Power Converters

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1. Basic Requirements

1. Typical requirements for d.c. applications (storage rings, cyclotrons, beam-lines, etc.):

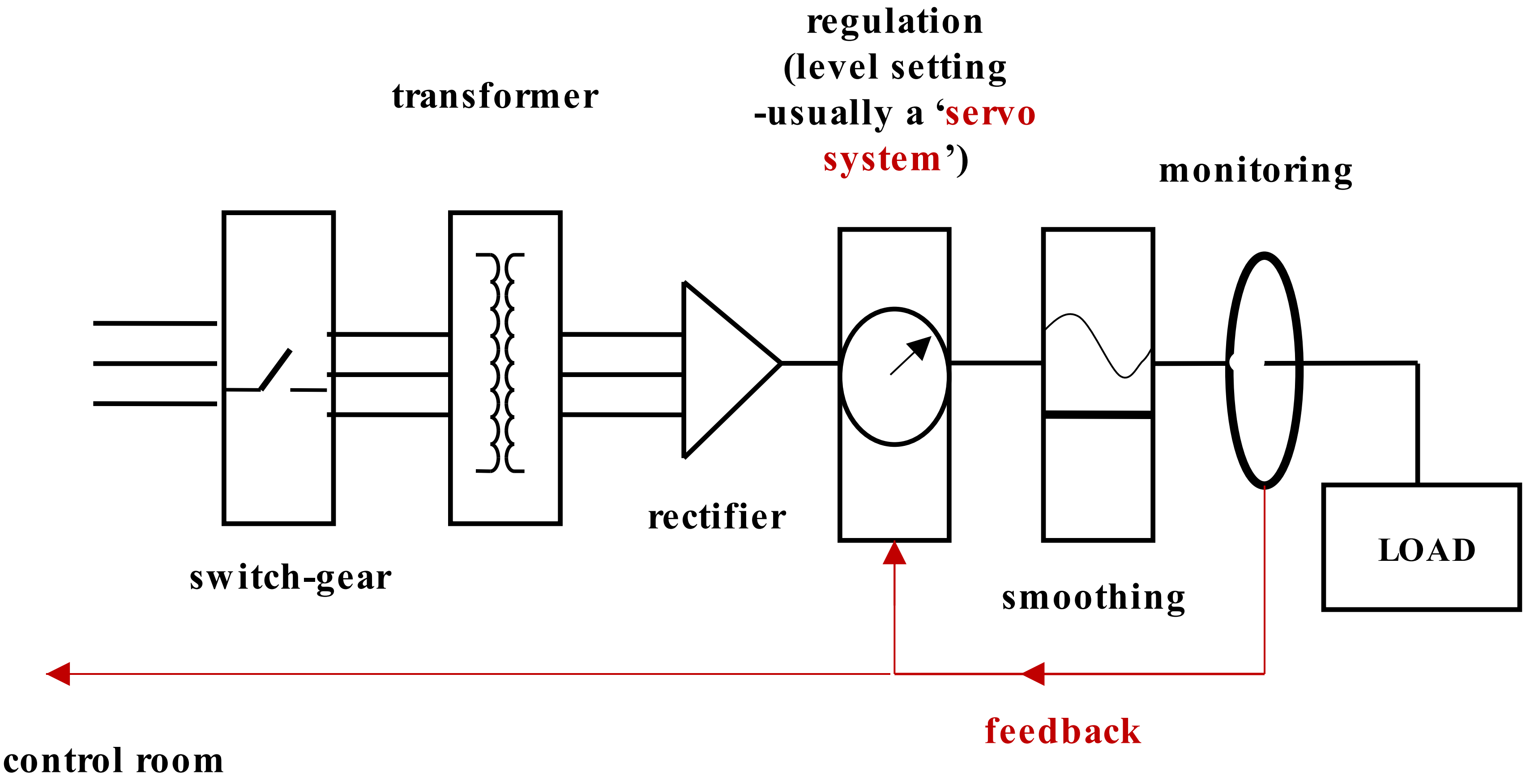
- smooth dc (ripple < $1:10^5$);
- amplitude stability between $1:10^4$ and $1:10^5$;
- amplitude adjustment over operating range (often 1:10).

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':



Typical components (cont.)

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;

Typical components (cont.)

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;

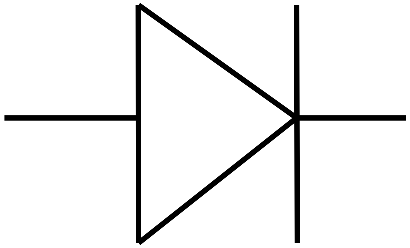
vi) monitoring:

- for feed-back signal for servo-system;
- for monitoring in control room;
- for fault detection.

Switches - diodes

75 V; 0.15 A

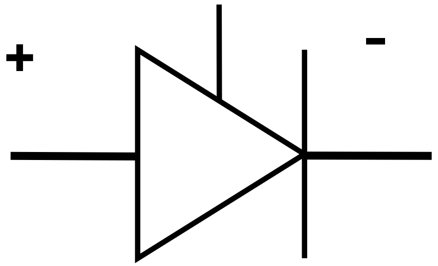
10 A; 300 V

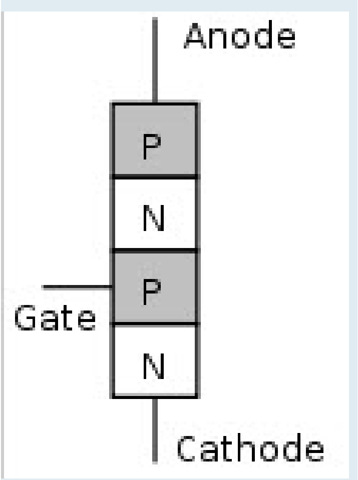


350 A; up to 2.5 kV

- 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.

