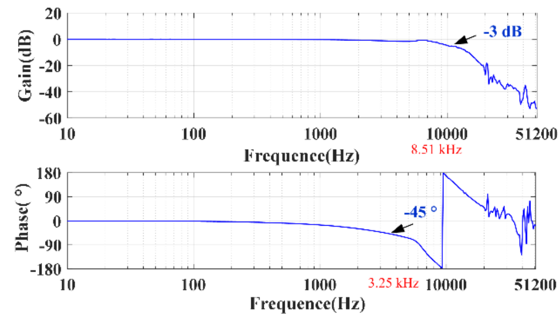

Figure 6: Bandwidth of HCCMPS.

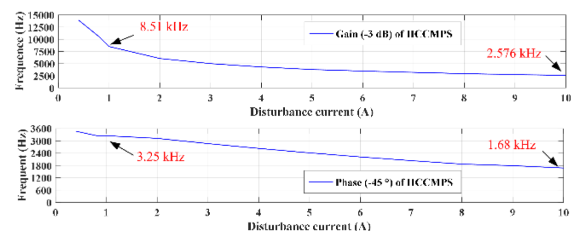

Figure 7: HCCMPS current curve between different disturbance currents and bandwidth.

CONCLUSION

The successful utilisation of the Danisense DP50IP-B as the current feedback component in the HCCMPS system showcases the prototype's impressive output current capacity and demonstrates precise control technology. The outstanding stability of the HCCMPS system's output current is validated by measuring the current performance, exhibiting performance excellence within ±10 ppm in the ±20-ampere output current range. Additionally, the bandwidth and phase performance of the HCCMPS system are notably impressive. The HCCMPS system, with its remarkable output current stability and precise control capabilities using Danisense DP50IP-B, is a compelling choice for future updates to TPS correction magnet power sources.

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