A DUAL TRIANGLE TIMING CIRCUIT FOR IMPROVED PERFORMANCE OF 4-QUADRANT H-BRIDGE SWITCHERS*

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Abstract

Fermilab is in the process of upgrading its Booster Correction Element System to include full field correction element magnets to correct position and chromaticity throughout the booster cycle. This upgrade requires power supplies with maximum outputs of ±180V/±65A, with current bandwidths of 5k Hz and with slew rates of min to max current in 1ms. For seamless operation around zero current and voltage, we use continuous switching on both sides of the bridge. Although the straightforward way of coordinating the switching on both sides of the bridge can be accomplished with one triangle timing wave and one voltage reference, we have found that using two triangle waves yields a switching coordination that effectively doubles the frequency of the differential ripple on the load and allows for better filtering of the output ripple.

INTRODUCTION

The Booster machine at Fermilab is a 15 Hz alternate gradient accelerator. Several years ago an upgrade was proposed and approved to install NEW corrector magnets that include dipole, quadrupole and sextupole correction both normal and skew. [1, 2, 3]

The power supply incorporates a raw bulk DC supply and individual switcher modules off this bulk supply. Six locations are positioned around the booster ring each handling 48 corrector magnet coils.

The power supplies designed for this application are considered second generation. The first generation supplies were designed and built for the Main Injector machine at Fermilab approximately 10 years ago. The main changes for these Booster supplies is the use of dual FET's for each switching element, filters with higher bandwidth and so called dual side switching for better zero crossing performance.

The fundamental switching unit parameters are given below:

- Output Voltage +/- 180 V
- Output Current (65A unit) +/- 65 A
  (40A unit) +/- 40 A
- Current Loop Bandwidth 5k Hz

The raw supply filter for these units was also beefed up to minimize the 15 Hz current that is required from the AC line input during Booster ramping.

The particular switching configurations and switch timing signals are the subject of this paper.

H-BRIDGE SWITCHING ELEMENT CONFIGURATION

Single Side Switching

This particular four quadrant switcher has FET's as the switch elements. A pictorial diagram of the switching elements is given in Figure 1. Each switch element is made up of 2 FET switches and are driven from the same gate drive signal with separate gate resistors.

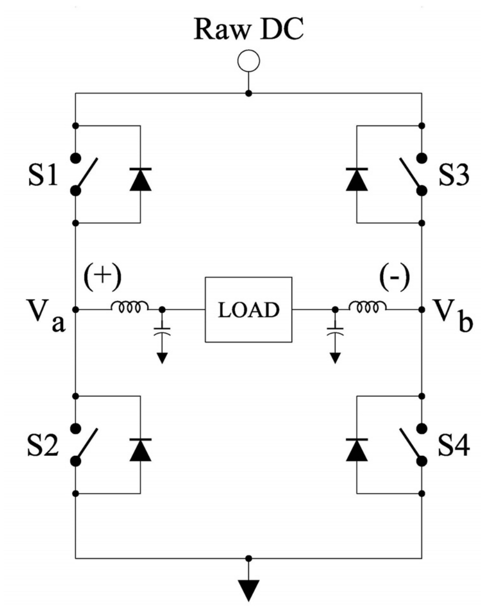

Figure 1: Switch configuration.

The initial drive signal for the switches in our first generation units required either S2 or S4 to be closed and PWM the other side of the load. The most obvious down side to this configuration is in zero crossing distortion.

Single Triangle Dual Side Switching

In the past, if good zero crossing was required, the bridges were setup such that the bridge on either side of the load was switching, with S1 – S4 getting the same gate drive and S2 – S3 getting the NOT of S1 – S4.

With this configuration as shown in Figure 2, you can see that for a phase voltage of 25% full scale, the load is first given a positive voltage, Va – Vb, for 5/8 th's of the duty cycle and then given a negative voltage for the remaining 3/8 th's of the duty cycle. (*For this discussion Raw DC is assumed to be 180 volts, load resistance is ~1 ohm and the load inductance is 1m Henry. Load current is nominally 40 amps.)*

