

## 1.12 MVA Peak Two Quadrant Pulse Switch Mode Power Supply for SNS Injection Bump Magnet

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### Abstract

This paper describes a two quadrant, 1.12 MVA (+1400A, +/-800V) peak rated switch mode power supply for SNS Injection Bump Magnets. For each bump magnet (13 m $\Omega$ , 160 $\mu$ H), the power supply must supply controlled pulses at 60 Hz repetition rate. The pulse current must rise from zero to maximum in less than 1 millisecc in a controlled manner, flat top of up to 2 millisecc, and should fall in a controlled manner to less than 1.4A within 500 $\mu$ s. To meet the controlled fall of the current and the current ripple requirements, voltage loop bandwidth of 10 kHz and switching frequency of at least 100 kHz are required. To achieve high power high frequency switching with IGBT switches, a series connected topology with three phase shifted (0 $^\circ$ , 60 $^\circ$  & 120 $^\circ$ ) converters each with 40 kHz switching frequency (IGBT at 20kHz), has been proposed. In this paper, the circuit topology, key system specifications and experimental results for the power supply are described in detail. The major problem was to meet required performance during current fall time below 50A due to the very narrow pulse width and non-linearity from IGBT turn-on/off times. Future work is required to solve the non-linear problem at low current.

### 1 INTRODUCTION

This paper deals with the description, specification, experimental and simulation results of 1.12MVA switch mode converter. In section 2, the basic converter topology including control philosophy and system parameters is described. The key specifications are outlined in section 3. The simulation results are outlined in section 4. In section 5, the experimental results show disagreement between experimental and simulation results only at low current values. Section 6 discusses the major conclusions of this research.

### 2 BASIC CONVERTER SYSTEM

Figure 1 shows the essential elements of the two quadrant switch mode converter system.

- Input transformer, TR1, with one delta connected primary and three isolated secondaries.
- Three diode bridges, BRA, BRB and BRC to provide three isolated dc voltages.
- Three one stage LC (LFA, LFB and LFC, CFA, CFB, and CFC) filters with corner frequency of 7.5 Hz to reduce the 360 Hz ripple and provide energy storage for supplying the reactive power of the pulse load.
- Damping capacitors (CFA, CFB and CFC) and damping resistors (RDA, RDB, and RDC) to reduce DC voltage change during load pulsations and step perturbation in the input line.

- Three 1,400A, 300V, high power IGBT, H bridges (HA, HB and HC) with four 800A, 600V IGBT's in parallel in each bridge, sharing inductors, LEM current sensors, driver boards, snubbers, water cooled heatsinks, etc.
- Three H bridge outputs are connected in series. Each IGBT is switching at 18kHz but the gatings of three bridges are phase shifted by 0 $^\circ$ , 60 $^\circ$  and 120 $^\circ$ , respectively. This results in the output switching frequency of 108kHz. Also complementary IGBT in each bridge leg is not gated. On the other hand, the reversed diodes of the IGBTs are used for achieving continuous current.
- Two stage output filters (Lo1, Co1, Lo2, Co2), with corner frequency about 20kHz, reduce the switching frequency voltage ripple in the output.
- Output damping capacitor (Co3) and resistor (Ro3) improve output transient performance for the pulsing applications
- The control strategy for the high frequency converter employs an outer magnet current (Io) loop with an inner unfiltered voltage (Vr) loop.  
Current sensor 9V equals 1,400A  
Voltage sensor 5V equals 1,000V  
Current loop (P) Gain=4  
Voltage loop (PI) Gain=1,  $\tau=22\mu$ s
- Two stage output filters (Lo1, Co1, Lo2, Co2), with corner frequency about 26kHz, reduce the switching frequency voltage ripple in the output.
- Damping capacitor (Co3) and resistor (Ro3) improve output transient performance for the pulsing applications
- The control strategy for the high frequency converter employs an outer magnet current (Io) loop with an inner unfiltered voltage (Vr) loop.
- Parameters for the switch mode converter in Figure 1 are:

Vab=460V, Vo= $\pm$ 800V, Io=1,400A  
TR1 460V/225V/225V/225V  
LFA=LFB=LFC= 10 mH  
CFA=CFB=CFC= 43.2mF  
CDA=CDB=CDC= 80 mF  
RDA=RDB=RDC= 0.7 $\Omega$   
LO1=LO2= 6 $\mu$ H  
CO1=CO2= 6 $\mu$ F  
RO1= 1 $\Omega$ , CO3=20 $\mu$ F

### 3 KEY SYSTEM SPECIFICATIONS

This section identifies the significant performance requirements/results for input and output of the pulse converter.

