Power Converters

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6. The delay-line mode of resonance.
1. Basic Requirements

1. Typical requirements for d.c. applications (storage rings, cyclotrons, beam-lines, etc.):
   - smooth dc (ripple < $1:10^5$);
   - amplitude stability between $1:10^4$ and $1:10^5$;
   - amplitude adjustment over operating range (often $1:10$).

2. Additionally, for accelerating synchrotrons:
   - energy storage (essential so as not to dissipate stored energy at peak field when ‘resetting’ for next injection)
   - amplitude control between minimum and maximum current (field);
   - waveform control (if possible).
2 - Basic components.

Generic structure of a ‘Power Converter’:

- Transformer
- Rectifier
- Regulation (level setting - usually a ‘servo system’)
- Smoothing
- Monitoring
- Switch-gear
- Control room
- Feedback
- Load
i) switch-gear:
   • on/ off;
   • protection against over-current/ over-voltage/ earth leakage etc.

ii) transformer:
   • changes voltage – ie matches impedance level;
   • provides essential galvanic isolation load to supply;
   • three phase or (sometimes 6 or 12 phase);

iii) rectifier/ switch (power electronics):
   • used in both d.c. and a.c. supplies;
   • number of different types – see slides 7, 8, 9, 10;
iv) regulation:
- level setting;
- stabilisation with high gain servo system;
- strongly linked with ‘rectifier’ [item iii) above];

v) smoothing:
- using either a passive or active filter;

vi) monitoring:
- for feed-back signal for servo-system;
- for monitoring in control room;
- for fault detection.
Switches - diodes

- conducts in forward direction only;
- modern power devices can conduct in ~ 1 μs;
- has voltage drop of (< 1 V) when conducting;
- hence, dissipates power whilst conducting;
- ratings up to many 100s A (average), kVs peak reverse volts.

75 V; 0.15 A

10 A; 300 V

350 A; up to 2.5 kV
Switches - thyristors

- Withstands forward and reverse volts;
- then conducts in the forward direction when the gate is pulsed;
- conducts until current drops to zero and reverses (to ‘clear’ carriers);
- after ‘recovery time’, again withstands forward voltage;
- switches on in ~ 5 µs (depends on size) – as the forward voltage drops, it dissipates power as current rises;
- therefore $\frac{dI}{dt}$ limited during early conduction;
- available ratings are 100s A average current, kVs forward and reverse volts.
Switches - thyristors

[Diagram of thyristor symbol and 4 layers with terminals labeled as anode, gate, and cathode]
Switches – i.g.b.t.s

The insulated gate bi-polar transistor (i.g.b.t.):

- gate controls conduction, switching the device on and off;
- far faster than thyristor, can operate at 10s of kHz;
- dissipates significant power during switching;
- is available at ~ 2 kV forward, 100s A average.
- will not withstand appreciable reverse volts (a series blocking diode sometimes needed);
- will not conduct reverse current (sometimes a parallel reverse ‘free-wheeling’ diode is needed).
3. DC Supplies

A single phase full-wave rectifier:

Classical ‘full-wave’ circuit:

• uncontrolled – no amplitude variation or control;
• large ripple – large capacitor smoothing necessary;
• only suitable for small loads.
DC – a 3 phase diode rectifier

Three phase, six pulse system:

- no amplitude control;
- much lower ripple (~ 12% of 6th harmonic – 300 Hz) but low-pass filters still needed.
Thyristor phase control

Replace diodes with thyristors - amplitude of the output voltage is controlled by retarding the conduction phase:

Full conduction – like diode

Half conduction

Zero volts output

Negative volts output – ‘inversion’.

But current must always be in the forward direction.
Full 12 pulse phase controlled circuit.

- like all thyristor rectifiers, is ‘line commutated’;
- produces 600 Hz ripple (~ 6%)
- smoothing filters still needed.
The thyristor rectifier.

The ‘standard’ circuit until recently:

- gave good precision (better than $1:10^3$);
- inversion protects circuit and load during faults;
- has bad power factor with large phase angles ($V$ and $I$ out of phase in ac supply);
- injected harmonic contamination into load and $50$ Hz a.c. distribution system at large phase angles.
Modern d.c. ‘switch-mode’ system.