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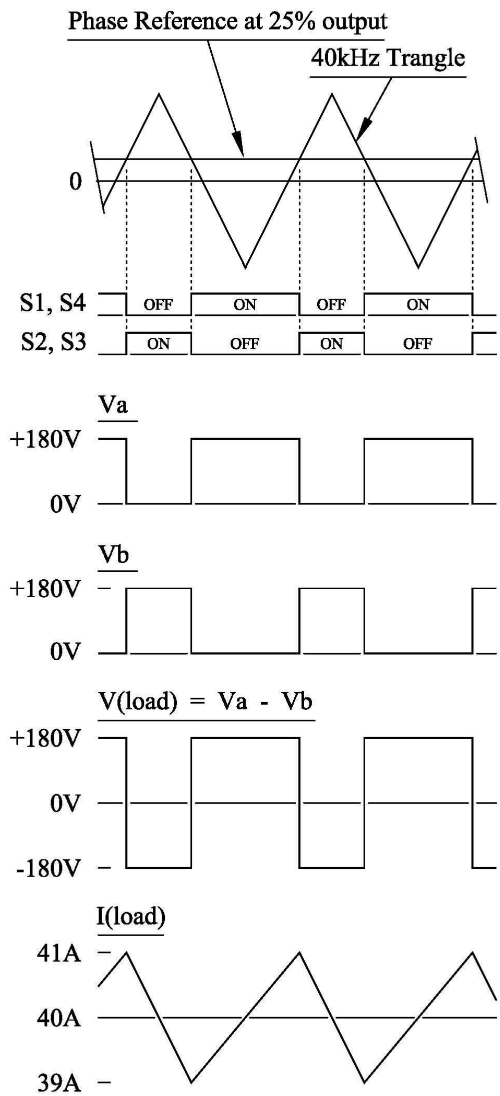

Figure 2: Single triangle dual side switch drive.

In the limit when zero phase reference is supplied the load will get a square wave voltage of 50% duty cycle +/- Raw DC.

A down-side to this configuration is that the load will see maximum ripple current at zero volts out.

Dual Triangle Dual Side Switching

With the addition of an inverted triangle signal input to the S3 – S4 bridge as the phase reference, the timing is modified such that the voltage across the load is now unipolar and twice the frequency of the 40k Hz triangle ramp. This configuration is shown in Figure 3.

With a quick look at Figure 3, you can see that the 40k Hz fundamentals from Va and Vb are in phase and cancel across the load. The resultant 80k Hz voltage gives a load current ripple that is +/- 0.2 A rather than the original +/- 1 A.

In another implementation of this switching scheme the phase detector is fed a (+) phase reference for the S1 – S2 bridge and a (-) phase reference for the S3 – S4 bridge, giving the same timing effect.

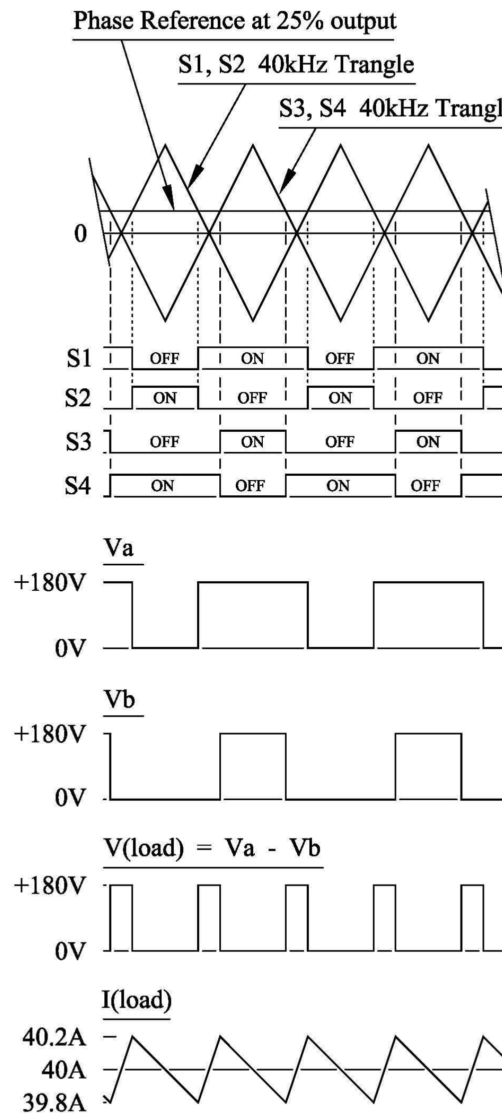

Figure 3: Dual triangle dual side switching.

OUTPUT FILTER

We have chosen to put single ended filters on each output in order to reduce load current ripple and to also filter the common mode PS voltage transmitted to the tunnel. With the addition of the output filter, the reduction of ripple current between the two cases is further enhanced. The output filter is given in Figure 4 below.

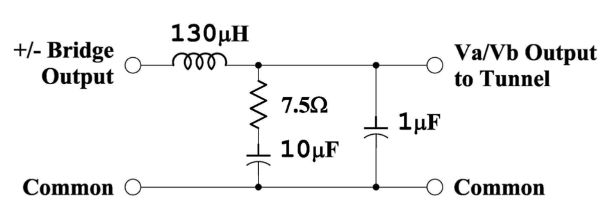

Figure 4: Output filter.

The Bode plot of the output filter is given in Figure 5 below. The chosen filter is second order and falls at 40dB per decade.

