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Reliability assessment and improvement for a fast corrector power supply in TPS

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ABSTRACT

Fast Orbit Feedback System (FOFB) can be installed in a synchrotron light source to eliminate undesired disturbances and to improve the stability of beam orbit. The design and implementation of an accurate and reliable Fast Corrector Power Supply (FCPS) is essential to realize the effectiveness and availability of the FOFB. A reliability assessment for the FCPSs in the FOFB of Taiwan Photon Source (TPS) considering MOSFETs' temperatures is represented in this paper. The FCPS is composed of a full-bridge topology and a low-pass filter. A Hybrid Pulse Width Modulation (HPWM) requiring two MOSFETs in the full-bridge circuit to be operated at high frequency and the other two be operated at the output frequency is adopted to control the implemented FCPS. Due the characteristic of HPWM, the conduction loss and switching loss of each MOSFET in the FCPS is not same. Two of the MOSFETs in the full-bridge circuit will suffer higher temperatures and therefore the circuit reliability of FCPS is reduced. A Modified PWM Scheme (MPWMS) designed to average MOSFETs' temperatures and to improve circuit reliability is proposed in this paper. Experimental results measure the MOSFETs' temperatures of FCPS controlled by the HPWM and the proposed MPWMS. The reliability indices under different PWM controls are then assessed. From the experimental results, it can be observed that the reliability of FCPS using the proposed MPWMS can be improved because the MOSFETs' temperatures are closer. Since the reliability of FCPS can be enhanced, the availability of FOFB can also be improved.

1. Introduction

The concentric-ring-based synchrotron light source of Taiwan Photon Source (TPS) in National Synchrotron Radiation Research Center (NSRRC) composed of the booster and storage rings was constructed and operated since 2014. Using a linear accelerator, the booster ring in TPS rises the electron beam from 150 MeV up to 3 GeV at a 3 Hz repetition rate and then the storage ring in a circumference of 518.4 m is used to emit photons from the electron beam. The beam size of the storage ring is small; therefore, the beam position must be controlled accurately and stably in the order of tens of μm. A Fast Orbit Feedback System (FOFB) used in the storage ring to eliminate undesired disturbances and to suppress the beam orbit instability was therefore installed and tested in TPS since 2016. The FOFB system modifies the current setting of the corrector with 10 kHz update rate. The maximum corrected current value is set at 1% of the 10 A output, equivalent to 0.1 A per 100 μs. The design and implementation of an accurate and reliable Fast Corrector Power Supply (FCPS) is essential to realize the effectiveness and availability of the FOFB. A FCPS should be able to deliver 1 A with −3 dB bandwidth up to 3 kHz and the rise time and settling time of the FCPS should fall within 100 μs. Fig. 1 shows the structure of storage ring, beam position monitor (BPM), and corrector magnet in FOFB [1,2]. Ref. [2] summarized the infrastructure of the FOFB and the preliminary beam tests in TPS. Refs. [3,4] proposed the FCPS to serve as the driving source to feed the fast corrector magnet in the FOFB system to achieve both wide bandwidth and fast transient response. The relationship between the switching duty cycles and the output of error amplifier was represented in [3] and the PWM controller with an offset was then proposed to enhance wide bandwidth. A rigorous mathematical modeling derived by the state-space averaging method for a FCPS in the FOFB was proposed in Ref. [5]. Ref. [6] represented the designs of the power and control circuits, the component layout, and the test results for the APS upgrade of a multi-bend achromat storage ring requiring FCPSs for the fast correction magnets. Ref. [7] represented an efficient power supply to feed low-energy corrector magnets in particle accelerator applications where a controlled current with trapezoidal profile and four-quadrant operation was achieved. FCPS is one of the most important devices in FOFB. If one of FCPSs fails, the performance of FOFB will be significantly degraded and the TPS might need to be

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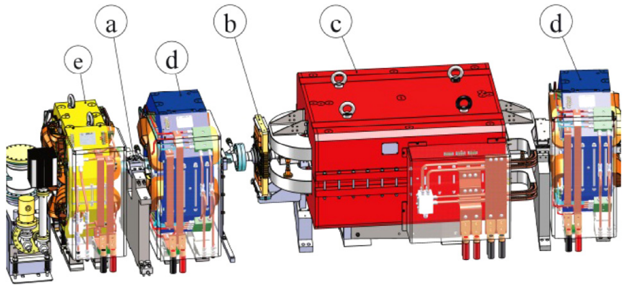

Fig. 1. Main structure of FOFB where (a) BPM, (b) Fast corrector magnet, (c) Dipole magnet, (d) Quadrupole magnet, (e) Sextupole magnet.

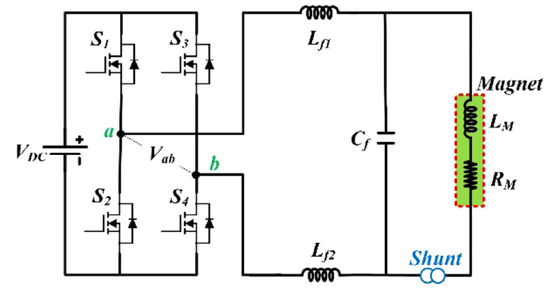

Fig. 2. Circuit architecture of a FCPS with full-bridge topology.