The i.g.b.t. allows a new, revolutionary system to be used: the ‘switch-mode’ power supply (see your mobile phone charger!):
Mode of operation

Stages of power conversion:

• incoming a.c. is rectified with diodes to give ‘raw’ d.c.;
• the d.c. is ‘chopped’ at high frequency (> 10 kHz) by an inverter/chopper using i.g.b.t.s;
• a.c. is transformed to required level;
• transformer size is $\propto \frac{1}{\omega}$ (determined by $\partial \Phi / \partial t$ in transformer core) so is much smaller and cheaper at high frequency;
• transformed a.c. is rectified – diodes;
• filtered (filter is much smaller at 10 kHz);
• regulation is by feed-back to the inverter (much faster, therefore greater stability and faster protection);
• response and protection is very fast.
The inverter is the heart of the switch-mode supply:

The i.g.b.t. s provide full switching flexibility – switching on or off according to external control protocols.

Point A: direct voltage source; current can be bidirectional (e.g., inductive load, capacitative source).
Point B: voltage square wave, bidirectional current.
4. Cycling converters - what do we need to do?

We need to raise the magnet current during acceleration - will ‘ordinary’ A.C. do?

But the required magnetic field (therefore the required magnet current) is **unidirectional** – acceleration low to high energy: - so ‘normal’ a.c. is inappropriate:

- only $\frac{1}{4}$cycle used;
- excess rms current;
- high a.c. losses;
- high gradient at injection.
Nature of the Magnet Load

Magnet current: $I_M$
Magnet voltage: $V_M$
Series inductance: $L_M$
Series resistance: $R$
Distributed capacitance to earth $C$. 

![Diagram of magnet load with symbols for series inductance, resistance, and capacitance]
‘Reactive’ Power and Energy

voltage: \[ V_M = R I_M + L \frac{d I_M}{dt}; \]

‘power’: \[ V_M I_M = R (I_M)^2 + L I_M \frac{d I_M}{dt}; \]

stored energy: \[ E_M = \frac{1}{2} L_M (I_M)^2; \]

\[ \frac{d E_M}{dt} = L (I_M) \frac{d I_M}{dt}; \]

so \[ V_M I_M = R (I_M)^2 + \frac{d E_M}{dt}; \]

resistive power loss; reactive’ power – alternates between +ve and –ve as field rises and falls;

The challenge of the cyclic power converter is to provide and control the positive and negative flow of energy - energy storage is required.
Waveform criteria – eddy currents.

Generated by alternating magnetic field cutting a conducting surface:

- eddy current in vac. vessel & magnet; \( \propto \frac{\partial B}{\partial t} \);
- eddy currents produce:
  - negative dipole field - reduces main field magnitude;
  - sextupole field – affects chromaticity/ resonances;
- eddy effects proportional \( \frac{1}{B} \left( \frac{\partial B}{\partial t} \right) \) – critical at injection.
Waveform criteria – discontinuous operation

Circulating beam in a storage ring slowly decays with time – very inconvenient for experimental users.

Solution – ‘top up mode’ – discontinuous operation by the booster synchrotron – beam is only accelerated and injected once every \( n \) booster cycles, to maintain constant current in the main ring.
Fast and slow cycling accelerators.

‘Slow cycling’:
- repetition rate 0.1 to 1 Hz (typically 0.3 Hz);
- large proton accelerators;

‘Fast cycling’:
- repetition rate 10 to 50 Hz;
- combined function electron accelerators (1950s and 60s) and high current medium energy proton accelerators;

‘Medium cycling’:
- repetition rate 1 to 5 Hz;
- separated function electron accelerators;
Example 1 – the CERN SPS

A slow cycling synchrotron.

Original dipole power supply parameters (744 magnets):

- peak proton energy \(450\) GeV;
- cycle time (fixed target) \(8.94\) secs;
- peak current \(5.75\) kA;
- peak \(dI/dt\) \(1.9\) kA/s;
- magnet resistance \(3.25\) \(\Omega\);
- magnet inductance \(6.6\) H;
- magnet stored energy \(109\) MJ;
SPS Current waveform

![Graph showing the SPS Current waveform with time in seconds on the x-axis and current in amperes on the y-axis. The graph shows a ramp-up and ramp-down of current over time.]
SPS Voltage waveforms

![Graph showing SPS Voltage waveforms with labels for voltage (kV) and time (s).]
SPS Magnet Power
Example 2 – NINA (ex D.L.)

