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LOW FREQUENCY RIPPLE CURRENT ATTENUATION FOR SLOW CORRECTOR POWER SUPPLIES IN THE APS UPGRADE*

Y. Ruan† and F. Rafael
Argonne National Laboratory, Lemont, IL, USA

Abstract

As part of the Advanced Photon Source Upgrade (APS-U), approximately one thousand bipolar power supplies were installed to power the slow corrector magnets. During the APS-U commissioning, a 1-Hz harmonic was detected in the beam motion. This harmonic originated from the 480V AC grid, caused by the booster ramping power supply operating at 1 Hz. The resulting grid disturbance introduced low-frequency ripples into both the corrector magnet power supplies and the L-Bend M1/M2 supplies, leading to the observed 1-Hz beam motion. This paper proposes two methods to mitigate these ripples in the corrector supplies: setpoint compensation using repetitive control, and regulation circuit adjustments through a simple jumper reconfiguration. The second approach was adopted and applied to all slow corrector magnet power supplies. Operational data showed that the low-frequency ripples were significantly attenuated in the corrector supplies, and in combination with fine-tuning of the L-Bend M1/M2 supplies, the 1-Hz beam motion was successfully eliminated.

INTRODUCTION

During the APS-U commissioning in early 2024, a 1-Hz beam motion was observed, and the booster ramping supply was identified as the source of the issue. The ramping supply operates at 1 Hz, causing the 480 VAC grid to sag every second, which in turn produces low-frequency ripples in the 80 raw power supplies that energize approximately 1,000 bipolar power supplies for the slow corrector magnets around the storage ring. These AC/DC raw supplies use uncontrolled rectifiers, meaning that grip ripples are directly transferred to the DC output. Similarly, the 1 Hz with other low frequency transients also affects the DC-Link voltage of the L-Bend M1 and M2 supplies, which also rely on uncontrolled rectifiers. The grid voltage sag, captured in Fig. 1, shows a drop of approximately 1.3%, followed by a recovery as the booster ramping supply current rises and falls.

One potential solution to address the 1-Hz ripple in the corrector supplies would involve replacing the high-power AC/DC raw supplies with PWM-controlled DC supplies. However, with over 1,000 units involved, this approach would be both costly and time-consuming.

In this paper, we propose and analyze two practical methods that require minimal hardware changes to address the issue: (1) setpoint compensation using repetitive control, which can be implemented through controller firmware; and (2) analog regulation loop adjustment via a simple jumper reconfiguration. Simulation models were developed using MATLAB/Simulink, and results confirmed the effectiveness of both methods. Due to its simplicity and ease of implementation, the jumper reconfiguration was approved and applied to all slow corrector supplies during the August 2024 shutdown. Operational data confirmed that low-frequency ripples were significantly attenuated, with reductions of 19.8× for the 1-Hz ripple, 13.9× for the 2-Hz ripple, and 9.1× for the 3-Hz ripple.

Further tuning of the L-Bend M1/M2 supplies was conducted in September 2024 to mitigate grid disturbances. With the fine-tuning of the slow correctors and M1/M2 supplies, the 1-Hz harmonic was successfully eliminated from the beam motion.

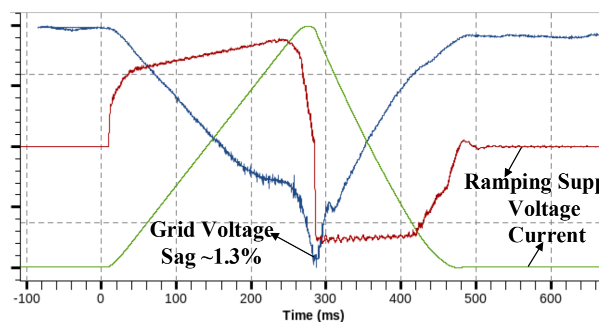

Figure 1: The voltage sag in the AC grid caused by the booster ramping supply.

