A 250 kW Four Quadrant Switch Mode Converter for the 1.4 GeV PS-Booster Beam Transfer Lines at CERN

S.Dewan (DPS), R.Holmes (IE), K.Reiniger (TRIUMF),
F.Voelker (CERN), J.Zeng (UOT)

Abstract

This paper describes a four quadrant, 250kW(550V, 450A) switch-mode, zero current soft switching (ZCS) power converter for a 1.4 GeV beam transfer line magnet. The ZCS technique is the preferred approach for the high power switch-mode converters employing Insolated Gate Bipolar Transistors (IGBT) to reduce switching losses and EMI. This switch-mode power converter topology has been selected because of the high dynamic response, low output ripple, and low input current harmonics. In this paper, the circuit topology, function of the system components, key system specifications and experimental results for a 250kW switch-mode converter are described in detail. The experimental results include output current transient response and conducted electromagnetic interference (EMI, measurements at both AC input and DC output). The design and development process employed is based on virtual electrical simulation of the system. This technique has been essential for the successful development of this unit.

1 INTRODUCTION

This paper deals with the description, specification, experimental and simulation results of 250 kW switch mode converter for pulse magnet power supplies. In section 2, the basic converter topology including control philosophy and system parameters is described. The key specifications are outlined in section 3. The experimental results including input and output EMI are outlined in section 4. The simulation results and the prototype development process are discussed in section 5.

2 BASIC CONVERTER SYSTEM

Figures 1 and 2 show the essential elements of the 250 kW four-quadrant switch mode converter system.

- EMI filter (EMI1) reduces conducted EMI to the input source.
- Reactors (Ls and Lp) and capacitor (Cp) provide required reduction of the input harmonic currents.
- Diodes (D1 to D6) convert three-phase AC voltage to DC voltage.
- Two stage LC filters (Lf1, Lf3, Cf1, Cf3), with a corner frequency of approximately 40 Hz, reduce the line harmonic voltage from the converter output.
- Damping capacitor (Cf2) and resistor (Rd2) reduce dc voltage change during the step change in the input source voltage.
- Three 100kW high power inverter modules are connected with the primaries of the three 18 kHz isolation transformers (TR1A, TR1B, TR1C) in parallel and the secondaries in series. This configuration is extremely rugged and, the current sharing in the three modules is ensured by this circuit topology.
- Each high frequency inverter module consists of a high frequency filter (Lhf, Chf) that ensures that switching frequency currents generated by the inverter does not flow back to the line. IGBTs (S1 to S4) are connected in a full bridge configuration and switched at 18 kHz to convert the DC to high frequency (18 kHz) AC.
- Diodes DO1 to DO4 rectify the high frequency AC to DC.
- Two stage output filters (Lo1, Co1, Lo2, Co2), with a corner frequency about 2 kHz, 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 inverter employs an outer magnet current (I_o) loop with an inner unfiltered voltage (V_r) loop.
- Figure 2 shows the basic four quadrant regenerative circuit and its connections with converter in figure 1. This circuit consists of; Isolation IGBT switch T5 for disconnecting from the high frequency converter, Isolating diode D5 and energy storage capacitor C5, SCR reversing switch Q1 to Q4, crowbar SCR (SC) to protect over-voltage on C5, output EMI filter (EMI2) to reduce conducted EMI in the magnet current. A regenerative three phase SCR bridge (T1 to T6) operating at a fixed delay angle of 150 degrees and the source isolation transformer TRG.
- Parameters for the 250 kW switch mode converter in figures 1 and 2 are:
  Vab=400V, Vo=550V, Io=450A;
  Ls=190μH, Lp=293μH, Cp=460μF;
  Lf1=Lf3=0.8 mH, Cf1=Cf3=30,000μF;
  Cf2=90,000μF, Rd2=0.365 Ω;
  Lhf=10μH, Chf=40μF;
  Turn Ratio of TR1, TR2, & TR3 N=0.5;
  Lo1=Lo2=100μH, Co1=100μF, Co2=60μF;
  Co3=500μF, Ro3=0.28Ω;
  Voltage ratio of TRG is 1.25, C5 = 60,000μF.

0-7803-7191-7/01/$10.00 ©2001 IEEE.

