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## **HIGH POWER SWITCH-MODE POWER CONVERTERS FOR THE 1.4 GEV PS BOOSTER BEAM TRANSFER LINES AT CERN**

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

### *Abstract*

*This paper will be published in the Proceedings of EPAC'2000,  
7th European Particle Conference, 26-30 June, Vienna, Austria*

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## *Foreword*

The power converters needed to upgrade the 1.4 GeV/c Booster beam lines have been designed and built in Canada. After a series of 37 converters with power of 15, 31.5 and 35 kW, Canadian industry has successfully produced six 100 kW and two 250 kW units. Water cooled IGBT (Insulated Gate Bipolar Transistor) H-bridges, switched at 18 kHz, ferrite transformers and fast diode rectifiers have been used.

This realisation shows that modern switch-mode technology is now conquering the place of classical thyristor solutions in the power range up to 1 MW.

The note describes and documents the 100 kW converters, emphasizing the extensive use of computer simulations and giving insight into some interesting design aspects.

*Friedrich Völker*

# High Power Switch-mode Power Converters for the 1.4 GeV PS-Booster Beam Transfer Lines at CERN

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

## Abstract

For preparing the proton injector chain for the Large-Hadron-Collider (LHC) at CERN, the PS-Booster has been upgraded from 1 to 1.4 GeV. New switch-mode, zero current soft switching (ZCS) power converters, with DC output ratings ranging between 15 and 250 kW (550V and 500A) have been developed for the 1.4 GeV beam transfer line magnets. The ZCS technique is the preferred approach for the high power switch-mode converters employing Insulated Gate Bipolar Transistors (IGBT) to minimize switching losses and EMI. The switch mode power converters have been selected because of the high dynamic response, low output ripple, and low input current harmonics. In this paper, the circuit topology, function of system components, key system specifications and experimental results for a 100 kW switch mode converter are described in detail. 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 results and the development process of 100 kW switch mode converters for DC and pulse magnet power supplies. In section 2, the basic converter topology including the control philosophy is described. The key specifications and experimental results are outlined in section 3. The performance of the switch mode converter has been compared with phase control converter in section 4. The simulation/design/development process is discussed in section 5.

## 2 BASIC CONVERTER SYSTEM

Figure 1 shows the essential elements of the 100 kW switch mode converter system:

- EMI filter (EMI1) reduces conducted EMI to AC input source.
- Reactors ( $L_s$ ,  $L_p$ ) and capacitor ( $C_p$ ) provide required reduction of the input harmonic currents.
- Diodes (D1 to D6) convert three-phase AC voltage to DC voltage.
- Two stage LC filters ( $L_{f1}$ ,  $L_{f3}$ ,  $C_{f1}$ ,  $C_{f3}$ ), with a corner frequency of approximately 40 Hz, reduce the line harmonic voltage from the converter output.

- Damping capacitor ( $C_{f2}$ ) and resistor ( $R_{d2}$ ) reduce DC voltage change during the step change in the input source voltage.
- High frequency filter ( $L_{hf}$ ,  $C_{hf}$ ) ensures that switching frequency currents generated by the inverter do 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.
- 18 kHz high frequency transformer (TR1) provides the (isolated) desired output voltage.
- High frequency diodes (Do1, Do2) convert the 18 kHz AC voltage to DC voltage.
- Free wheeling diode (DF) provides a path for the current when Do1 and Do2 are not conducting.
- Two stage output filters ( $L_{o1}$ ,  $C_{o1}$ ,  $L_{o2}$ ,  $C_{o2}$ ), with a corner frequency of about 2 kHz, reduce the switching frequency voltage ripple in the output.
- Output damping capacitor ( $C_{o3}$ ) and resistor ( $R_{o3}$ ) improve output transient performance for the pulsing applications.
- The control strategy employs an outer magnet current ( $I_o$ ) loop with an inner unfiltered voltage ( $V_o$ ) loop. The inner voltage loop has also another inner primary current ( $I_p$ ) loop. This  $I_p$  loop ensures that transformer TR1 does not saturate due to transients and asymmetry in switching properties of the IGBT switches.
- The parameters for the 100 kW switch mode converter shown in figure 1 are:

$V_{ab}=400$  V,  $V_o=200$  V,  $I_o=500$  A;  
 $L_s=475$   $\mu$ H,  $L_p=700$   $\mu$ H,  $C_p=192$   $\mu$ F;  
 $L_{f1}=L_{f3}=1.2$  mH,  $C_{f1}=C_{f3}=12,000$   $\mu$ F;  
 $C_{f2}=36,000$   $\mu$ F,  $R_{d2}=0.365$   $\Omega$ ;  
 $L_{hf}=10$   $\mu$ H,  $C_{hf}=40$   $\mu$ F;  
Turn Ratio of TR1:  $N=0.5$ ;  
 $L_{o1}=L_{o2}=100$   $\mu$ H,  $C_{o1}=100$   $\mu$ F,  $C_{o2}=60$   $\mu$ F;  
 $C_{o3}=500$   $\mu$ F,  $R_{o3}=0.28$   $\Omega$ .

