PULSED CAPACITOR DISCHARGE POWER CONVERTERS:
AN INTRODUCTORY OVERVIEW

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ABSTRACT
The applications where pulsed power converters are used are recalled and the converters classified according to the specificity of their basic constituent power parts and electronics. Present technical solutions are described and development trends mentioned while specialized reports are referred to for more technical details.

1. INTRODUCTION

Under the term 'pulsed power converters' one understands the family of apparatus based on the charge-discharge of either lumped element Pulse Forming Networks (PFN) or of capacitor banks, designed to produce current pulses with a duration of up to several tens ms and an amplitude of over 1.2 MA.

These power converters are used, instead of dc or programmed converters, to achieve high magnetic fields in very compact deflecting or focusing devices and to perform particular time dependent current patterns for accelerator operations, as shown by the following non-exhaustive list of possible applications (usual current levels are given to characterize the equipment):
- Beam transport bending and quadrupole magnets (< 3 kA)
- Correction and steering dipoles (< 100 A), [1]
- Transversal beam position scanning dipoles (< 200 A)
- Switching magnets to select final beam destination (< 3 kA)
- Switching magnets for beam distribution or recombination (< 1 kA)
- Magnets for local excitation of beam oscillations for ejection (< 2 kA)
- Quadrupoles for gamma transition schemes (< 2 kA)
- Thin monoturn septum magnets (< 50 kA)
- Current carrying targets for p- production (< 0.5 MA)
- Coaxial lenses to collect neutrino parents or p- behind a target (< 0.5 MA)
- Lithium and plasma lenses either to focus the primary p beam in front of the target, or to collect p- or for final focus schemes (< 1.2 MA)
- Super strong quadrupoles for colliding beam focusing (< 0.5 MA) [2]
- Particle collecting and matching solenoids behind e+ production targets (< 20 kA)
- Special radiation-hard post target magnets (< 100 kA)
- Complete fast cycling ultra-compact accelerators and beam extraction gantry systems for medical and industrial applications (< 25 kA) [3,4].

The advantages of pulsed power converters (high efficiency and reduced power consumption, compact magnets, possibility of pulse-to-pulse current modulation in time and amplitude, possibility of multiple pulsing, fast rise time and precise current flat-top regulation) are to be compared with some penalizing features (pulsed low

*) This topic was not presented at the School but is included here to widen the scope of the syllabus.
cos $\phi$ power demand from the mains, higher ac current harmonics content, need of accurate timing pulses to control the charge-discharge sequence, less conventional technology and mode of operation). Nevertheless, thanks to the high adaptability of designs for an ever increasing number of applications, pulsed power converter technology has accompanied the evolution of particle accelerators and will certainly play an even more important role in the frame of future very high energy linear lepton colliders.

2. COMPOSITION OF PULSED CONVERTERS FOR CAPACITOR CHARGE, ENERGY STORAGE AND DISCHARGE

To classify the pulsed power converters one can consider them as consisting of a number of basic functional subassemblies, namely:

i) a mains fed energy supply and charging circuit;

ii) an energy storage PFN or capacitor bank, possibly with third harmonic current pulse shaping;

iii) a discharge circuit, possibly including an energy conversion or recovery unit, an active filter for current flat-top regulation, a pulse transmission line and a load impedance matching transformer;

iv) electronics to fulfil the control, monitoring, timing and regulation functions.

2.1 Charging circuit

The type of charging circuit depends both on the time available and on the power level of the pulsed converter. As indicated in Table 1, the most common methods are resonant capacitor charging (Fig. 1) [5], use of a higher frequency chopper (Fig. 2) and linear charging (Fig. 3) [3]. In general for charging times $> 0.3$ s the mean value of the charging current is kept constant for linear charging of the energy storage element. More recent designs foresee charging at constant active input power to alleviate mains loading, especially in the case of higher power ratings.

<table>
<thead>
<tr>
<th>Charging time (s)</th>
<th>Implemented charging circuit solutions</th>
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<tbody>
<tr>
<td>$&lt; 0.05$</td>
<td>Resonant charging with controlled charge interruption or 'deQuing'</td>
</tr>
<tr>
<td>$0.05 - 0.3$</td>
<td>Higher frequency chopper</td>
</tr>
<tr>
<td>$&gt; 0.3$</td>
<td>6-pulse or 12-pulse (if $&gt; 200$ kW) thyristor controller on primary of stepping-up transformer</td>
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2.2 Energy storage circuit

Lumped element PFN's ($R_o = 25$ Ohm) have been designed to produce current pulses of up to 200 $\mu$s duration with rise and fall time better than 0.1 $\mu$s at a repetition frequency of 1 Hz (Fig. 4) [6]. They require special low-inductive pulse capacitors.
Fig. 1 Power converter with resonant charging within 8 ms for e-e+ converter solenoid of the LEP injector