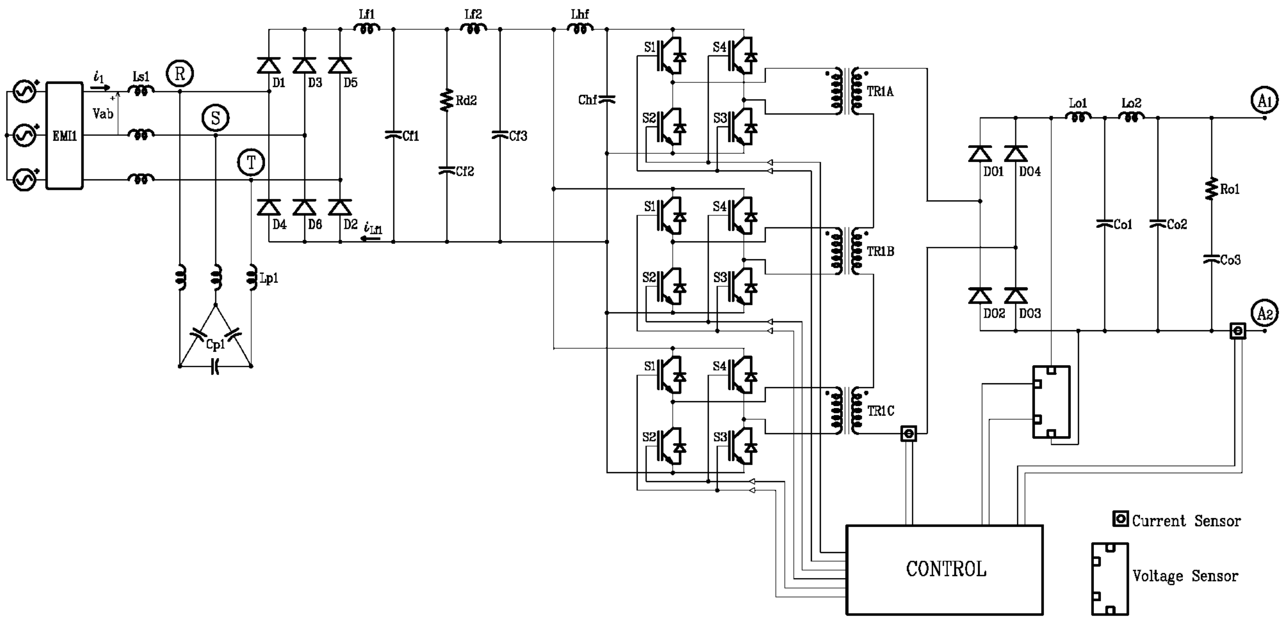

Figure 1: Basic 250 kW Switch Mode Converter System as Input to Four Quadrant Regeneration- Circuit (Fig.2)

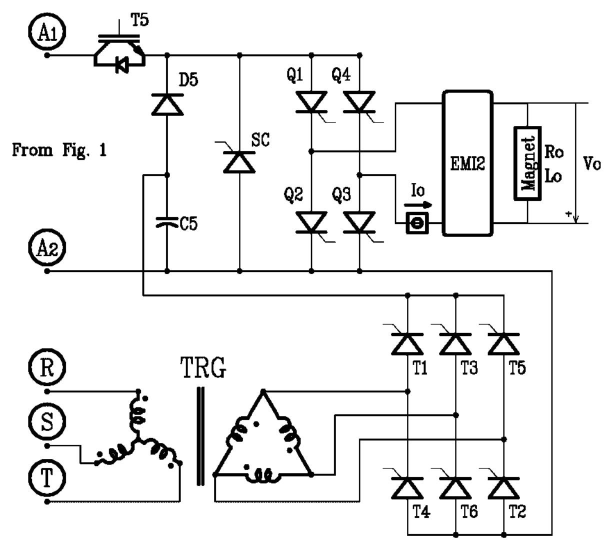

Figure 2: Basic Four Quadrant Regenerative Circuit with 250 kW Converter in Figure 1

3 KEY SYSTEM SPECIFICATIONS

This section identifies the significant performance requirements/results for input and output of the 250 kW converter. Both simulation and experiments have verified that the required performance has been met.

3.1 Input

Voltage RMS	400V±10%
Current RMS	410A
Current Harmonic Distortion	<21A(5%)
Efficiency at Full Load	> 95%
Efficiency at 50% Load	> 90%
EMI	EN-5501/Gr-1CI-A , VDE-08715 Grade N

3.2 Output

DC Voltage, Continuous	0 to 550V
DC Current, Continuous	0 to 450A
Unfiltered Voltage Loop Bandwidth	>2,000Hz
Closed Current Loop Bandwidth	> 300 Hz
Low Frequency Output Voltage Ripple up to 1 kHz	< 100 mV_{P-P}
High Frequency Output Voltage Ripple greater than 1 kHz	< 200 mV_{P-P}
Dynamic Response in Current Mode with Magnet R=0.42Ω, L=370 mH (Time constant 925ms)	Settling time to 100ppm of rated current within 750 ms for modulation of +100% to –100%

4 EXPERIMENTAL RESULTS

Input line current and output voltage ripple (low and high frequency) results are similar to the results presented in 100 kW paper [1]. Tables 1 and 2 show EMI results at input and output of the unit, respectively. Figures 3 and 4 show the waveforms at full power for magnet voltage (Vo) magnet current (Io) and energy storage capacitor C5 voltage (V5) during rise, flat and fall periods of the magnet current. Figure 5 shows the magnet voltage and current waveforms during reversal of magnet current from +100% to –100%.