Switches - thyristors

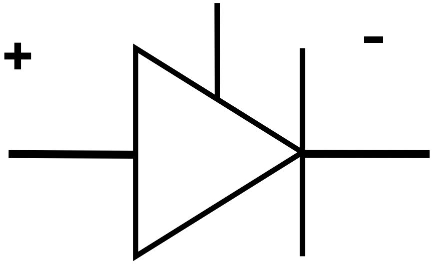


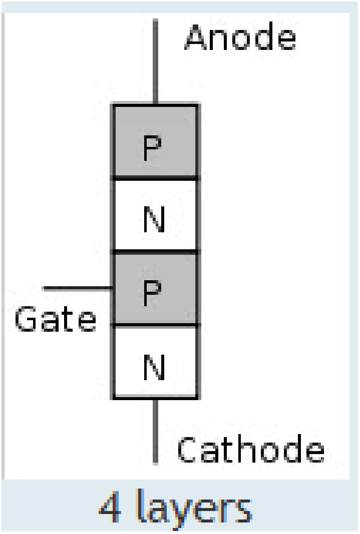


4 layers

- 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 dI/ dt limited during early conduction;
- available ratings are 100s A average current, kVs forward and reverse volts.

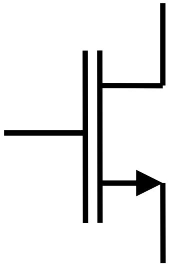
Switches - thyristors

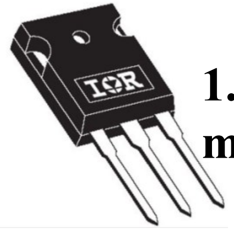




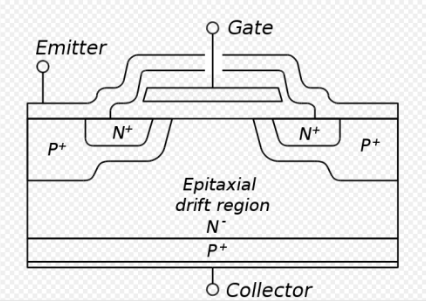
Switches – i.g.b.t. s

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





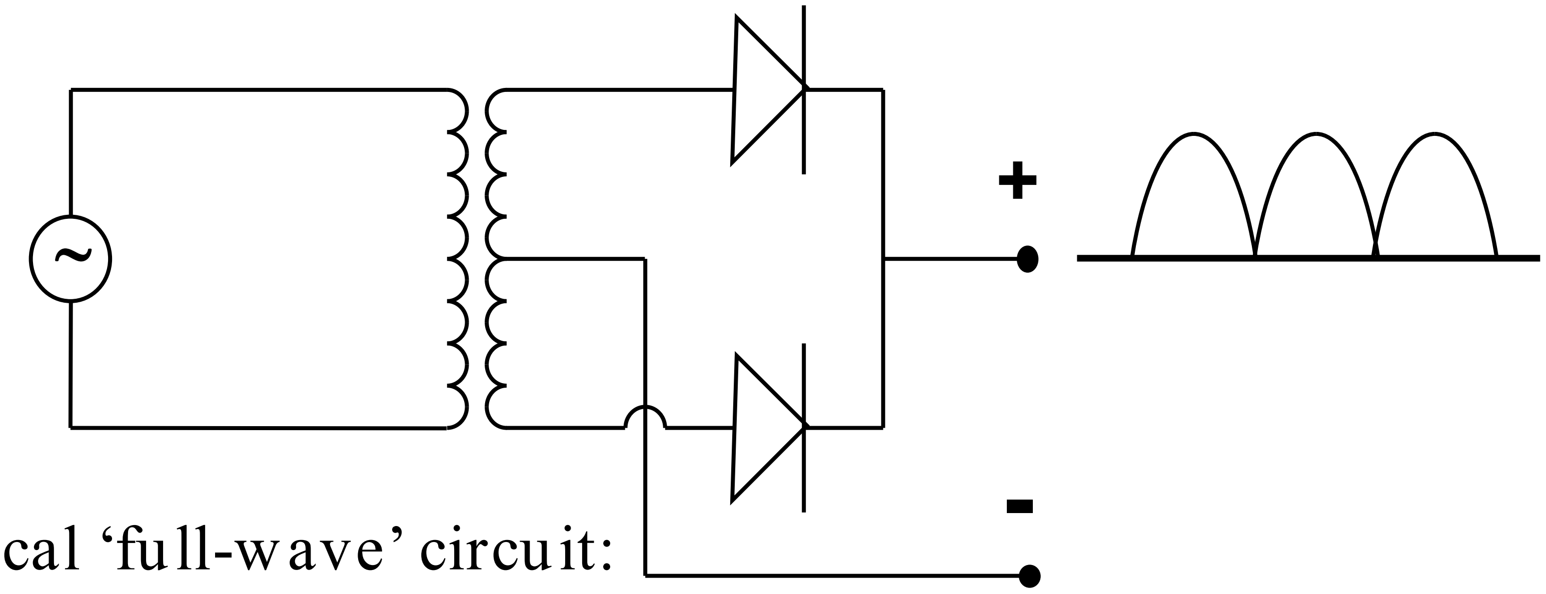
1.2 kV module



- 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

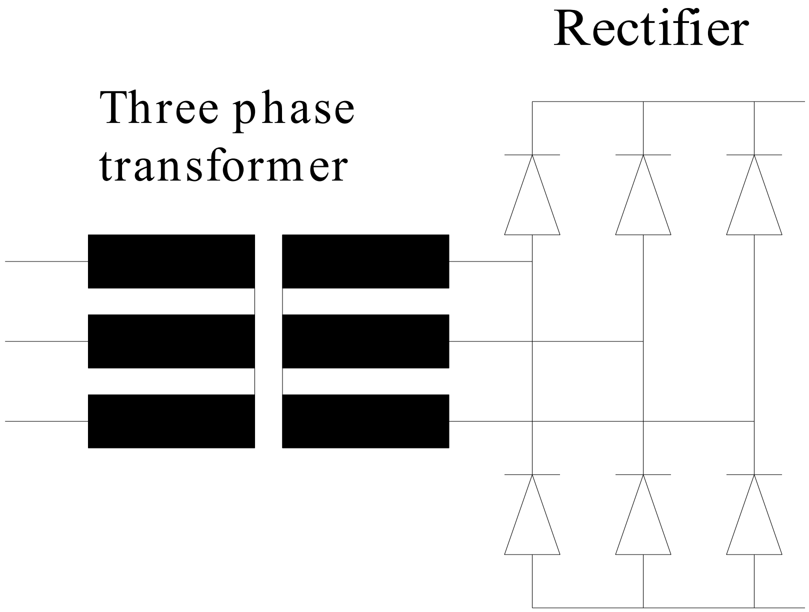
A single phase full-wave rectifier:

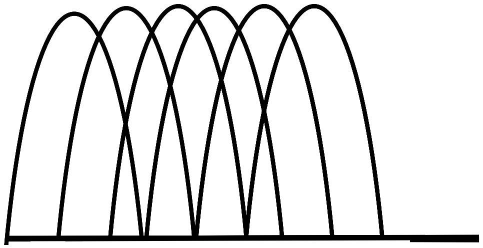


Classical 'full-wave' circuit:

- uncontrolled – no amplitude variation or control;
- large ripple – large capacitor smoothing necessary;
- only suitable for small loads.

DC – a 3 phase diode rectifier



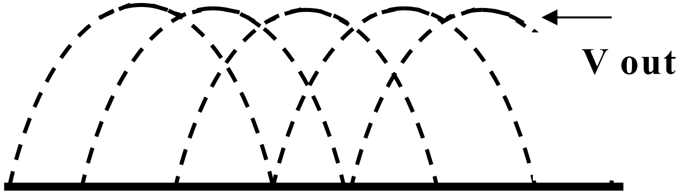


Three phase, six pulse system:

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

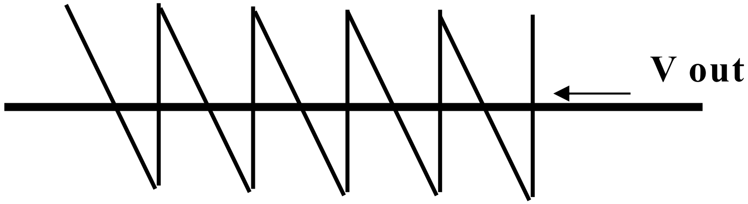
Thyristor phase control

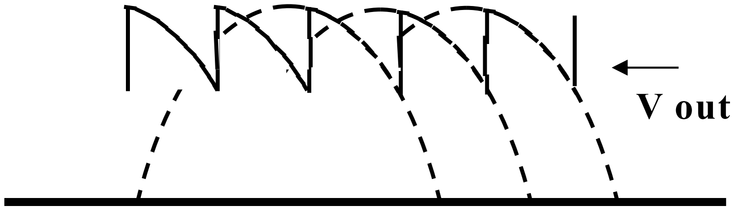
Replace diodes with thyristors - amplitude of the output **voltage** is **controlled** by retarding the conduction phase:



Full conduction – like diode

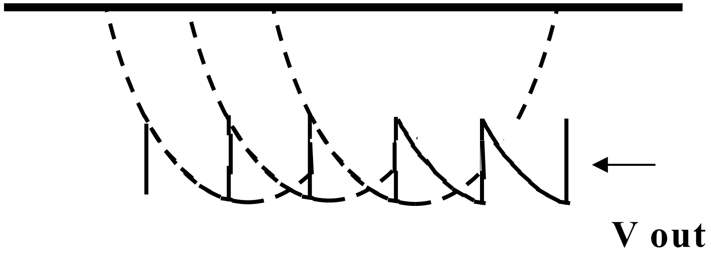
Zero volts output





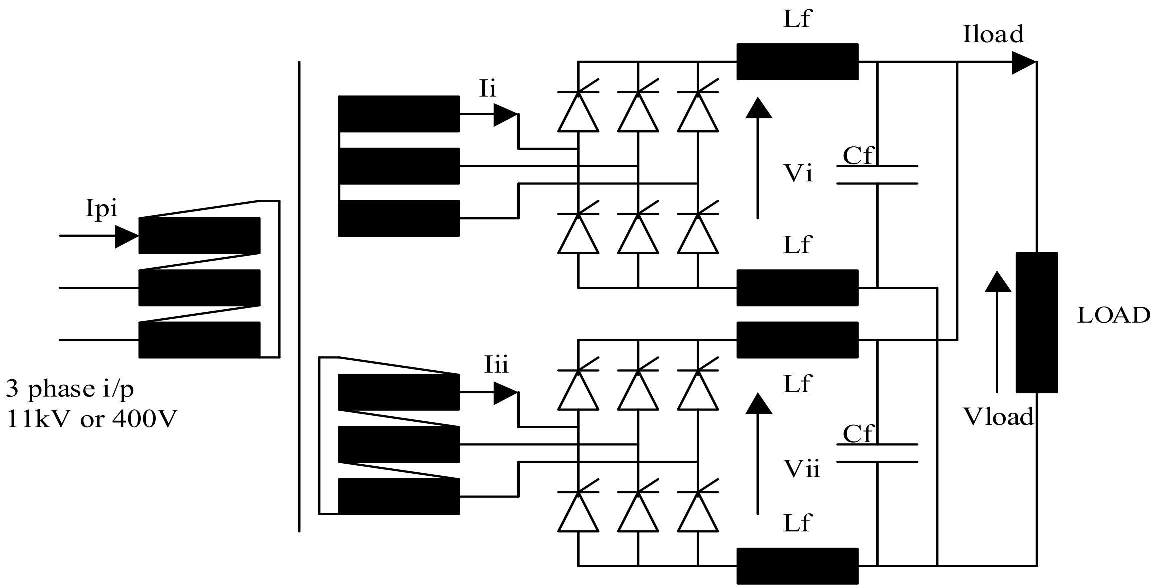
Half conduction

Negative volts output-‘inversion’.



But current must <u>always</u> 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.