RIPPLE ATTENUATION OF BIPOLAR SUPPLIES

Power Circuit of the Bipolar Supply

Figure 2 illustrates the power circuit and control scheme of the bipolar power supply, which was designed in-house at Argonne [1, 2]. This is a DC/DC supply, with its input voltage provided by a raw AC/DC supply. The raw supply consists of a multi-winding stepdown transformer and two 6-pulse rectifiers that convert the 480-VAC grid voltage to approximately 40 VDC. Across the storage ring mezzanine, there are 80 such raw supplies, powering more than 1,000 bipolar supplies.

An FPGA-based controller, designed in -house, serves as the interface between the power supply and the Experimental Physics and Industrial Control System (EPICS). The controller receives the current setpoint from EPICS and converts it into a reference signal, which is then fed to the analog proportional-integral (PI) regulation circuit in the bipolar power supply. Each controller can manage up to eight bipolar supplies.

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† yruan@anl.gov

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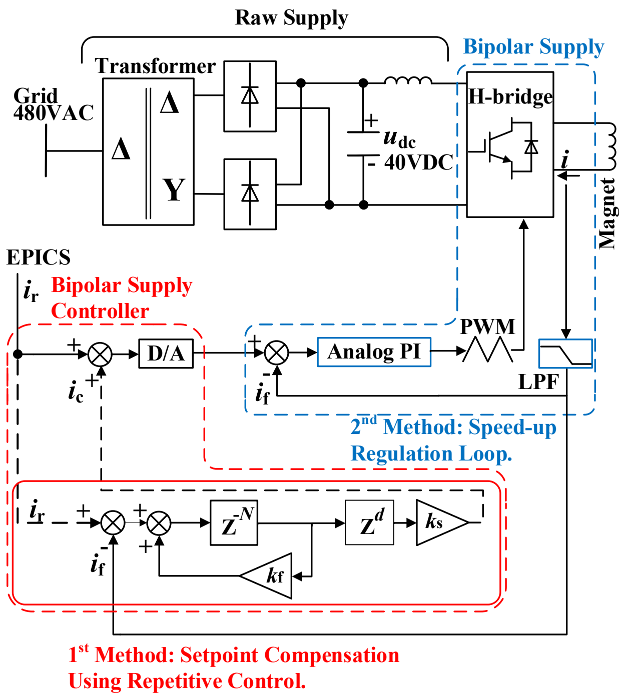

Figure 2: Bipolar power supply configuration, illustrating two methods for mitigating the 1-Hz ripple induced by grid disturbance.

The output current of each bipolar supply is fed back to the regulation circuit through a Direct Current Current Transformer (DCCT) transducer and a shunt resistor. This feedback ensures that the output current closely tracks the setpoint by adjusting the duty cycle of the H-bridge, which is composed of four power MOSFETs.

Despite the use of a large capacitor bank in the raw supply, the ripples caused by grid voltage sags still appear on the DC output, affecting the output current of the bipolar supplies. The regulation loop in the slow corrector supplies is not fast enough to effectively attenuate these disturbances, leading to low-frequency ripples in the current, primarily in the 1- to 10-Hz range.

With nearly 1,000 such supplies, addressing the issue by modifying hardware—such as increasing the capacitor banks in the raw supply or replacing the raw supply with regulated DC supplies—would be both costly and time-consuming. Therefore, two alternative methods were analyzed and simulated to resolve the issue, both requiring no additional hardware.

Setpoint Compensation Using a Repetitive Controller

The first method is setpoint compensation through repetitive control, as illustrated in Fig. 2. This approach can be implemented within the controller firmware. Repetitive control is designed to enhance the performance of systems experiencing periodic disturbances or repetitive signals. In this paper, the disturbance is the periodic grid voltage sag.

The repetitive controller effectively rejects or compensates for these periodic disturbances by creating a model of the repetitive disturbance and employing that model within the controller to cancel out future occurrences. Additionally, repetitive controllers can be used in power electronics converters to reduce harmonic distortion [3].