Fig. 2 Power converter with higher frequency chopper charging for the storage ring injection septum magnets at ESRF (presently under construction)

Fig. 3 Converter with linear charging through thyristor controller on primary of transformer rectifier assembly for the AAC lithium lens pulser
When approximately sinusoidal current pulses are required, simple capacitor banks are used. The most common energy storage capacitor for pulsed applications is the mixed dielectric type (plastic film, paper) with aluminium armatures and either natural (mineral or castor oil) or synthetic oil impregnation. These capacitors are specified as industrial 50 Hz ac units with appropriate ratings to simplify their procurement [7]. In certain cases the capacitor bank is subdivided into two parts, or an extra parallel LC circuit is added to it, in order to superpose a third harmonic component of given amplitude to the basic sinusoidal discharge current (Fig.5).

Concerning the maximum stored energy, which is kept to about 20 kJ per cubicle for reasons of industrial safety, a power converter has been recently built with a capacitor bank of 200 kJ for the pulser of the p- collecting lithium lens (see Fig.3) [8]. A tentative classification of the energy storage circuits is shown in Table 2.

### Table 2*)

**Energy storage circuit classification**

<table>
<thead>
<tr>
<th>Voltage level</th>
<th>Stored energy</th>
<th>Type of capacitors</th>
<th>Third harmonic</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U &lt; 1 \text{ kV (LV)}$</td>
<td>$E &lt; 1 \text{ kJ}$</td>
<td>Industrial $&lt; 20 \text{ kJ}$</td>
<td>Not present</td>
</tr>
<tr>
<td>$1 \text{ kV} &lt; U &lt; 10 \text{ kV}$</td>
<td>$1 \text{ kJ} &lt; E &lt; 20 \text{ kJ}$</td>
<td>Special</td>
<td>Separate LC (Fig.5 (1))</td>
</tr>
<tr>
<td>$U &gt; 10 \text{ kV}$</td>
<td>$E &gt; 20 \text{ kJ}$</td>
<td>Special</td>
<td>Integrated LC (Fig.5 (2))</td>
</tr>
</tbody>
</table>

*) N.B. Tables 2 and 3 list different characteristics of pulsed power converters without systematic relation between lines of different columns.

### 2.3 Discharge circuit

The PFN or the energy storage capacitor bank is discharged into the magnet load by means of thyristors, thyratrons or, more rarely, by ignitron switches. Ignitrons have practically been replaced by thyristors while thyratrons are still used where high voltage, high current and $di/dt$, fast rise time and pulse repetition rate are required.
A number of different discharge schemes are in use, as shown in Fig. 6, depending on:

- the type of magnet and the degree of magnet current reversal
- the energy recuperation method, i.e. through an auxiliary inductance (1,2), through the magnet load (3) or through the charging choke (4)
- the degree of voltage reversal on the capacitors.

When pulse-to-pulse peak magnet-current modulation is required, the residual energy in the capacitors is dissipated between pulses (if the subsequent peak current value is expected to be smaller than that produced by the voltage after energy recuperation). Double pulsing within the same operating cycle requires either fast recharge of the capacitors by means of an auxiliary circuit or the presence of multiple discharge branches, which are charged in parallel and discharged in sequence.

In applications where a current plateau of $T_p \geq 100 \mu s$ duration and current stability and reproducibility $DI/I$ better than $10^{-4}$ is required, the energy storage section is equipped with additional third harmonic pulse-shaping components and with a choke for the insertion of an active filter (Fig. 7). This is a MOS-amplifier of class C, with its separate supply and isolated drive, acting in a fast servo-loop and absorbing any peak current variation due to residual ripple of charging voltage or current shape, and to non-compensated thermal drift of the capacitance and of the circuit resistances [9,10].
The discharge circuit can either feed the magnet directly through a pulse transmission line or feed the primary of an impedance matching transformer with a turns-ratio N:1, whose high current secondary is connected to the magnet. The transformer turns-ratio determines both the discharge current amplitude (I/N) and its pulse duration which is proportional to Nπ(LC)^{1/2}. The transformer has normally a three-limb construction with interleaved windings, located on the central limb, for minimum stray inductance. Either a dc current bias, directly or via an auxiliary tertiary winding, or an air gap of the order of 5 mm are foreseen in the magnetic circuit to cope with the dc component of the excitation current. Transformers with turns-ratio of 6:1, 8:1, 10:1, 12:1, 20:1, 24:1 have been used for pulsed septum magnet applications. The lithium lens pulser (1.2 MA, 4kV) [8] has a 1.5:1 auto-transformer followed by an 18:1 toroidal pulse transformer with dc current bias. A possible classification of the discharge circuits is given in Table 3.
Figure 8 Advanced pulsed power converter layout for beam injection/ejection monotron septum magnets with complex operating requirements
3. ELECTRONICS FOR CONTROLS, TIMING, MONITORING AND REGULATION