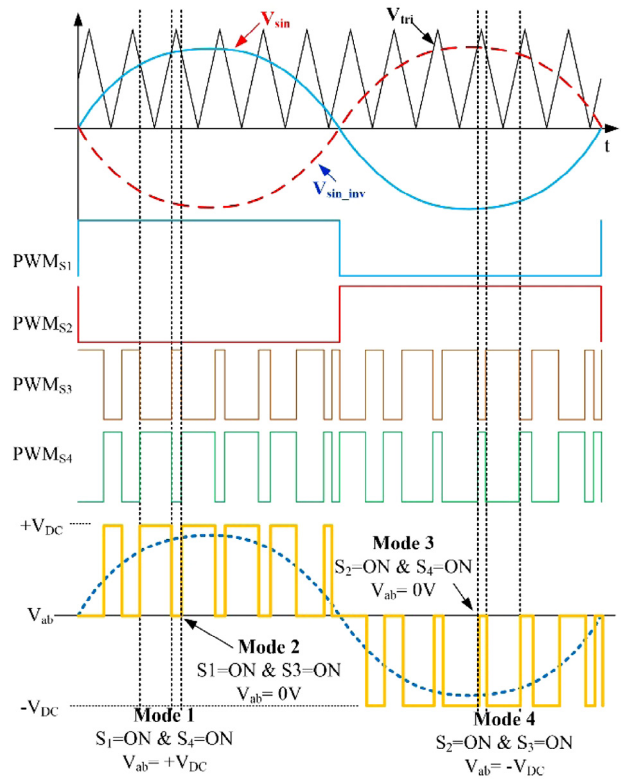

Fig. 3. Fundamental waveforms of the FCPS.

shut down for failure diagnosis, detection and component replacement. Therefore, how to improve the reliability of FCPS is one of the most important issues to enhance the performance of FOFB.

The reliability of FCPS greatly depends on the choices of circuit components, circuit topology and control scheme. The FCPS used in FOFB of TPS is mainly composed of a full-bridge topology with four MOSFETs and a low-pass filter. A Hybrid Pulse Width Modulation (HPWM) [8], requiring two of the four MOSFETs in the full-bridge circuit to be operated at high frequency and the other two be operated at the output frequency, is adopted to control the FCPS. The advantage of HPWM is that the conversion efficiency can be improved. However, due the switching characteristic of HPWM, the conduction loss and switching loss of MOSFETs in the FCPS are not close and two of the MOSFETs in the FCPS will therefore suffer higher temperatures. While the MOSFETs operate at higher temperatures, the circuit reliability of FCPS will be significantly reduced [9,10]. Some techniques have been proposed to solve the thermal imbalance of power devices [11–14]. Ref. [11] proposed a new phase-shift control technique to swap the leading leg and the lagging leg with each other by either alternating control for a phase-shift full-bridge converter. The thermal imbalance of power devices can then be effectively reduced. Ref. [12] represented the current sharing of IGBTs in parallel with thermal imbalance. An active gate control method used to achieve current balancing was also proposed and verified by experiments. Ref. [13] proposed some useful approaches to control the semiconductor junction temperature along with the implementation of several emerging applications. The use of integrated per-die buffers with selective gate driving to minimize the thermal differences within a high current SiC power module was proposed in [14]. The experimental results demonstrated that a drop of 15 °C in the hottest die using selective gate driving can achieve a lifetime increase of up to 3 times. A Modified PWM Scheme (MPWMS) designed to keep the higher conversion efficiency of HPWM, average MOSFETs' temperatures and improve circuit reliability is proposed in this paper. A reliability assessment including the indices of Mean Time to Failure (MTTF), Mean Time to Repair (MTTR), Mean Time Between Failure (MTBF), availability and unavailability etc., for the FCPSs in the FOFB of TPS considering MOSFETs' temperatures is represented in this paper. A FCPS prototype rated as ±10 A/±50 V controlled by HPWM and MPWMS is implemented. Experimental results measure the MOSFETs' temperatures of the FCPS controlled by the HPWM and the proposed MPWMS. The reliability indices under different PWM controls are then assessed. From the experimental results, it can be observed that the reliability of FCPS using the proposed MPWMS can be improved because the MOSFETs' temperatures are closer. Since the reliability of FCPS can be enhanced, the availability of FOFB can also be improved.

2. Basic circuit and operations of a FCPS

Fig. 2 shows the basic circuit architecture of the FCPS in the FOFB of TPS designed and implemented by the power supply group of NSRRC. In Fig. 2, V_{DC} and S_1 to S_4 are the input DC voltage and the MOSFETs of full-bridge circuit, respectively. A low-pass filter is composed of L_{f1}, L_{f2} and C_f. "Shunt" as shown in Fig. 2 is a high precision shunt resistor used as current sensor. L_M and R_M are the equivalent load of a corrector magnet. The theoretical PWM control signals PWM_{S1} to PWM_{S4} for the MOSFETs S_1 to S_4 and the bridge output voltage V_{ab} are shown in Fig. 3. V_{tri}, V_{sin} and V_{sin_inv} in Fig. 3 are the triangular carrier signal, positive sinusoidal reference signal and negative sinusoidal reference signal, respectively. The HPWM is adopted to control the implemented FCPS [8]. As an example, two MOSFETs, S_1 and S_2, are driven at high frequency and the other two, S_3 and S_4, are driven at the output frequency. There are four operational modes in the FCPS. Fig. 4 shows the equivalent circuits of modes 1 and 2 for the positive bridge output voltage. The modes of negative bridge output voltage are similar to the modes of positive bridge output voltage.

The advantage of HPWM is that the conversion efficiency can be enhanced. However, due the switching characteristic of HPWM, the conduction loss and switching loss of MOSFETs in the FCPS are not close and two of the MOSFETs in the FCPS will suffer higher temperatures and result in lower circuit reliability of FCPS. Therefore, a Modified PWM