A fast cycling synchrotron

Original magnet power supply parameters;

- peak electron energy 5.0 GeV;
- cycle time 20 m secs;
- cycle frequency 50 Hz
- peak current 1362 A;
- magnet resistance 900 mΩ;
- magnet inductance 654 mH;
- magnet stored energy 606 kJ;
NINA Voltage waveform

Inductive voltage

Resistive voltage
NINA Power waveform

Power Convertors
Neil Marks
CAS, Prague 2014
Cycling converter requirements

Summing up - a power converter system needs to provide:

- a unidirectional alternating waveform;
- accurate control of waveform amplitude;
- accurate control of waveform timing;
- storage of magnetic energy during low field;
- if possible, waveform control;
- if needed (and if possible) discontinuous operation for ‘top up mode’.
5. Cycling converters - so how do we do it?

It depends on whether we are designing for:

Slow;

Medium; or

Fast;

cycling accelerators.
‘Slow Cycling’ Mechanical Storage

Thyristor waveform control – rectifying and inverting (see slide 13.

- d.c. motor to make up losses
- high inertia fly-wheel to store energy
- a.c alternator/synchronous motor
- rectifier/inverter
- magnet

Examples: all large proton accelerators built in 1950/60s.
‘Nimrod Power Supply’

of the 7 GeV weak-focusing synchrotron, NIMROD – note two units, back to back.

The alternator/synchronous motor.

fly-wheel

d.c. motor
‘Slow cycling’ direct connection to supply network

National supply networks have large stored (inductive) energy; with the correct interface, this can be utilised to provide and receive back the reactive power of a large accelerator.

Compliance with supply authority regulations must minimise:

- voltage ripple at feeder;
- phase disturbances;
- frequency fluctuations over the network.

A ‘rigid’ high voltage line in is necessary.
Example – SPS Dipole supply

14 converter modules (each 2 sets of 12 pulse phase controlled thyristor rectifiers) supply the ring dipoles in series; waveform control!

Each module is connected to its own 18 kV feeder, which are directly fed from the 400 kV French network.

Saturable reactor/ capacitor parallel circuits limit voltage fluctuations.
**Medium & fast** cycling **inductive** storage.

Fast and medium cycling accelerators (mainly electron synchrotrons) developed in 1960/70s used inductive energy storage:

Inductive storage was roughly half the capital cost per stored kJ of capacitative storage.

The ‘standard circuit’ was developed at Princeton-Pen accelerator – the ‘White Circuit’.
White Circuit – single cell.

Examples: Boosters for ESRF, SRS; (medium to fast cycling ‘small’ synchrotrons).
White circuit (cont.)

Single cell circuit:

• magnets are all in series ($L_M$);
• circuit oscillation frequency $\omega$;
• $C_1$ resonates magnet in parallel: $C_1 = \frac{\omega^2}{L_M}$;
• $C_2$ resonates energy storage choke: $C_2 = \frac{\omega^2}{L_{Ch}}$;
• energy storage choke has a primary winding closely coupled to the main winding;
• only small ac present in d.c. source;
• no d.c. present in a.c source;
• **NO WAVEFORM CONTROL.**
White Circuit magnet waveform

Magnet current is biased sin wave – amplitude of $I_{AC}$ and $I_{DC}$ independently controlled.

Usually fully biased, so $I_{DC} \sim I_{AC}$
For high voltage circuits, the magnets are segmented into a number of separate groups.
Multi-cell White circuit (cont.)

Benefits for an ‘n’ section circuit

• magnets are still in series for current continuity;
• voltage across each section is only $1/n$ of total;
• maximum voltage to earth is only $1/2n$ of total;
• choke has to be split into n sections;
• d.c. is at centre of one split section (earth point);
• a.c. is connected through a paralleled primary;
• the paralleled primary **must** be close coupled to secondary to balance voltages in the circuit;

  • still NO waveform control.
Modern **Capacitative Storage**

For **Medium** cycling accelerators:

Technical and economic developments in electrolytic capacitors manufacture now result in capacitative storage being lower cost than inductive energy storage (providing voltage reversal is not needed).

