A NEW CURRENT REGULATOR FOR THE APS STORAGE RING CORRECTION MAGNET BIPOLAR SWITCHING MODE CONVERTERS*

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Abstract

The correction magnets in the Advanced Photon Source's storage ring are powered by PWM-controlled bipolar switching-mode converters. These converters are designed to operate at up to ±150 A. The original control circuit used a polarity detection circuit with a hysteresis to determine which IGBT was needed to regulate the current with a given polarity. Only the required IGBT was switched with PWM pulses while others were held on or off continuously [1, 2]. The overall IGBT switching losses were minimized by the design. The shortcoming of the design was that the converter's output was unstable near zero current because of the hysteresis. To improve the stability, a new current regulator using a different PWM method has been developed to eliminate the requirement of the polarity detection. With the new design, converters can operate smoothly in the full range of ±150 A. The new design also meets tighter specs in terms of the ripple current and dynamic response. This paper describes the design of the new regulator and the test results.

CORRECTOR CURRENT REGULATOR

Original Design

The corrector magnet is driven by a standard H-bridge converter consisting of four IGBTs as shown in Figure 1.

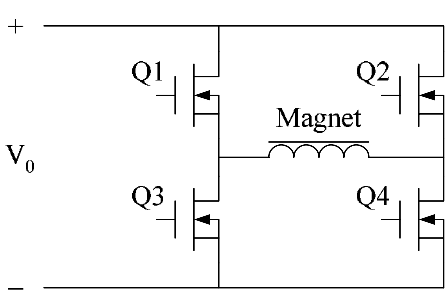

Figure 1: H-bridge converter for correction magnet.

The converter can produce a current in the magnet in either direction. For most of the correctors, especially the slow correctors, the operation current is unidirectional, either positive or negative. In this case, only one IGBT switch is required to regulate the current. The others are either on or off depending on the current direction. For instance, to produce a positive current (from left to right), only IGBT Q1 needs to be PWM-controlled to regulate the current. IGBT Q4 is on all the time while Q2 and Q4 are off. The advantage of this control scheme is that only one IGBT is switching at high frequency. The overall switching losses are minimized. The original regulator design took advantage of this feature and used a polarity detector to determine the required mode for each IGBT. In order to reduce the sensitivity to EMI noises around zero current, a hysteresis was employed in the detector as shown in Figure 2. This design works well when the operation current is above the threshold of the hysteresis, otherwise an unstable operation occurs, as shown in Figure 3. Additionally, if a corrector is required to operate in AC mode near a zero current, the transition across the zero is unsmooth, as shown in Figure 4. This in turn may cause difficulties for real-time beam orbit correction.

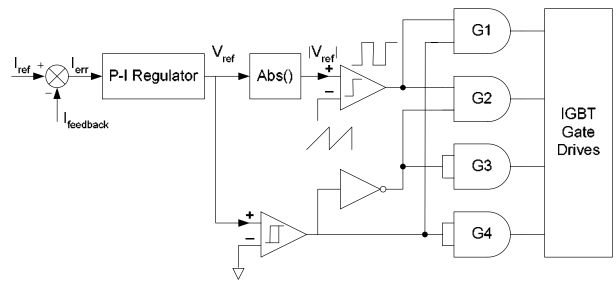

Figure 2: Original corrector current regulator.

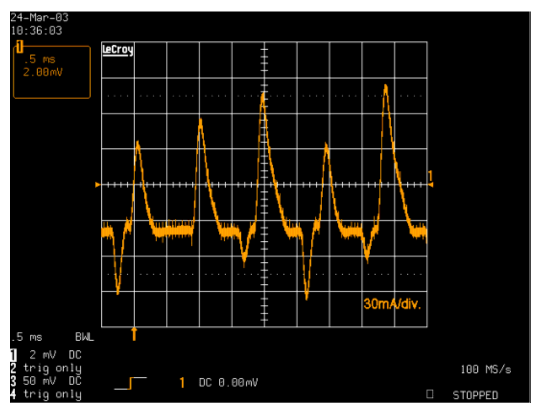

Figure 3: Unstable current due to the hysteresis.

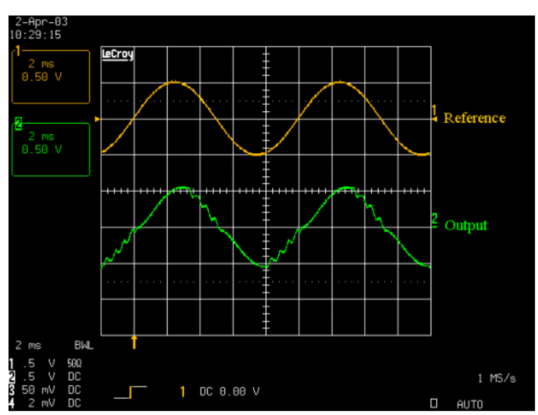

Figure 4: Unsmooth transition through zero current.