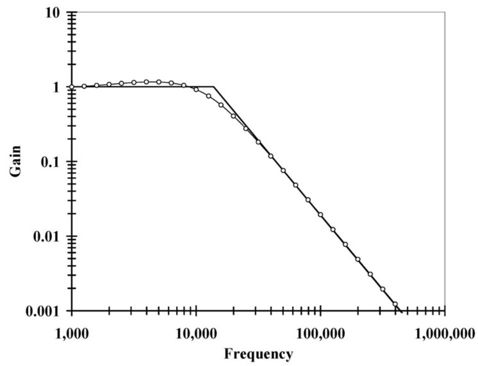

Figure 5: Output filter gain.

Magnet currents are given in Figure 6 below. For comparison the single triangle dual side switching peak to peak current ripple is 0.2 amps and with the dual triangle dual side switching the peak to peak ripple is reduced to 0.01 amps.

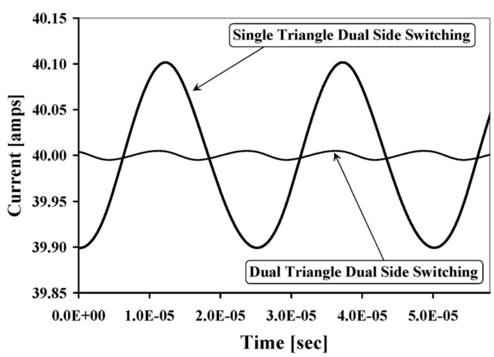

Figure 6: Output load current (at phase reference of 25%).

The peak to peak ripple of the load current varies with respect to the output voltage. Figure 7 is a comparison between the two cases. The single triangle dual side switching has its peak ripple at low output voltage. The dual triangle dual side switching has its peak at half voltage out and is about a factor of 10 less than the half voltage value of the single triangle case.

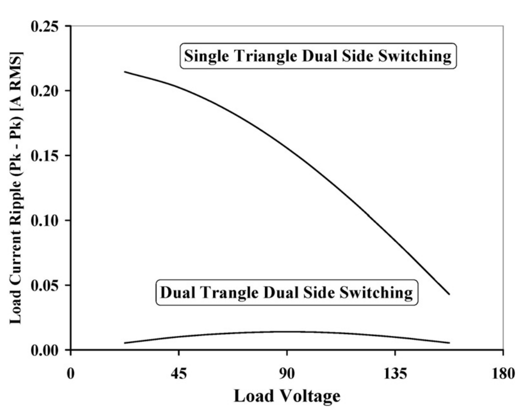

Figure 7: Load current ripple vs. output voltage.

INPUT FILTER CURRENT

An input filter is added to the bridge input of each switchmode unit to isolate the switching currents from the Raw DC supply. The input filter is given in Figure 7 below.

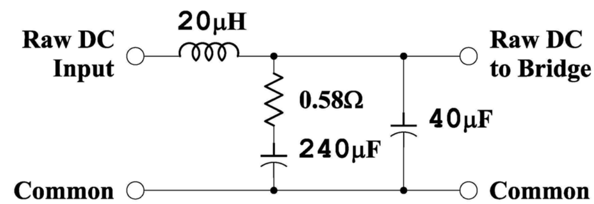

Figure 8: Bridge input filter.

In comparing the two cases, with respect to input current that must come from the 40uF capacitor, the single triangle case draws much more ripple current from this filter capacitor.

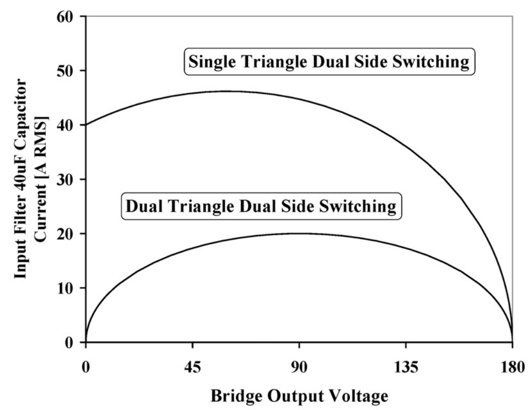

Figure 9: Input filter (40uF) capacitor (current comparison @ 40A load current).

CONCLUSION

In conclusion the Dual Triangle Dual Side Switching configuration has shown its advantages. There is a large decrease in output ripple with identical filters and just the timing of the triangle input to the bridge.

The RMS current required from the input capacitor to the bridge is much less and thus is much better with respect to the current rating of the input capacitor.

REFERENCES

[1] E.J. Prebys, et al., "Booster Corrector System Specification", Fermilab Beams-doc-1430, 2004.

[2] V.S. Kashikhin et al., "A New Correction Magnet Package for the Fermilab Booster Synchrotron" in Proc. of 2005 PAC, Knoxville, Tennessee, pp. 1204-1206.

[3] C.Drennan, et al.,, "System overview for the multi-element corrector magnets and controls for the Fermilab Booster," , in Proc. of 2007 PAC, Albuquerque, New Mexico, pp. 449-451.