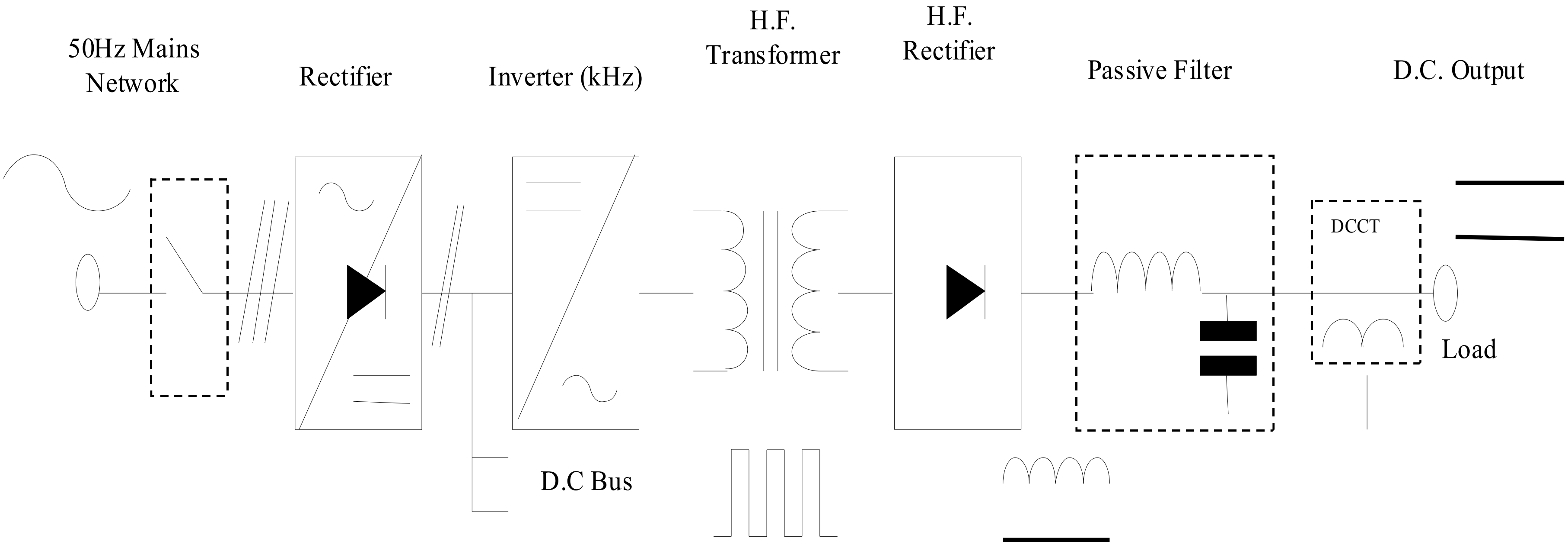
The thyristor rectifier.

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!):



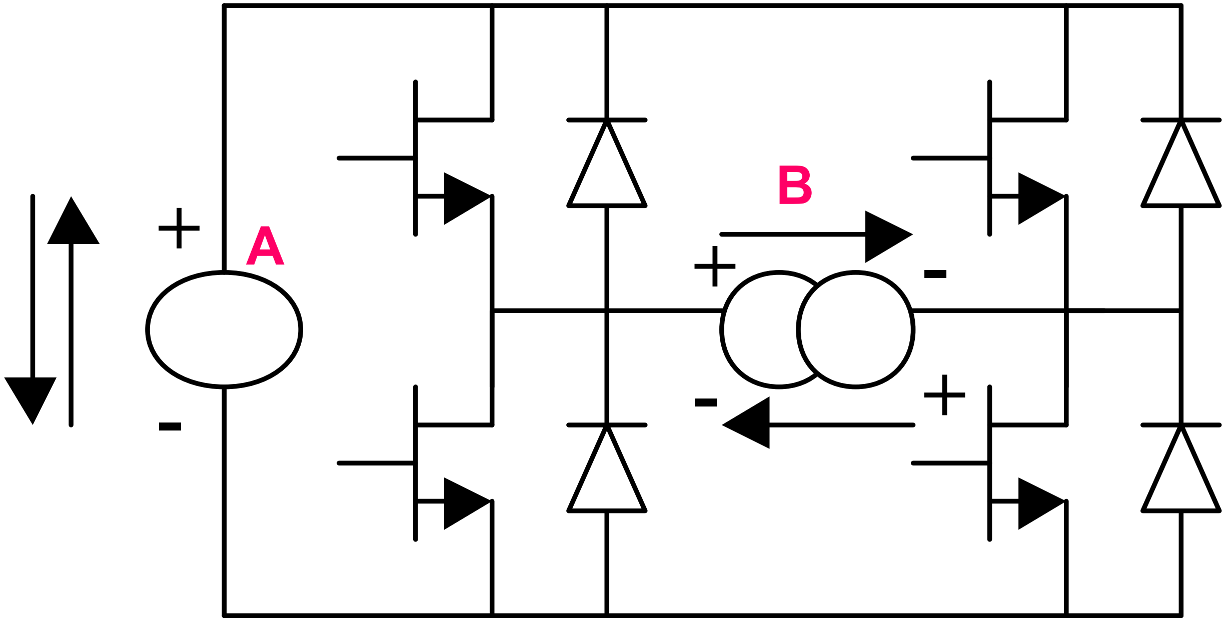
Mode of operation

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.

Inverter – or ‘Chopper’

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 (eg, inductive load, capacitative source).