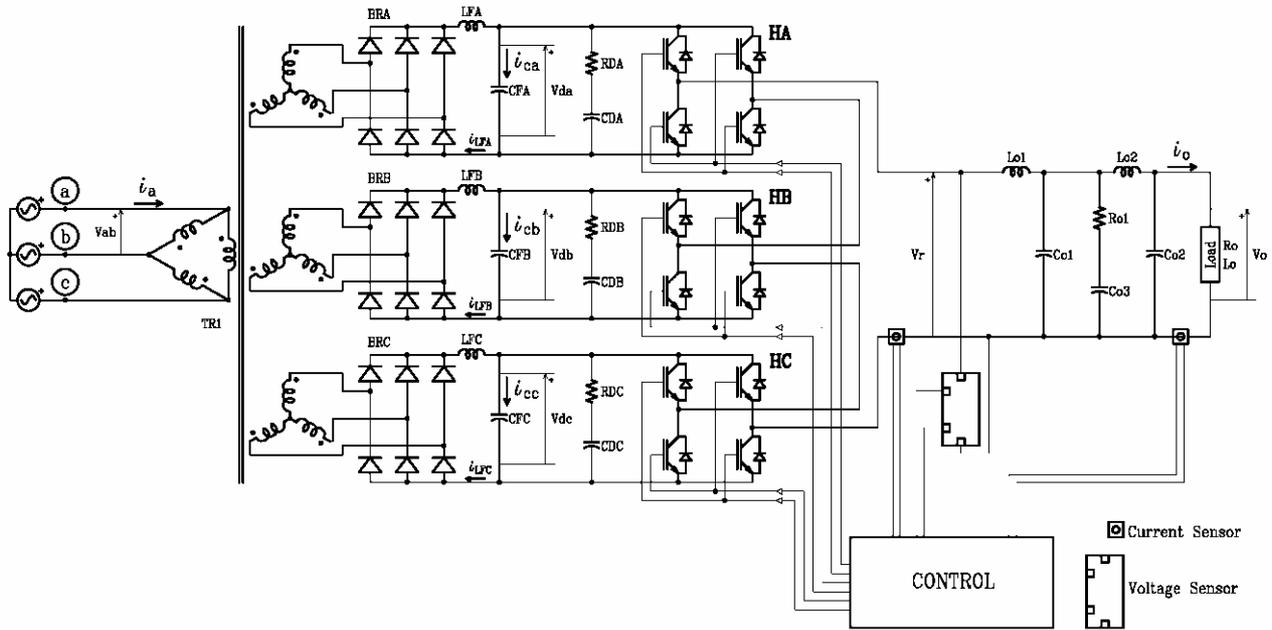


Figure 1 Basic 1.12MVA converter System

### 3.1 Input

Voltage RMS	460V, +10%, -5%
Current RMS	50A

### 3.2 output

DC Voltage	0 to 800V, 0 to -800V
DC Current	0 to 1,400A max. Pulsed (400Arms equivalent)
Pulse Repetition Frequency	60Hz
Switching Frequency	108kHz
Large Signal Current Response	> 2kHz at 45° Shift at 1.4kA
Load Current Tracking	See Figure 2
Load Current Fall time	< 0.5msec. From 1.4kA to 0
Current Stability In Flat Top	< 0.1% (1.4A)
Magnet Load	L= 160μH, R=0.013Ω

### Note:

1. The linear rise plus the flat top of the current reference waveform varies from 2 to 3 ms and since fall varies from 280 μs to 1 ms, the worst case pulse width is 4 ms.
2. The fall time for the reference is 280 μs and the load current falls to less than 1.4A in less than 500 μs. Any overshoot on the current waveform shall settle in less than 300 μs.

## 4 SIMULATION RESULTS

This section provides the following simulation results:

- i. Figure 3 shows output current  $i_o$ , and output voltage ( $v_o$ ) for rated value of  $i_o$
- ii. Figure 4 shows output current  $i_o$ , and output voltage ( $v_o$ ) for  $i_o$  near zero
- iii. Figure 5 shows input ac voltage  $v_{ab}$  and  $i_1$  at 60 Hz pulse repetition rate
- iv. Figure 6 shows the dc voltage  $v_{da}$  and capacitor CFA current  $i_{ca}$  for one dc section at 60 Hz pulse repetition rate

These results meet the required critical specification close to zero output current. Also Figure 6 shows how the dc link capacitors, in three isolated dc inputs, provide the energy storage for the load inductance.