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New Design

To overcome this drawback, a new regulator has been developed using a PWM control scheme called "Unipolar Voltage Switching" [3]. This scheme controls all four IGBTs with PWM pulses. Two references with the same amplitude but opposite signs are compared with a triangular waveform to generate two sets of PWM pulses, PWM1 and PWM2. The set produced by reference V_{ref} is used to control Q1 and Q3; the set produced by $-V_{ref}$ is used to control Q2 and Q4. The resulting voltage across the magnet has the same waveform as that produced by subtracting PWM2 from PWM1. Figure 5 illustrates the PWM pulses and the magnet voltage produced by this control scheme.

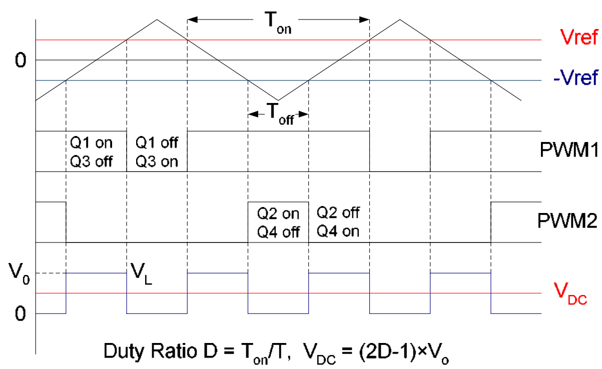

Figure 5: PWM pulses and magnet voltage.

One can notice that the instant magnet voltage only changes from zero to the DC bus voltage for positive output and zero to the negative DC bus voltage for negative output. This is where the name "Unipolar Voltage Switching" came from. Figure 6 shows the logic circuit for realizing this control scheme.

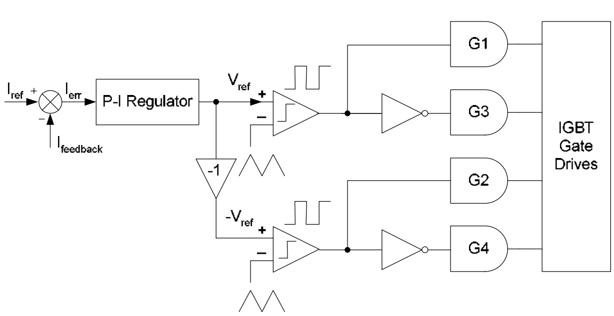

Figure 6: New corrector current regulator.

COMPARISON OF TWO DESIGNS

Output DC Voltage

For the original design, the converter output voltage is equal to the DC bus voltage when Q1 (or Q2) is on and equal to zero when Q1 (Q2) is off. For a given duty ratio *D*, the average voltage across the magnet is equal to

$$V_{DC} = \pm \frac{T_{on}}{T} \times V_0 = \pm D \times V_0 \,, \tag{1}$$

where *D* varies from 0 to 1. The polarity of the output voltage is decided by the polarity detector instead of the duty cycle.

For the new design, the average voltage across the magnet is equal to

$$V_{DC} = (2D - 1) \times V_0 \,, \tag{2}$$

where *D* has a range of 0 to 1. As the duty cycle changes from 0 to 1, the average output voltage changes from $-V_0$ to $+V_0$.

Peak-to-Peak Ripple Current

Even if the same PWM switching frequency is used for both designs, the fundamental ripple current frequency *f* is different. *f* for the original design is the same as the PWM switching frequency. For the new design, *f* is effectively doubled. This can be easily observed from the output voltage waveform in Figure 5.

Assuming that the voltage drop on the resistive component of the load is equal to V_{DC}, the peak-to-peak ripple current for the original design can be calculated as

$$I_{ripple} = \frac{V_0}{L} TD(1 - D) \,, \tag{3}$$

where *L* is the inductance of the load.

Similarly, for the new design the peak-to-peak ripple current is equal to

$$I_{ripple} = \begin{cases} \frac{V_0}{L} T(1-2D)D & \text{for } 0 < D \le 0.5 \\ \frac{V_0}{L} T(2D-1)(1-D) & \text{for } 0.5 < D \le 1 \end{cases} . \tag{4}$$

From Eqs. (3) and (4), one can find the maximum ripple current for the original design to be $I_{ripple,\max} = TV_0 / 4L$ at $D = 0.5$, and for the new design $I_{ripple,\max} = TV_0 / 8L$ at $D = 0.25$ or 0.75. The maximum ripple current in the new design is reduced by 50%. This is a natural result of the doubled effective switching frequency. Figure 7 shows a comparison of the peak ripple currents in two designs.