Given that the disturbance period is 1 second, the buffering number N in the repetitive signal generator Z^{-N} is derived as $N = 1/T_s$, where T_s is the sampling period. The repetitive control functions as a learning pattern by integrating regulation errors from past periods and using that information to compensate the setpoint, thereby improving accuracy over time.

The phase-lead block Z^d is included in the loop to compensate the phase lag by d sampling periods. The gains k_s and k_f are typically set to values less than 1.0 to stabilize the system.

A simulation model is built by MATLAB/Simulink with a repetitive controller incorporated to assess its performance in attenuating periodic disturbances from the DC input. A resistive load is periodically engaged for a short duration at the DC input to simulate the periodic disturbance. The simulation results are presented in Fig. 3. Upon activation, the repetitive control gradually reduces the transient ripple from 0.5 mA to 0.05 mA (peak-to-peak) within a few cycles (seconds), representing a reduction by a factor of 10.

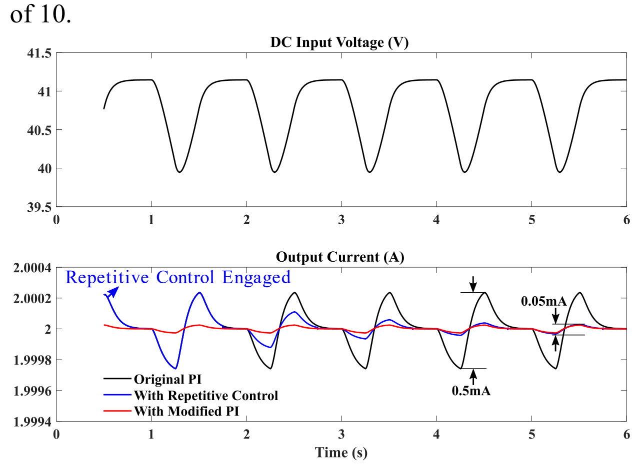

Figure 3: Simulation results demonstrating various methods to attenuate the 1-Hz ripple in bipolar power supplies.

Regulation Loop Modification

The second method involves adjusting the proportional-integral (PI) control parameters to accelerate the regulation response. Fortunately, the regulation board includes several jumpers that allow for switching to higher PI coefficients. This adjustment requires reconfiguring three jumpers, as illustrated in Fig. 4, to modify the low-pass filter for the current sensing circuit and to adjust the PI coefficients.

(1) The cutoff (corner) frequency of the second-order active low-pass filter (LPF) in the current sensing circuit is increased from 4.12 kHz to 41.2 kHz by repositioning two jumpers.

(2) The resistance and capacitance in the PI loop are modified from 49.9 kΩ and 1 µF to 402 kΩ and 0.1 µF, resulting in increases of the proportional and integral coefficients by factors of 8 and 10, respectively. This adjustment is achieved by repositioning one jumper.

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With the modified PI parameters achieved through jumper reconfiguration, the transient ripple is significantly attenuated by a factor of 10, as shown in Fig. 4.

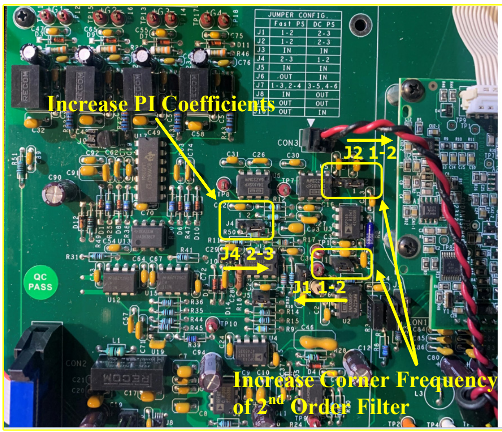

Figure 4: Jumper reconfiguration for the slow corrector supplies.

OPERATIONAL RESULTS

The setpoint compensation and jumper reconfiguration methods demonstrate similar effectiveness in attenuating the transient ripple. However, reconfiguring a few jumpers is faster and more practical than implementing setpoint compensation, which requires development and updating of the control firmware. The jumper reconfiguration method was applied to all bipolar supplies in the storage ring during the August 2024 shutdown and was completed within two weeks.