## 3 KEY SYSTEM SPECIFICATIONS AND EXPERIMENTAL RESULTS

This section identifies the significant performance requirements/results for input and output of the 100 kW switch mode converter. Both simulation and experiments have verified these results.

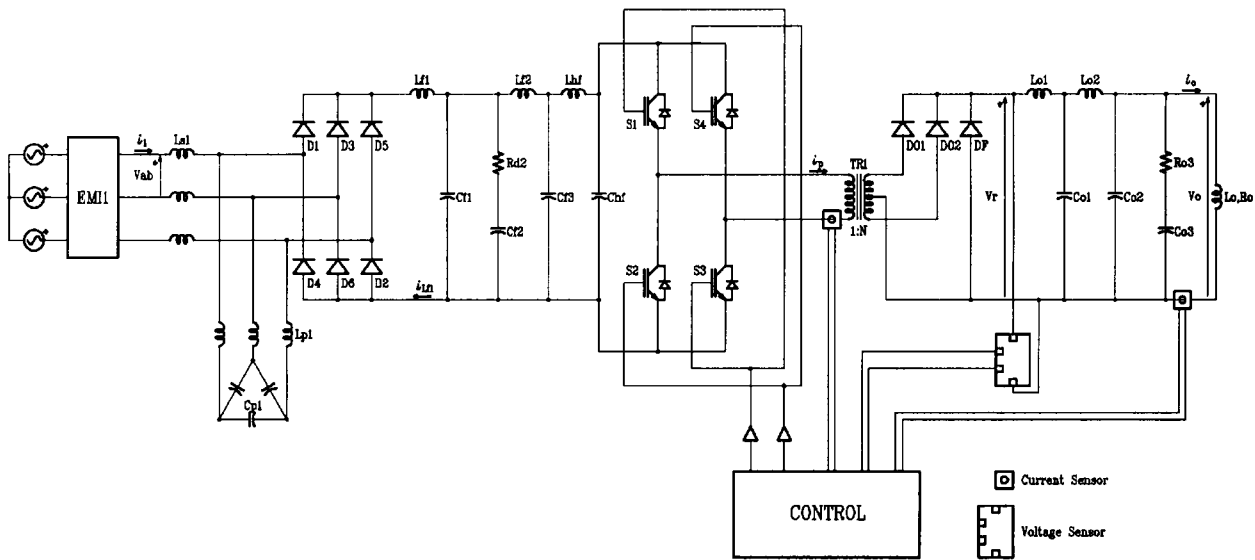


Figure 1: Basic 100 kW Switch Mode Converter System (ZCS)

### 3.1 Input

Voltage RMS	400 V $\pm$ 10%
Current RMS	164 A
Current Harmonic Distortion	<8 A (5%)
Efficiency at Full Load	> 90%
Efficiency at 50% Load	> 85%
EMI	EN-55011/Gr-1CI-A , VDE-08715 Grade N

AC input line current at rated power is shown in figure 2. Also, EMI results are presented in table 1.

### 3.2 Output

DC Voltage, Continuous	0 to 200 V
DC Current, Continuous	0 to 500 A
Unfiltered Voltage Loop Bandwidth	>2,000 Hz
Closed Current Loop Bandwidth	> 300 Hz
Low Frequency Output Voltage Ripple up to 1 kHz	< 20 mV <sub>p,p</sub>
High Frequency Output Voltage Ripple greater than 1 kHz	< 200 mV <sub>p,p</sub>

Figures 3 and 4 show the worst case low frequency and high frequency output voltage ripple, respectively.

Table 1: Worst Case EMI Test Data of 100kW Switch Mode Converter

Freq (MHz)	RF Level (dB $\mu$ V)	Receiver Detector (P/QP/AVG)	QP Limit (dB $\mu$ V)	AVG Limit (dB $\mu$ V)	Margin (dB)
0.16	54.9	QP	79.0	66.0	-24.1
0.16	54.7	AVG	79.0	66.0	-11.3
0.19	54.3	QP	79.0	66.0	-24.7
0.19	54.3	AVG	79.0	66.0	-11.7
0.23	55.5	QP	79.0	66.0	-23.5
0.23	55.4	AVG	79.0	66.0	-10.6
0.26	56.3	QP	79.0	66.0	-22.7
0.26	56.2	AVG	79.0	66.0	-9.80
0.30	51.8	QP	79.0	66.0	-27.2
0.30	51.8	AVG	79.0	66.0	-14.2

**Note:** the emissions were scanned from 150 kHz to 30 MHz at AC mains via a LISN, and all emissions less than 30 dB below the limits were recorded.