3.1 Controls

The computer control interface in the CERN-PS is a single transceiver board [10], which can be either fully digital (STD) or have analogue current reference and acquisition (STH-hybrid). Control is based on four 8-bit words for actuation, reference setting, current and status acquisition. The control protocol foresees four exclusive actuation bits: OFF - STANDBY - ON - RESET, and the corresponding acquisition bits. The current reference and acquisition have either 12-bit (STH) or 14-bit (STD) resolution. A number of indicator bits provides information on detailed operational situations (e.g. internal or external interlocks and faults).

3.2 Timing

The timing function is an essential aspect in pulsed power converters because they must be synchronized with the accelerator operation in order to achieve maximum stable field in the corresponding magnets when the beam is present. This means that before each discharge one must ensure that the capacitors have been charged to the required level, that the voltage has been stabilized and that all precautions have been taken to avoid short-circuiting of the charging section during the capacitor discharge. Similarly, the discharge must be completed and the switches must have recovered their voltage blocking capability before recharging the capacitors.

To meet these constraints the operating cycle of a pulsed power converter has been subdivided into specific time intervals which are initiated by four timing pulses, at least two of which must come from the external general accelerator timing system. Whenever possible, all four pulses are delivered externally to the power converter for the highest possible operational reliability and transparency.

The four standard timing pulses are:

FOREWARNING (FW) which announces that the power converter is asked to operate during the next beam operation and initiates the charge of the energy storage capacitors

WARNING (W) which blocks the charging circuit once the capacitors have been charged and their voltage stabilized to the required level. This pulse sets the reference to zero and starts all actions foreseen to assure a safe discharge

START (ST) which triggers the discharge so that maximum current is reached in the magnet after a given time interval

MEASURE (MEA) which triggers Sample/Hold acquisition of the discharge current and which normally corresponds to the beam presence and to peak discharge current.

Because of the importance of the timing pulses for successful operation of any pulsed power converter, adequate pulse indication and time interval measuring facilities are part of the normal auxiliary equipment.

3.3 Monitoring

The magnet current is measured by means of pulse transformers (e.g. PEARSON, US) or high performance dcnt's (e.g. HOLEC, NL or DANPHYSIK, DK). The signal is used for the flat-top regulation loop, and for displaying the current waveform and peak value.
3.4 Regulation

Pulsed power converters with linear charge have, in general, either cascaded or parallel-switched voltage and current control servo-loops. Current control acts during the charging time. After initial soft start and subsequent full current charge, the current reference is reduced for better transients when approximately 90% of voltage is reached. Higher-gain voltage control takes over at transition to the final capacitor voltage level and during stabilisation before the W pulse.

The voltage regulation of resonant charging type power converters is done either by controlling the low voltage source and interrupting the resonant charge as soon as the desired voltage has been achieved (by extinction of the power thyristors) or by keeping the source voltage constant and 'deQuing' the resonant circuit.

A faster and more accurate voltage control is obtained by means of a higher frequency chopper in the charging power circuit. It is possible to profit from this by imposing constant active power demand from the mains during the charging period. For very large power ratings, solutions have been worked out to absorb roughly constant power even outside the charging time (i.e. during the W—FW time interval).

The flat-top regulation by an active filter, when present, constitutes a separate servo-loop with larger bandwidth (100 kHz). In this case the magnet current is directly compared to the reference and the error signal feeds the active filter via a suitably phase-corrected isolated drive circuit. On the base of the power circuit characteristics and by modelling the load, several corrections are applied to the loops to cope with non-linearities between charging voltage and pulse current, with thermal drift due to ohmic losses in the power circuit and with any required time and amplitude pattern of magnet pulse sequences. By these means too large variations of the operating point of the active filter are also avoided during equipment warm-up conditions.

4. CONCLUSIONS

The wide domain of pulsed power converters for particle accelerators has been introduced by means of several examples of recent realisations. The composition of the converters and the technical solutions have been briefly described and references made to more detailed specific technical reports. Trends of development concern the use of advanced power devices (e.g. IGBT's and GTO's) and microprocessors to implement smarter technical solutions and build mains and user friendly pulsed converters.

The combination of a lumped element PFN with an active ripple filter may become an interesting solution for particular applications. Modern semiconductor switches are entering applications where thyristors were dominating so far and pulse compression techniques with the help of modern magnetic materials are already being applied [12]. More sophisticated operations on present accelerators, and the next generation of high energy linear lepton colliders, will make extensive use of pulsed power converters. Development work in this field should therefore be energetically pursued.
REFERENCES