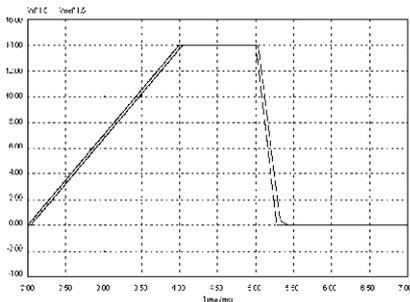


Fig.2 Output Current (100A/V) and Required Output Current Feedback (100A/V), According to System Specifications

## 5 EXPERIMENTAL RESULTS

To achieve experimental output current  $i_o$  waveform close to the simulated results, a minimum output current of nearly 20A is required to reduce oscillations and other circuit non-linearity near zero current. Figures 7 and 8 provide experimental results for rated and near zero output current. All other simulated results (except performance near zero current) essentially agree with experimental results.

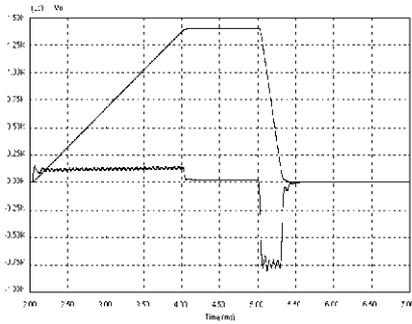


Figure 3 Output current  $i_o$ , and output voltage ( $v_o$ ) for rated value of  $i_o$  (Vert. 250/div, Hor. 0.5ms/div)

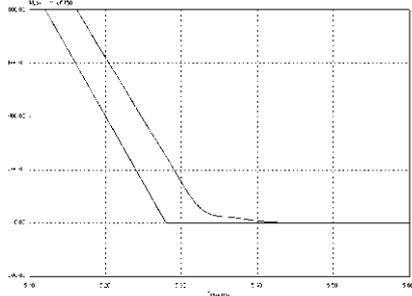


Figure 4 Output current  $i_o$  and output current command near zero value of  $i_o$  (Vert. 200/div, Hor. 0.1ms/div)

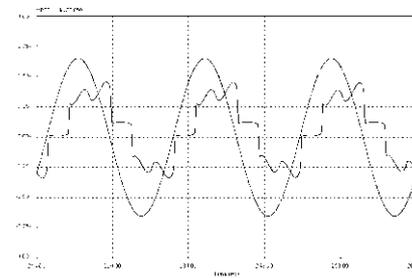


Figure 5 Input ac voltage  $v_{ab}$  and  $i_1*50$  at 60 Hz pulse repetition rate (Vert. 250/div, Hor. 10ms/div)

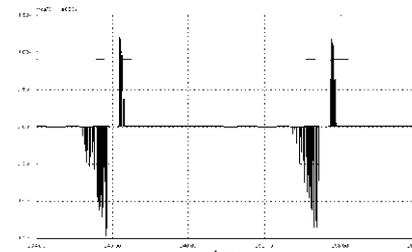


Figure 6 DC voltage  $v_{da}*3$  and capacitor CFA current  $i_{ca}$  for one dc section at 60 Hz pulse repetition rate (Vert. 500/div, Hor. 6ms/div)



Figure 7 Experimental output voltage (375V/div) and rated output current (450A/div) with dc bias of 20A

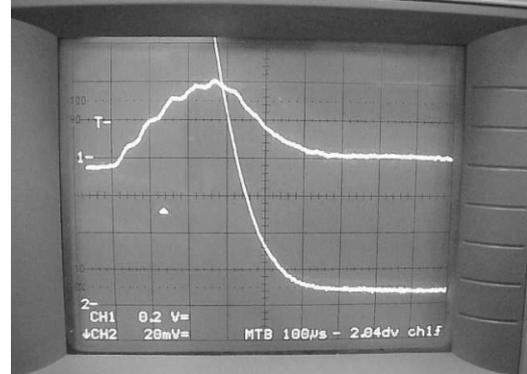


Figure 8 Experimental output voltage (375V/div) and rated output current (45A/div) with dc bias of 20A

## 6 CONCLUSIONS

This paper has discussed the features and results of a high power amplifier. The desired results could be achieved for magnet current from 1,400A to 20A. The requirement for the application is to achieve controlled fall time to 1.4A. This limitation is caused by the very low pulse width, turn on/turn off times of IGBT's, and other circuit nonlinearities at the low current. Further modification to the converter circuit to achieve desired low current performance will be presented in a subsequent paper. For any question, please contact

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