## 4 COMPARISON OF PHASE CONTROL AND SWITCH MODE

With new developments in IGBT technology, system modelling and EMI filter technologies, switch mode has become a viable option for magnet power supplies for both DC and pulsed applications. When compared with phase control, the advantages of the switch mode supplies are:

- At least 10 times greater voltage and current loop bandwidths.
- Lower output voltage ripple especially with pulse application.

- Lower output current ripple.
- Better tracking performance in pulse applications.
- Better settling performance in time and accuracy in pulse applications.
- High input power factor and negligible input current harmonics.
- Much lower audible noise.
- Less physical space for similar requirement.

The main disadvantage of the switch mode converters is higher losses (approximately 50% higher due to three stages of conversion) when compared with 12-pulse phase control designs.

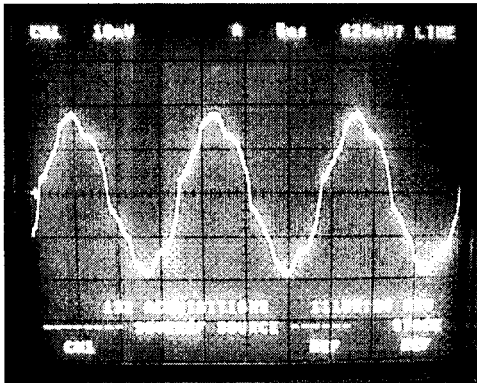


Figure 2: Input Line Current ( $i_l$ ) at output of 200 V, 500 A (100 A/div, 5 ms/div)

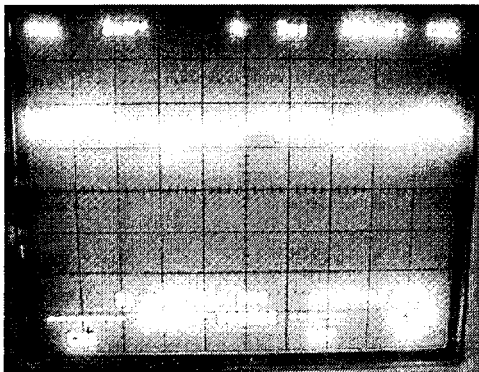


Figure 3: Low Frequency Output Voltage ( $V_o$ ) Ripple (20 mV/div, 2 ms/div)

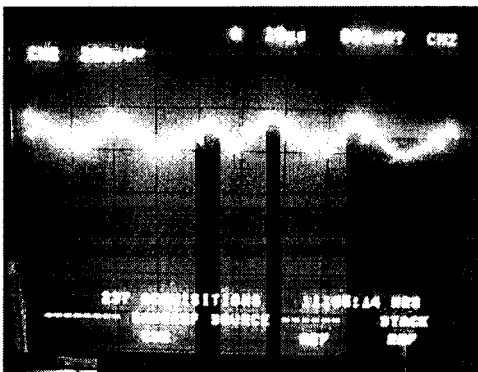


Figure 4: High Frequency Output Voltage ( $V_o$ ) Ripple (200 mV/div, 10 μs/div)

## 4 DESIGN/DEVELOPMENT PROCESS

During the process of development of the 100 kW power supply, electrical simulation was employed extensively from the beginning of the development. A commercial software package was used as simulation tool. This software package was enhanced by developing an interactive design software package, which accomplished the following tasks:

- Processed the data from simulation.
- Identified optimum power circuit and control configurations.
- Verified the transient and steady state system input and output parameters.
- Established the major component specifications, power losses and EMI filter requirements.
- Verified essentially all experimental results.

This virtual electrical prototyping by simulation has been extremely useful in the reduction/elimination of errors early in design. Essentially no component was ordered till the virtual prototyping process was completed. The simulation results for all the relevant performance, including system losses and EMI were close to the experimental results. We believe that this design process also provide the following:

- Increases product reliability.
- Reduces design cost.
- Maintains control of project schedule.
- Allows feasibility/cost evaluation of other ratings for converters of similar design.

The major difficulty in the development of the 100 kW power converters was that, for some components, suppliers did not meet the required specifications.

## 5 CONCLUSIONS

This paper has discussed the salient features of a 100 kW switch mode power converter. This converter was designed and tested using a virtual prototyping simulation process. The performance of this power converter is significantly better than the SCR phase control design especially for pulse applications. A 250 kW power converter is currently being developed and the results will be reported in a subsequent paper.

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