Table 1: Worst Case Input EMI Test Data of 250kW Four Quadrant Switch Mode Converter

Freq (MHz)	RF Level (dBuV)	Receiver Detector (P/QP/AVG)	QP Limit (dBuV)	AVG Limit (dBuV)	Margin (dB)
0.20	56.2	QP	79.0	66.0	-22.8
0.20	56.2	AVG	79.0	66.0	-9.8
0.75	46.4	QP	73.0	60.0	-26.6
0.75	46.3	AVG	73.0	60.0	-13.7
0.86	48.8	QP	73.0	60.0	-24.2
0.86	46.6	AVG	73.0	60.0	-13.4
1.05	55.5	QP	73.0	60.0	-17.5
1.05	55.5	AVG	73.0	60.0	-4.5
2.75	41.1	QP	73.0	60.0	-31.9
2.75	39.4	AVG	73.0	60.0	-20.6
5.23	50.5	QP	73.0	60.0	-22.5
5.23	49.4	AVG	73.0	60.0	-23.6

Table 2: Worst Case Output EMI Test Data of 250kW Four Quadrant Switch Mode Converter

Freq (MHz)	0.408	0.497	0.904	1.083	5.25	10.96
RF Level (dBuV)	87.8	89.8	90.7	63.1	87.6	63.1

Note: The emissions were scanned from 150 kHz to 30 MHz at AC mains via a LISN.

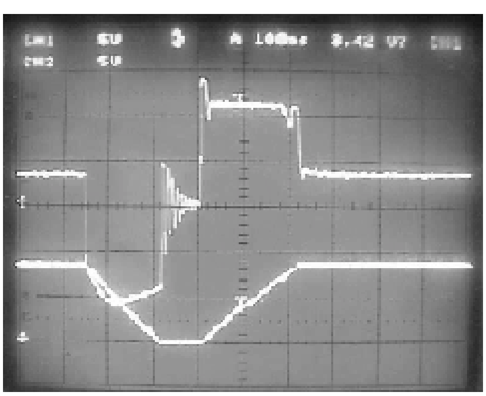

Figure 3: Magnet Voltage,Vo (275V/div, 100ms/div) and Magnet Current, Io (250A/div, 100ms/div)

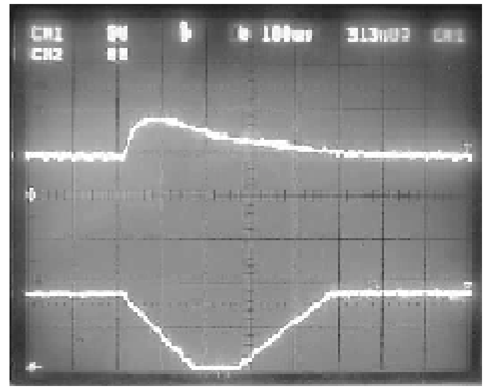

Figure 4: Energy Storage Voltage, V5 (330V/div) and Magnet Current, Io (250A/div, 100ms/div)

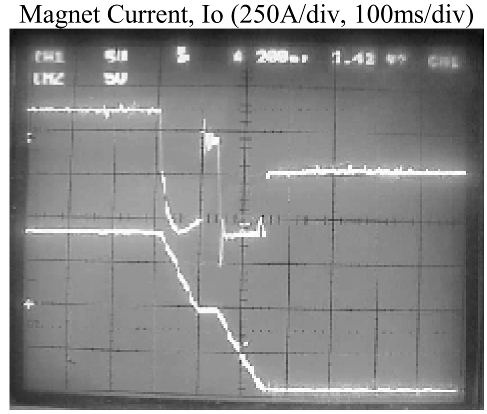

Figure 5: Magnet Voltage, Vo(275V/div, 200ms/div) and Magnet Current, Io (250A/div, 200ms/div)

5 SIMULATION RESULTS

This virtual electrical prototyping by simulation has been extremely useful in the reduction of design and implementation periods for the prototype. The simulation results for all the relevant performance, including system losses and EMI were close to the experimental results.

6 CONCLUSIONS

This paper has discussed the features and results of a 250kW four-quadrant switch mode converter. This converter was designed and tested using a virtual prototyping simulation process described in [1]. For any questions, please contact:

Shashi Dewan (sdewan@inverpower.com) or
Bob Holmes (iepower@iepower.com) .

REFERENCES

[1] S.Dewan et. al "High Power Switch-mode Power Converters for the 1.4 GeV PS-Booster Beam Transfer Lines at CERN", EPAC'2000, Vienna, June 2000.