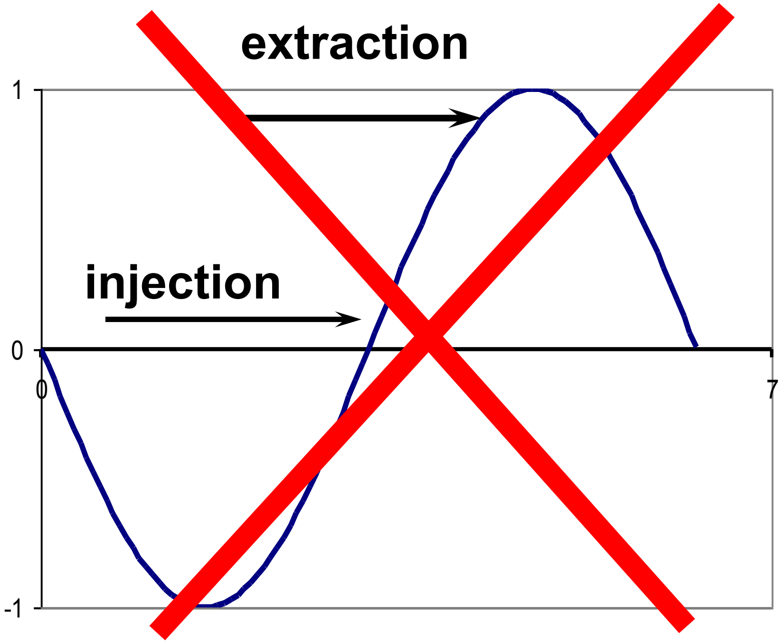
Point B: voltage square wave, bidirectional current.

4. Cycling converters- what do we need to do?

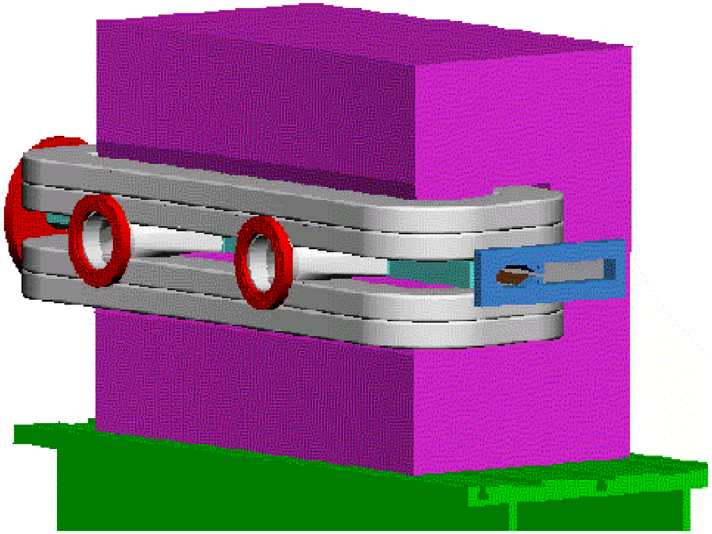
We need to raise the magnet current during acceleration - will 'ordinary' A.C. do?

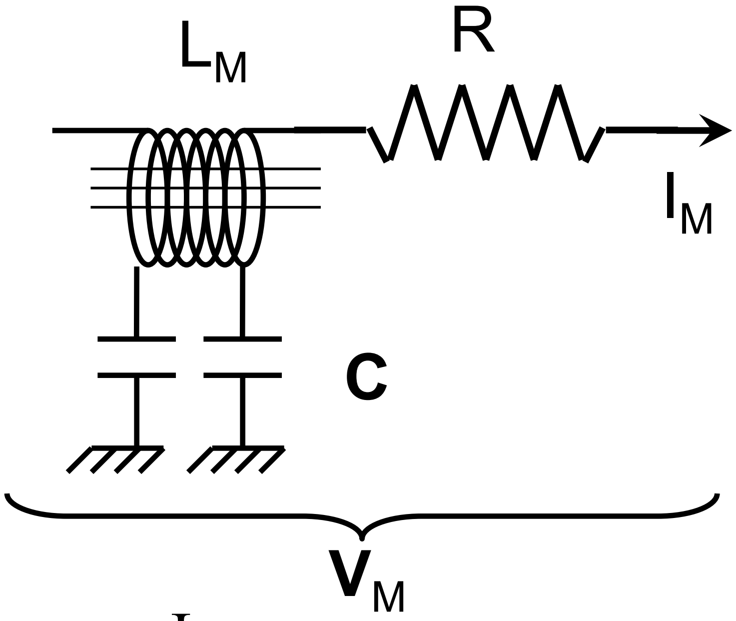
But the required magnetic field (therefore the required magnet current) is **unidirectional** – acceleration low to high energy: - so 'normal' a.c. is <u>inappropriate</u>:

- only ¼cycle 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.

‘Reactive’ Power and Energy

voltage: $V_M = R\,I_M + L\,(d\,I_M/dt)$;

‘power’: $V_M\,I_M = R\,(I_M)^2 + L\,I_M(d\,I_M/dt)$;

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

$d\,E_M/dt = L\,(I_M)\,(d\,I_M/dt)$;

so $V_M\,I_M = R\,(I_M)^2 + d\,E_M/dt$;

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.

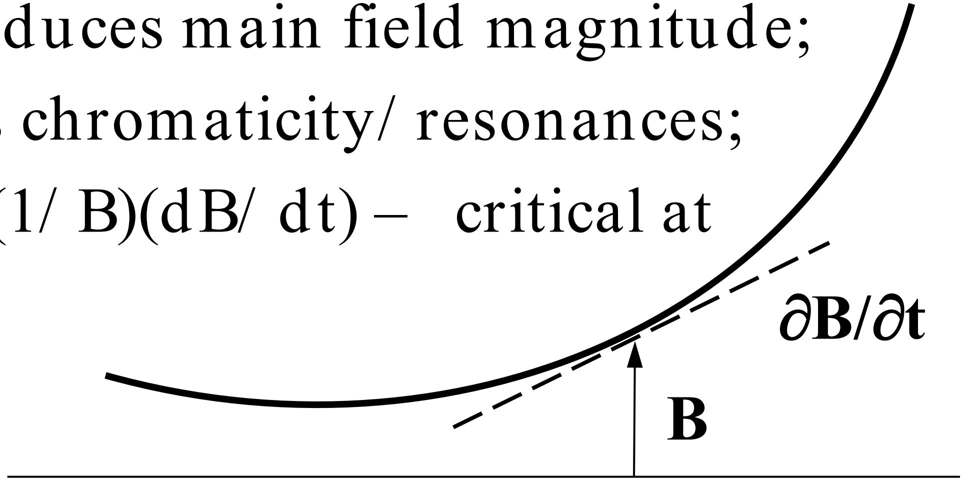
Generated by alternating magnetic field cutting a conducting surface:

eddy current in vac. vessel & magnet; $\propto \partial B/\partial t$;

eddy currents produce:

- negative dipole field - reduces main field magnitude;
- sextupole field – affects chromaticity/ resonances;

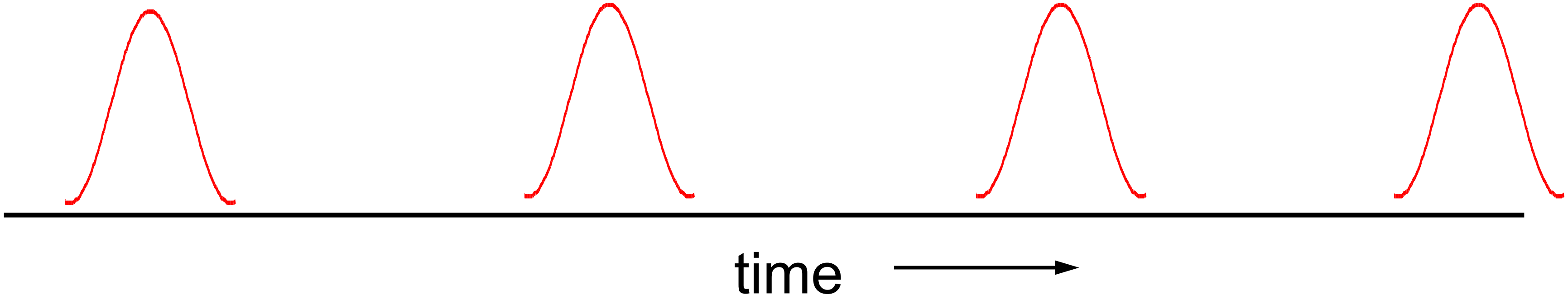
eddy effects proportional $(1/B)(dB/dt)$ – critical at injection.



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;

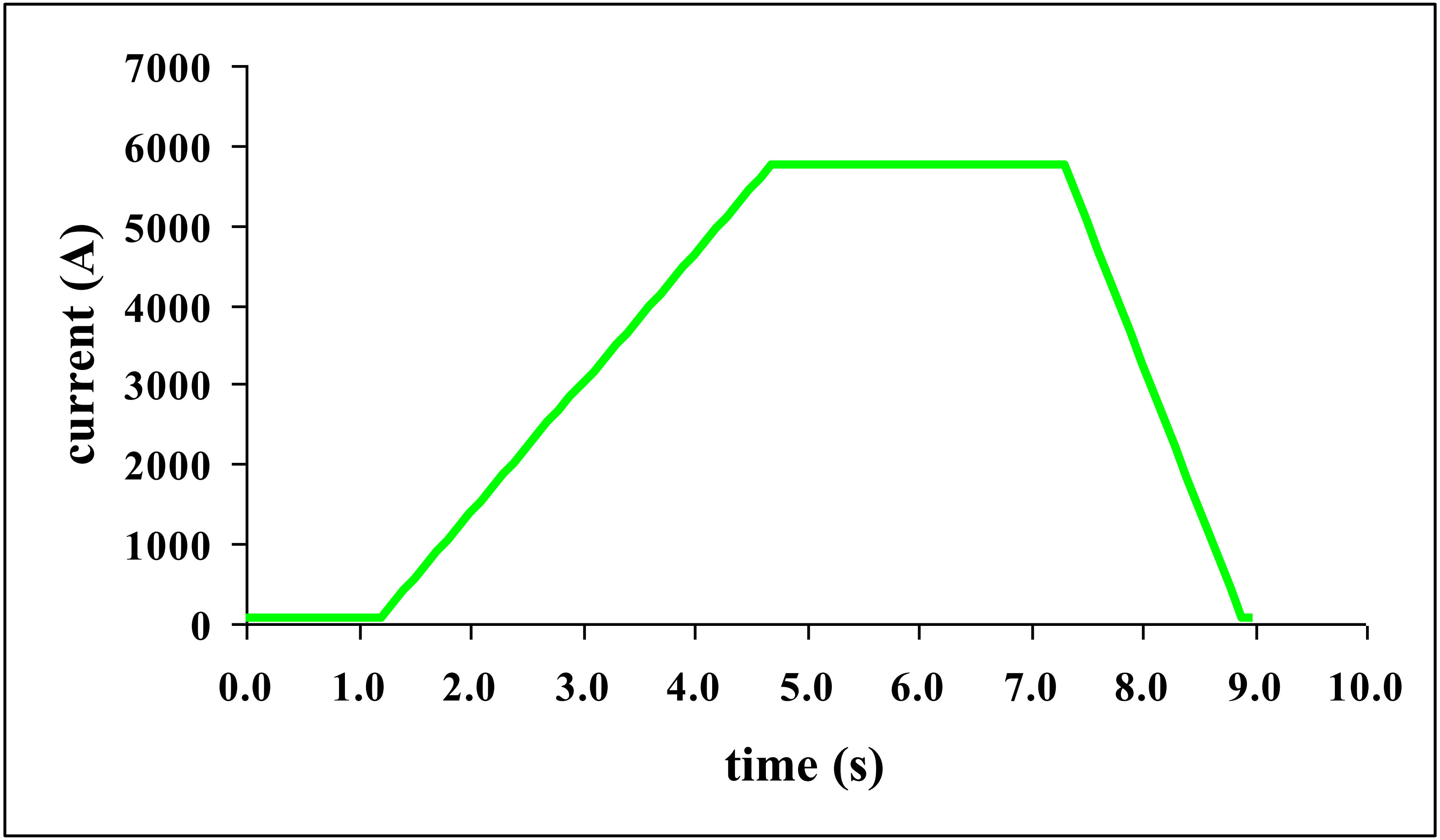
Example 1 – the CERN SPS

A slow cycling synchrotron.

