1400A, +/- 900V PEAK PULSE SWITCH MODE POWER SUPPLIES FOR SNS INJECTION KICKERS*

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Abstract
This paper describes simulation and experimental results for a 1400A, ±900V peak rated, switch mode power supply for SNS Injection Kicker Magnets. For each magnet (13 mΩ, 160μH), 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 millisecond in a controlled manner, flat top for up to 2 milliseconds, and should fall in a controlled manner to less than 4A within 500μs. The low current performance during fall time is the biggest challenge in this power supply. The simulation results show that to meet the controlled fall of the current and the current ripple requirements, voltage loop bandwidth of at least 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°, 60° & 120°) converters each with 40 kHz switching frequency (IGBT at 20kHz), has been achieved. In this paper, the circuit topology, relevant system specifications and experimental results that meet the requirements of the power supply are described in detail. A unique six pulse SCR rectifier circuit with capacitor storage has been implemented to achieve minimum pulse width 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.

INTRODUCTION
This paper deals with the description, experimental and simulation results of the 1,400A, ±900V switch mode converter with six pulse SCR rectifier circuit and storage capacitors. In section 2, the basic converter topology including system parameters is described. The relevant specifications are outlined in section 3. The simulation results are outlined in section 4. In section 5, the experimental results show good agreement between experimental and simulation results both at low and high current values. Section 6 discusses the major conclusions of this research.

BASIC CONVERTER SYSTEM
Figure 1 shows the essential elements of the two-quadrant switch mode converter system. For the function of components with lighter lines, refer to reference 1 for details.
All the essential circuit parameters on Fig.1 are the same as reference 1. Additional components added to improve low current performance are shown in thicker lines in Fig.1. The function and parameter values of these additional components are as follows;
- DC storage capacitor Cs to provide essentially a DC source of approximately 60V with low ripple to keep minimum pulse width in the IGBT switching modules. The value of Cs is 1.64F.
- DC filter choke La (30μH) to reduce the 360 Hz ripple in the six pulse rectifier
- Six pulse SCR rectifier (SCRs, Q1 to Q6) that operates in the inverting region at delay angle α=135°.
- An isolating transformer LRT (460:58V) to isolate the load from the 3 phase input

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

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

Output
- DC Voltage 0 to 900V, 0 to −900V
- 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
- Tracking Error 0.1%
- Load Current Fall time < 0.5msec. from 1.4kA to 4A
- 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 4A in less than 500 μs. Any overshoot on the current waveform shall settle in less than 300 μs.

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Figure 1 Basic 1,400A, ±900V Converter System with Energy Storage Capacitor CS and Six Pulse SCR Rectifier

Figure 2 Output current (100A/V) and required output current feedback (100A/V), according to system specifications

SIMULATION RESULTS

This section provides the following simulation results (in addition to the simulation results in reference 1):

i. Figure 3 shows output current $i_o$ and output voltage $v_o$ for rated value of $i_o$.

ii. Figure 4 shows energy storage capacitor current $i_{sc}$ and output current $i_o$ for rated value of $i_o$.

iii. Figure 5 shows filter inductor $L_a$ current $i_{La}$ and six pulse rectifier voltage $v_{WA}$ for rated value of $i_o$.

iv. Figure 6 shows output current $i_{oa}$ and output voltage $v_o$ for $i_o$ near zero for rated value of $i_o$.

These results meet the required critical specification close to zero output current. These results show how a minimum DC voltage is introduced in the circuit that absorbs and acts as a DC battery source. A storage capacitor CS only absorbs AC current, DC current $i_{oa}$ returns the active DC power to the ac source due to inverter region operation of the six pulse bridge (delay angle $\alpha=135^\circ$). The steady state DC storage capacitor voltage $(V_s)$ is 65V with 0.5V peak to peak ripple at pulsing frequency of 60 Hz.

Figure 3 output current $i_o$ (500A/div), and output voltage $v_o$ (500V/div) for rated value of $i_o$.

Figure 4 Energy storage capacitor current $i_{sc}$ (500A/div) and output current $i_o$ (500A/div) for rated value of $i_o$.
EXPERIMENTAL RESULTS

Experimental results shown in figures 7 to 10 are in close agreement with simulated results in figures 3 to 6.

CONCLUSIONS

This paper has discussed the features and results of a high power amplifier. The desired rise, flat top and fall time current results were achieved for pulse magnet current from 1,400A to 4A. The main problems are:

1). The peak to peak ripple current at flat top is about 4A (required is 1.4A)

2). The current tracking between two similar units should be better than 0.5%. A great deal of simulation work is needed to establish the most sensitive parameters that affect current tracking. Also means must be identified to correct for practical variations in load parameters.

Further modification to the converter circuit and controls to achieve desired ripple and tracking current performance will be presented in a subsequent paper. For any question, please contact Shashi Dewan (dewandps@aol.com) and Bob Holmes (iepower@iepower.com)

REFERENCES