# High Current, Low Voltage Power Converters for LHC. Present Development Directions.

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## *Abstract*

The superconducting LHC accelerator requires high currents (12.5kA) and relatively low voltage (~10V) for its magnets. The need to install the power converters underground is the driving force for reduced volume and high efficiency of the power converters. Moreover, the machine will require a very high level of performance from the power converters, particularly in terms of DC stability and dynamic response. To meet these requirements switch-mode techniques will be used. This paper gives a survey of current switch-mode converter topologies for high DC current output. The presentation is primarily focused on the various methods for low-loss switching in DC power converters operating with high switching frequency (20 - 50 kHz). A modular concept is being studied, using several current sources in parallel, to adapt to the various circuits and also provide redundancy.

## 1 INTRODUCTION

The LHC accelerator requires large currents and rather low voltages for its superconducting magnets. The installation of the power converters on the surface and the cabling to their underground magnets would be prohibitive because of the high DC currents. The underground installation is the driving force for reduced volume and high efficiency of the power converters.

A provisional list of power converters is given in the LHC Conceptual Design book [1]. An optimisation process is going on for voltages and types. The process is converging towards four main types of converters :

a) The first type of converter is the main dipole magnet converter. The LHC machine is divided in eight sectors, each powered by a separate power converter [2]. These eight power converters need to have a very large dynamic range to supply ± 185V during acceleration and normal de-excitation of the machine within reasonable time (20 minutes), but only about 1V while at injection energy. The steady state specification for physics is 12.5kA, 10V. Several studies have been launched to select topologies suitable for these converters.

b) Each quadrupole and each aperture of the LHC machine has associated with it a small dipole orbit corrector. In total there are about 720 for the arcs and about 260 in the dispersion and insertion regions. The best solution is to locate these converters in the LHC tunnel close to the quadrupole magnets : reduction of the cabling costs and of the power of the converter (±8V instead of ±115V at ±50A for a surface location). This underground installation is directly dependent on the possibility to get a very high reliability and redundancy (no access in the tunnel during operation periods) and radiation hardened devices (~10Gy in 10 years). An evaluation is underway at CERN to study the feasibility of this installation but will not be described in this paper.

c) The third type of converter corresponds to the converters for the main quadrupoles, the insertion quadrupoles, the separators, etc. The output specifications are [12.5kA, 15V], [12.5kA, 8V], [9kA, 8V] and [6kA, 8V]. Taking into account that the state-of-the-art for DC-DC power converter modules is in the range of 30 to 50 kW, these converters will be made up using a modular concept where several high-current sources ( [3.2kA, 8V] or [3.2kA, 15V] ) are placed in parallel; this concept can also provide redundancy. A total of around 700 modules will be used for the LHC.

d) Unipolar [600A, 12V] and true bipolar power converters [±600A, ±12V] are required to power the sextupoles, the sextupole and decapole spool piece circuits and the octupoles. In total there are about 320 converters (160 unipolar and 160 bipolar).

This paper gives a survey of current developments and trends for the two last types of converters.

The main requirements for the LHC converters are :

- high precision (<10 ppm)
- drastic reduction of the volume and weight due to the underground installation. All the power converters must fit in the existing underground LEP infrastructure.
- high efficiency (> 80% for the unipolar converters and > 70% for the bipolar converters). To permit an easy extraction of the remaining losses from the tunnel, water cooling of the converters is mandatory.
- galvanic isolation between mains and output load
- wide output current range (Imax/Imin ~ 50 )
- very high reliability and operational redundancy; access to the underground areas will be difficult and will take a long time.
- repairability. All converters must be designed with fast plug-in modules. The weight of each module must not exceed 25 kg to permit one operator to do a fast exchange.

To meet these requirements switch-mode techniques will be used. The presentation is primarily focused on the methods for soft-switching DC-DC power converters operating with high switching frequency (20 - 50 kHz).

## 2 SOFT-SWITCHING CONVERTERS

The above requirements for the LHC converters imply the use of high switching frequencies. Operation at higher frequencies results in a considerable size reduction (volume and weight) for transformers and filter and better dynamics. It gives a better rejection of the perturbations and a lower ripple of the output voltage. However, losses associated with high-frequency operation have to be kept as low as possible to achieve efficient power conversion. Switch-mode power conversion technologies have evolved from the basic PWM converters to the so-called soft-switching converters. The PWM converters process power by interrupting the power flow with abrupt switching (hard switching). This operation results in high losses dissipated in the switching elements during the turn-on and turn-off intervals. It is necessary to include complex and lossy protection snubbers against the effects of the hard-switching, resulting from the presence of parasitic components in the converter. High voltage and current stresses are applied to semiconductors devices. The attractive properties of soft-switching are :

- the large reduction of switching losses
- the improved reliability due to reduced stress
- a limited frequency spectrum, which means an advantage with respect to EMI and losses in passive components
- a reduction of weight and volume of the components resulting from the higher switching frequency
- a higher bandwidth resulting from the high internal switching frequency
- integration of parasitic elements in the commutation mechanism (e.g. leakage inductance of the transformer in the resonant circuit)

These benefits are realised by turning on or turning off each of the converter switches when either the switch voltage or the switch current is zero. The corresponding switching strategies are respectively known as Zero Voltage Switching (ZVS) or Zero Current Switching (ZCS).