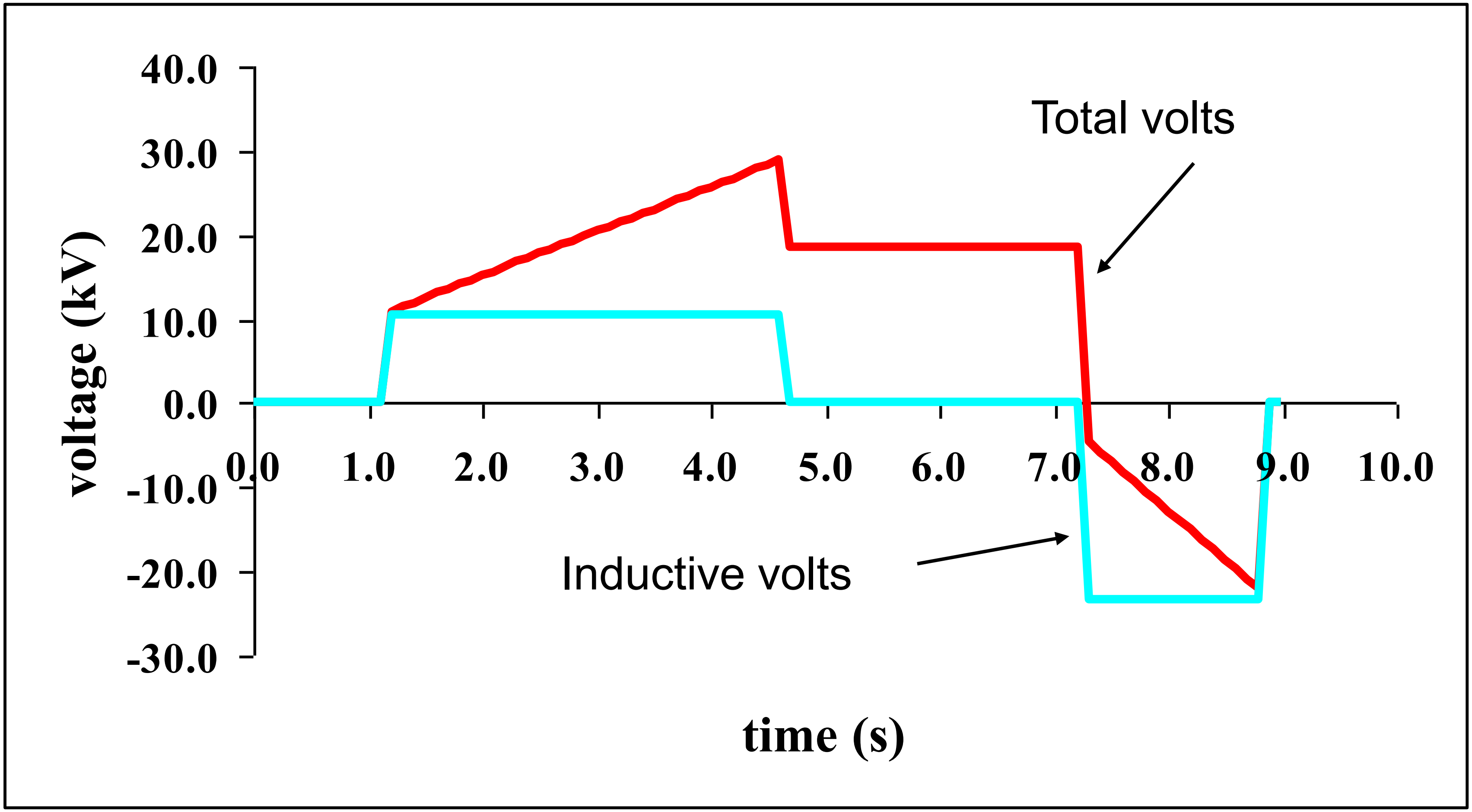
Original dipole power supply parameters (744 magnets):

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	Ω;
magnet inductance	6.6	H;
magnet stored energy	109	MJ;