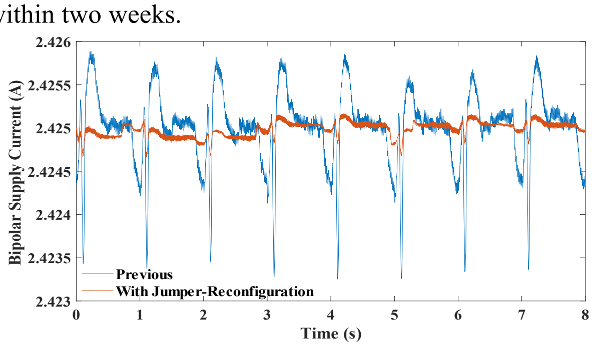

Figure 5: Current waveform of the S10B:V8 supply.

Figure 5 shows the current waveforms of magnet S10B:V8, with data collected by an oscilloscope, illustrating that the ripple current is noticeably smaller after the jumper reconfiguration. Figure 6 compares the ripple current spectrum before and after the jumper reconfiguration. Figure 7 presents the ripple current chart for characteristic frequencies below 60 Hz. The ripple spectrum clearly indicates that the periotic grid disturbance primarily introduces the lower frequency ripples in the range of 1 Hz to 10 Hz, which are significantly attenuated after the jumper reconfiguration.

The ripple currents at 1 Hz, 2 Hz, and 3 Hz were reduced from 0.162 mA, 0.176 mA, and 0.082 mA to 0.0127 mA, 0.0182 mA, and 0.009 mA, respectively, corresponding to reductions by factors of 19.8, 13.9, and 9.1. Additionally, the ripple current at 60Hz was reduced by a factor of 4.9, decreasing from 0.1857 mA to 0.0379 mA.

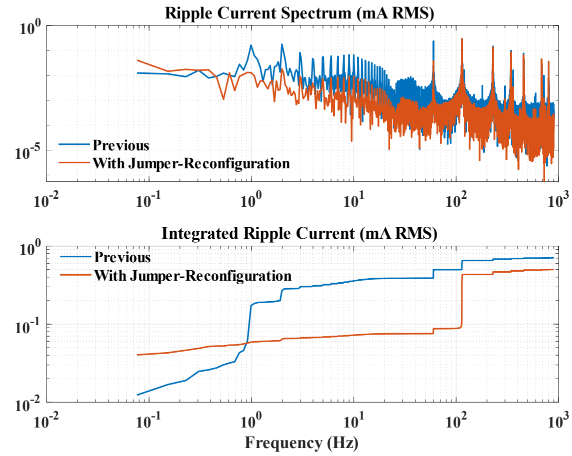

Figure 6: Ripple current spectrum of the S10B:V8 supply at 2.425 A.

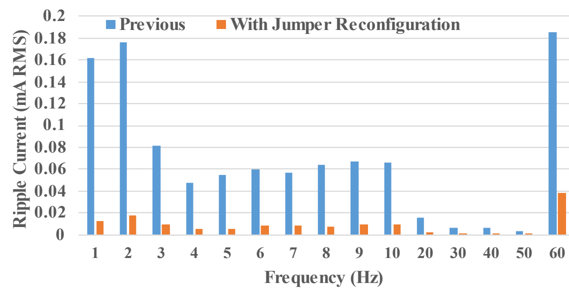

Figure 7: Ripple currents (mA RMS) in the frequency range from 1 Hz to 60 Hz.

CONCLUSION

The repetitive control-based setpoint compensation and jumper reconfiguration for PI adjustment were proposed to address the ripple issue arising from periodic grid disturbances. Simulation results indicated promising outcomes for both methods, and the jumper reconfiguration was approved and implemented on approximately 1,000 slow corrector supplies. Operational data collected from the S10B:V8 supply demonstrate that the low frequency ripples have been significantly attenuated.

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