In the power range of 5-50 kW, with available devices (IGBT 1200V) and circuit technologies, the soft-switching converters work with a frequency in the range of 20kHz to 100kHz and the industrial topologies are mainly the resonant or quasi-resonant converters (often called soft-switching PWM converters). All these topologies can be configured in three modules: Module 1: a diode rectifier on the AC mains (400V, 50Hz) with a damped L-C passive filter; Module 2: a voltage inverter and a reactive network to achieve the conditions of the soft commutation; Module 3: high frequency transformers, rectifier stage and output filter. Due to the high output current and low voltage, the secondary of the several HF transformers consists of two center tapped windings, which are connected to Schottky diodes.

## 3 UNIPOLAR CONVERTER TOPOLOGY

### 3.1 Resonant power converters

Resonant converters combine circuit topologies and switching strategies to provide soft-switching [6]. The ZVS operation is possible provided that the power semiconductors are driven at frequencies (f) above the natural frequency (fs) of the resonant L-C network. Conversely, the ZCS operation is obtained with an operating frequency below the resonant frequency. Power control is achieved by the variation of the operating frequency around the resonant frequency. The maximum power is obtained for a frequency close to the resonant frequency.

ZCS resonant converters ($f < fs$), in industrial applications have an operating frequency below half of the resonant frequency (discontinuous mode) to overcome the problem of the recovery current of the antiparallel diode during the turn-on of the main switches. To get a smaller variation of the operating frequency and a smaller inverter current at low power, a double resonant network is used [8]. For this topology, a ratio of 50 between the maximum and the minimum current can be obtained with a frequency range between 1.5 and 2. Unfortunately, these converters have the disadvantage of high current amplitudes for the internal resonant waveforms compared to their external waveforms. Especially, for low output power the amplitude of the resonant current is high which results in an important amount of circulating energy in the resonant circuit.

For ZVS resonant converters, the switches are used as dual thyristors [4]; this overcomes the problem of the recovery current of the diodes. Lossless capacitive snubbers can be used to reduce the turn-off switching losses. This reduction is achieved at the cost of a commutation limit due to the minimum current required to charge or discharge the snubber capacitors. The larger the snubber capacitors are, the sooner the loss of soft-switching occurs. The typical minimum current is in the order of a tenth of the maximum current. Development is under way to overcome this limitation.

### 3.2 Quasi-resonant power converters

For high output current and low voltage, the full-bridge ZVS-PWM converter is deemed more desirable than ZCS-PWM converter [3,5]. The control of the power semiconductors are such that, instead of turning off the diagonally opposite switches in the bridge simultaneously as for a classical PWM, a phase shift is introduced between the two legs of the bridge. This phase shift determines the output power and the control is made at fixed frequency. The switching in the leading leg is done at a nearly constant current; the energy for the parallel switch capacitances (parasitic and snubbers) and the parasitic capacitances of the transformer comes from the series inductance, the leakage inductance and the output filter inductance. This means that the energy stored is very large. For the lagging leg, the zero-voltage turn-on is achieved by using only the energy stored in the series inductance ("soft commutation inductance") and the leakage inductance of the transformer. Therefore, the soft-switching is lost for low load currents. Due to the unsymmetry between the two legs, the lossless snubbers do not need to have the same rating. It is more optimal to reduce the turn-off losses by using larger capacitances in the leading leg than in the lagging leg. The rating of the soft-commutation inductance is the result of a compromise : a large inductance results in a small effective duty cycle (slope of the rising and falling edges of the primary current) but ZVS is achieved over a greater current range. For the prototypes made for the LHC, the ZVS is lost for a current equal to around 30% of the maximum current. For a full bridge, the control of the switches must include a way to compensate any DC offset in the primary current which would saturate the transformer.

RC networks in parallel with the HF rectifier are used to damp the oscillations between the leakage inductance of the transformer and the capacitances of the Schottky diodes.

### *3.3 Future trends*

The present developments at CERN and in collaboration with the European industries and universities (agreements and contracts) are focused on the improvement of the above topologies. The main trend is the improvement of the Imax/Imin range with soft-switching using either ZVS double resonance or the addition of poles in the quasi-resonant converters [7].

## 4 BIPOLAR CONVERTER TOPOLOGY

The normal industrial topology for a four quadrant converter uses a 50Hz step-down transformer, a diode rectifier (PC1) and a PWM inverter (PC2). This solution has the disadvantage to use a large and heavy transformer. The efficiency is very low due to the presence of two conversion stages working at low voltage and high current. In addition the power flow is controlled by a hard-switching inverter working with high current. A [±2000A, ±10V] converter based on this topology has been delivered to CERN for the test of the sextupole magnets. During the phase where the magnet is acting as a generator, the energy is dissipated in a resistance ("brake chopper").

To improve this topology, the first conversion stage is replaced by a unipolar soft-switching converter (PC1). The output PWM inverter is acting as a polarity switch (the output level voltage is controlled by PC1) and it commutates only at a low voltage (minimum voltage of PC1). Both the efficiency and the volume are improved in comparison with the previous structure. Furthermore, in the context of the LHC, where unipolar [600A, 12V] and bipolar [±600A, ±12V] converters are required, the same PC1 can be used. A prototype [±1000A, ±15V] was developed in collaboration with industry. The PC1 is a quasi-resonant converter working at 35 kHz. The PC2 is switching at 100kHz when the output voltage is smaller than one volt. This structure also requires a "brake chopper".

A new structure using differential association of two-quadrant converters is under development with a university. The two-quadrant converters are direct DC/AC/DC converters ("all-silicon converters") using two dual converters (ZVS and ZCS converters) [6].

## 5 CONCLUSION

The results of the work described in this paper prove that soft-switching techniques are necessary and suitable for the LHC power converters. All the future efforts in development will be to select and improve the best topology with its control strategy for all the types of converters, especially for the bipolar converters.

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