Semi-conductor technology now allows the use of fully switchable i.g.b.t. ‘choppers’ (see slide 18) to control the transfer of energy to and from the magnet giving *waveform control*.

Medium sized synchrotrons (cycling at 1 to 5 Hz) now use this development for cheaper and dynamically controllable systems.

**Waveform Control & Discontinuous Operation!**
Example: S.L.S. Booster dipole circuit.

acknowledgment: Irminger, Horvat, Jenni, Boksberger, SLS
## SLS Booster parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value 1</th>
<th>Unit 1</th>
<th>Value 2</th>
<th>Unit 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combined function dipoles</td>
<td>48 BD</td>
<td></td>
<td>45 BF</td>
<td></td>
</tr>
<tr>
<td>Resistance</td>
<td>600</td>
<td>mΩ</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inductance</td>
<td>80</td>
<td>mH</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max current</td>
<td>950</td>
<td>A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stored energy</td>
<td>28</td>
<td>kJ</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cycling frequency</td>
<td>3</td>
<td>Hz</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Acknowledgment: Irminger, Horvat, Jenni, Boksberger, SLS
SLS Booster Waveforms
SLS Booster Waveforms

The storage capacitor only discharges a fraction of its stored energy during each acceleration cycle:
Assessment of switch-mode circuit

Comparison with the White Circuit:
• the s.m. circuit does not need a costly energy storage choke with increased power losses;
• within limits of rated current and voltage, the s.m.c. provides flexibility of output waveform;
• after switch on, the s.m.c. requires less than one second to stabilise (valuable in discontinuous ‘top up’ mode).

However:
• the current and voltages possible in switched circuits are restricted by component ratings.
Diamond 3 GeV Booster parameters for SLS type circuit

<table>
<thead>
<tr>
<th>Parameter</th>
<th>low turns</th>
<th>high turns</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of turns per dipole:</td>
<td>16</td>
<td>20</td>
</tr>
<tr>
<td>Peak current:</td>
<td>1271 A</td>
<td>1016 A</td>
</tr>
<tr>
<td>Total RMS current (for fully biased sine-wave):</td>
<td>778 A</td>
<td>622 A</td>
</tr>
<tr>
<td>Conductor cross section:</td>
<td>195 mm²</td>
<td>156 mm²</td>
</tr>
<tr>
<td>Total ohmic loss:</td>
<td>188 kW</td>
<td>188 kW</td>
</tr>
<tr>
<td>Inductance all dipoles in series:</td>
<td>0.091 H</td>
<td>0.142 H</td>
</tr>
<tr>
<td>Peak stored energy all dipoles:</td>
<td>73.3 kJ</td>
<td>73.3 kJ</td>
</tr>
<tr>
<td>Cycling frequency:</td>
<td>5 Hz</td>
<td>5 Hz</td>
</tr>
<tr>
<td>Peak reactive alternating volts across circuit:</td>
<td>1.81 kV</td>
<td>2.26 kV</td>
</tr>
</tbody>
</table>

Note: operating frequency higher than the SLS; the 16 or 20 turn options were considered to adjust to the current & voltage ratings available for capacitors and semi-conductors.
6. Delay-line mode of resonance

Most often seen in cycling circuits (high field disturbances produce disturbance at next injection); but can be present in any system.

Stray capacitance to earth makes the inductive magnet string a delay line. Travelling and standing waves (current and voltage) on the series magnet string: different current in dipoles at different positions!

\[ \text{BAD 😞😞😞!} \]
Standing waves in magnets chain.
Delay-line mode equations

$L_M$ is total magnet inductance;

$C$ is total stray capacitance;

Then:

surge impedance:

$$Z = \frac{v_m}{i_m} = \sqrt{\frac{L_M}{C}};$$

transmission time:

$$\tau = \sqrt{L_M C};$$

fundamental frequency:

$$\omega_1 = \frac{1}{2 \sqrt{L_M C}}.$$
Excitation of d.l.m.r.

The mode will only be excited if rapid voltage-to-earth excursions are induced locally at high energy in the magnet chain (‘beam-bumps’); the next injection is then compromised:

- keep stray capacitance as low as possible;
- avoid local disturbances in magnet ring;
- solutions (damping loops) are possible.
The End!

May the Power be with you!