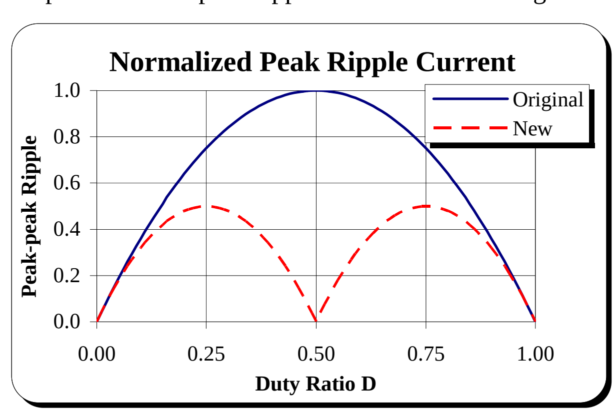

Figure 7: Comparison of peak-to-peak ripple currents.

Voltage Feedforward

The DC bus for a converter is not a perfect bus. The test has shown that a feedforward signal from the DC bus voltage can help to reduce the harmonic current caused by the harmonic voltage in the bus, especially for the 360-Hz component.

In the original design the amplitude of the saw-tooth signal for the PWM is directly proportional to the bus voltage. If the bus voltage has an increase, the peak voltage of the saw-tooth will have an increase, causing a reduction in the duty ratio of the PWM pulses. The smaller duty ratio counterbalances the effect of the increased bus voltage. Instead of controlling the amplitude of the triangular signal, the new design uses a difference approach based on the relation between the output voltage, the bus voltage, and the reference:

$$V_{DC} \propto V_{ref} \times V_0 . \tag{5}$$

When there is a ΔV_0 change in the bus voltage, there needs to be a ΔV_{ref} change in the reference to reduce or cancel the effect of ΔV_0. Then,

$$\Delta V_{DC} \propto \Delta V_{ref} \times V_0 + V_{ref} \times \Delta V_0 . \tag{6}$$

To cancel the effect of ΔV_0, ΔV_{ref} needs to be equal to

$$\Delta V_{ref} = -\frac{V_{ref} \times \Delta V_0}{V_0} . \tag{7}$$

The reference that is used to compare with the triangular signal is thus

$$V_r = V_{ref} + \Delta V_{ref} = V_{ref} - \frac{V_{ref} \times \Delta V_0}{V_0} . \tag{8}$$

In the practical implementation, V_0 can be treated as a constant.

In the new design, a bandpass filter is used to measure the change in the bus voltage. The passband frequency of the filter is from 0.1 Hz to 1.5 kHz. The measured signal is multiplied with the output of the P-I controller, which is V_{ref}, and then subtracted from V_{ref} to produce V_r. This scheme can be easily realized with an AD633 from Analog Devices.

TEST RESULTS

The new design has been tested for various conditions. The test results have shown that the converter runs stably through the whole range of ±150 A. It can also follow a sinusoidal or a triangular reference through zero current smoothly. Figures 8 and 9 show two measured waveforms. Table 1 shows some key improvements of the new design.

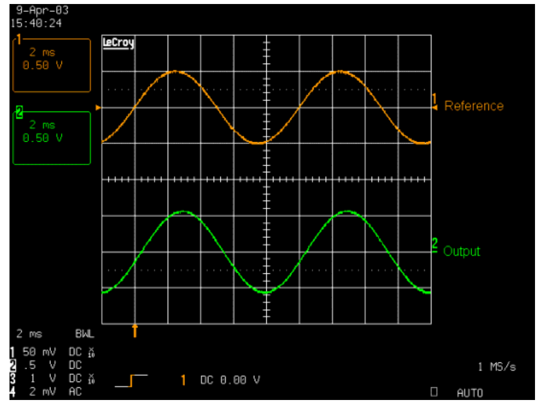

Figure 8: Current waveform for a sinusoidal reference.

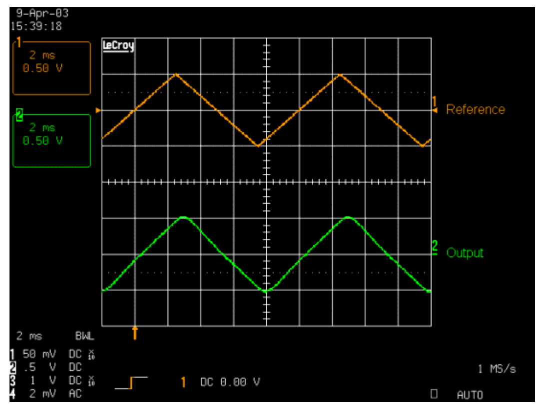

Figure 9: Current waveform for a triangular reference.

Table 1: Performance Comparison

	Original Design	New Design
24 hour stability ($\Delta I/I_{max}$)	$\pm 12\times10^{-6}$	$\pm 10\times10^{-6}$
Current ripple	±110 mA	±55 mA
Ripple frequency	20 kHz	40 kHz
Transition through zero current	Nonlinear and unstable	Stable and track the setpoint
Small signal bandwidth (1%)	N/A	> 1 kHz

REFERENCES

[1] Y.G. Kang, "Correction Magnet Power Supplies for APS Machine," PAC'91, San Francisco, CA, May 6-9, 1991, p. 911.

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[3] N. Mohan et al., Power Electronics: Converters, Applications, and Design, Second Edition, John Wiley & Sons, Inc., 1995.