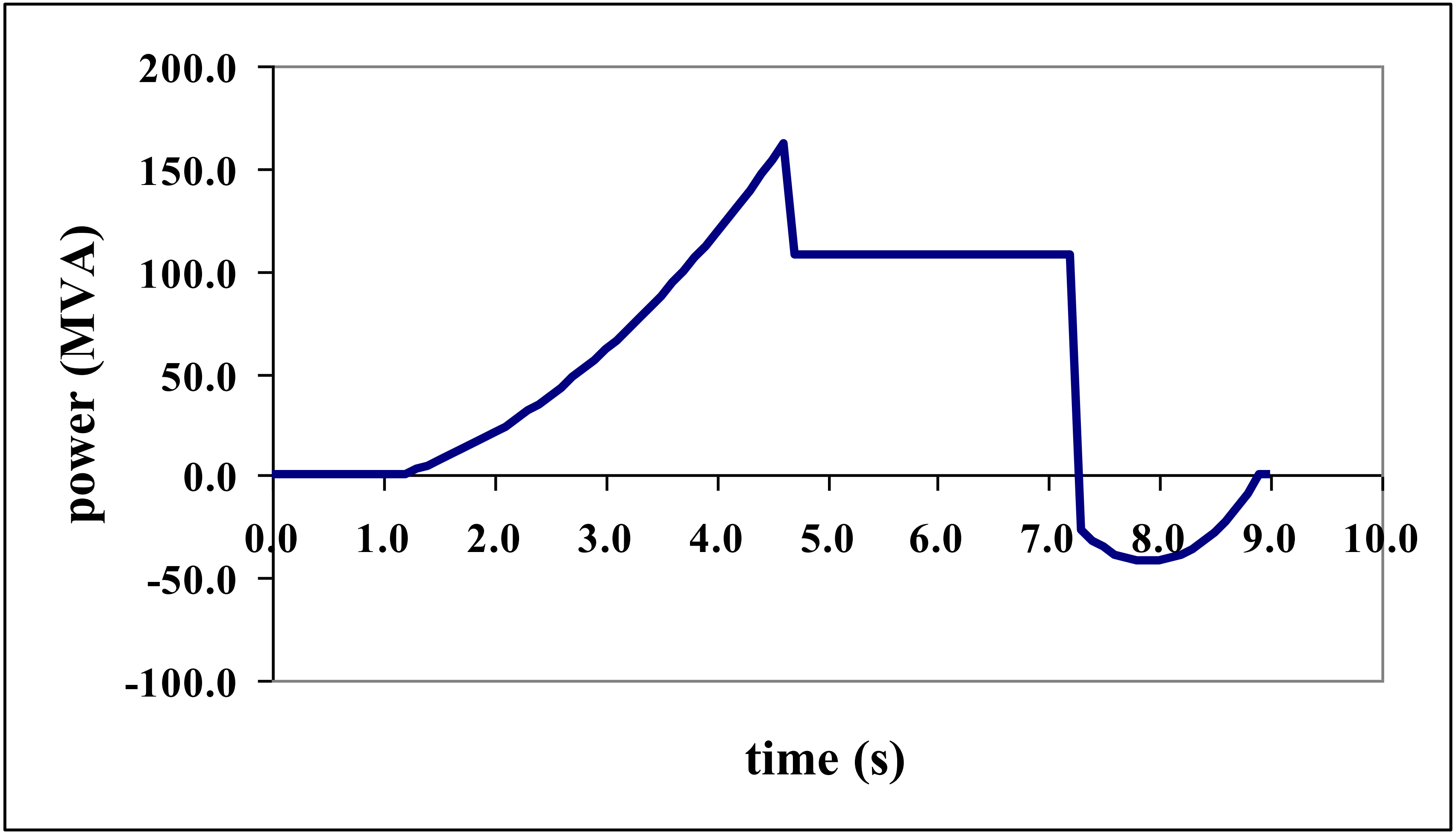
SPS Current waveform



SPS Voltage waveforms



SPS Magnet Power



Example 2 – NINA (ex D.L.)

A fast cycling synchrotron

Origional 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;

Science & Technology
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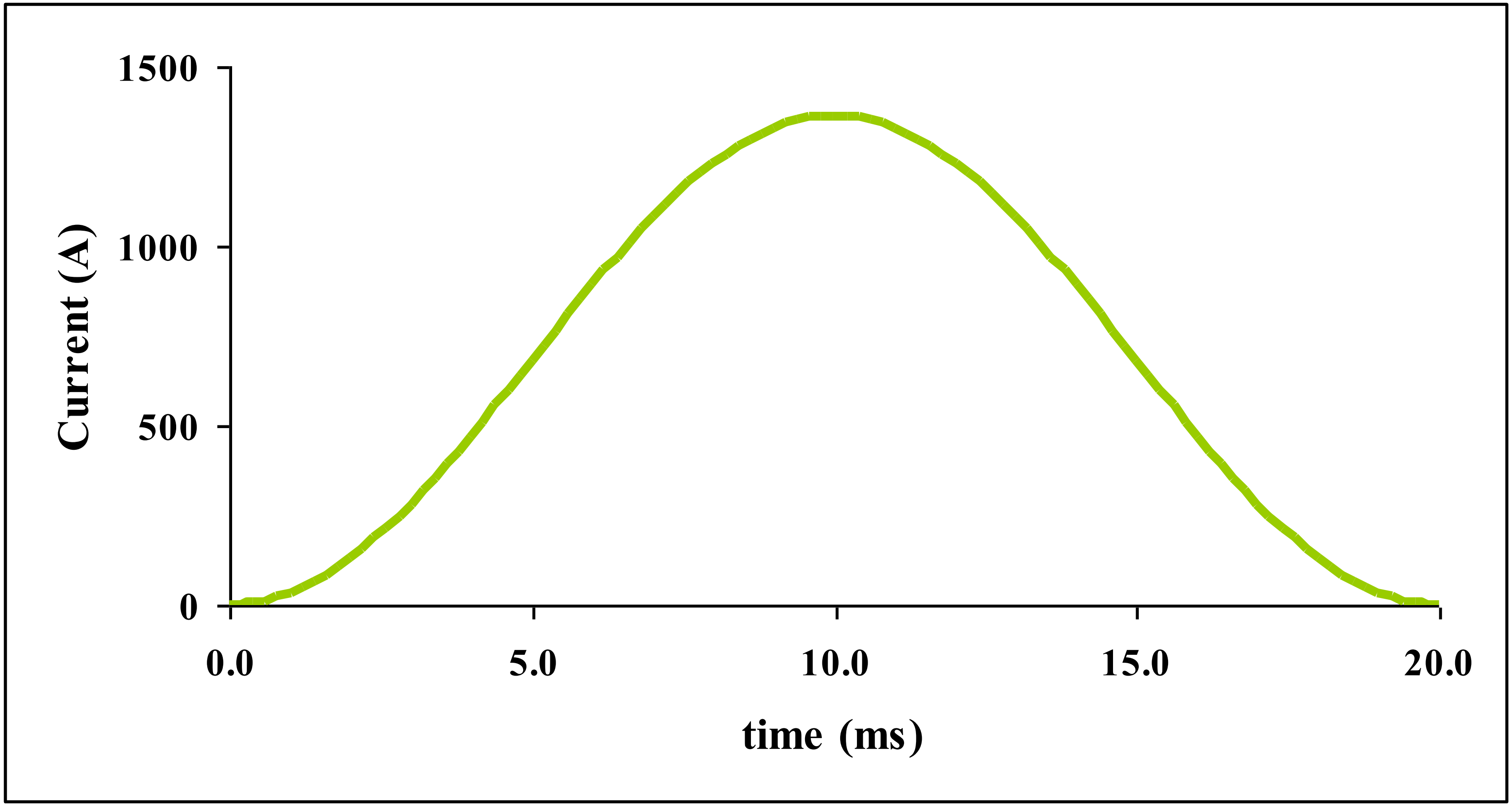
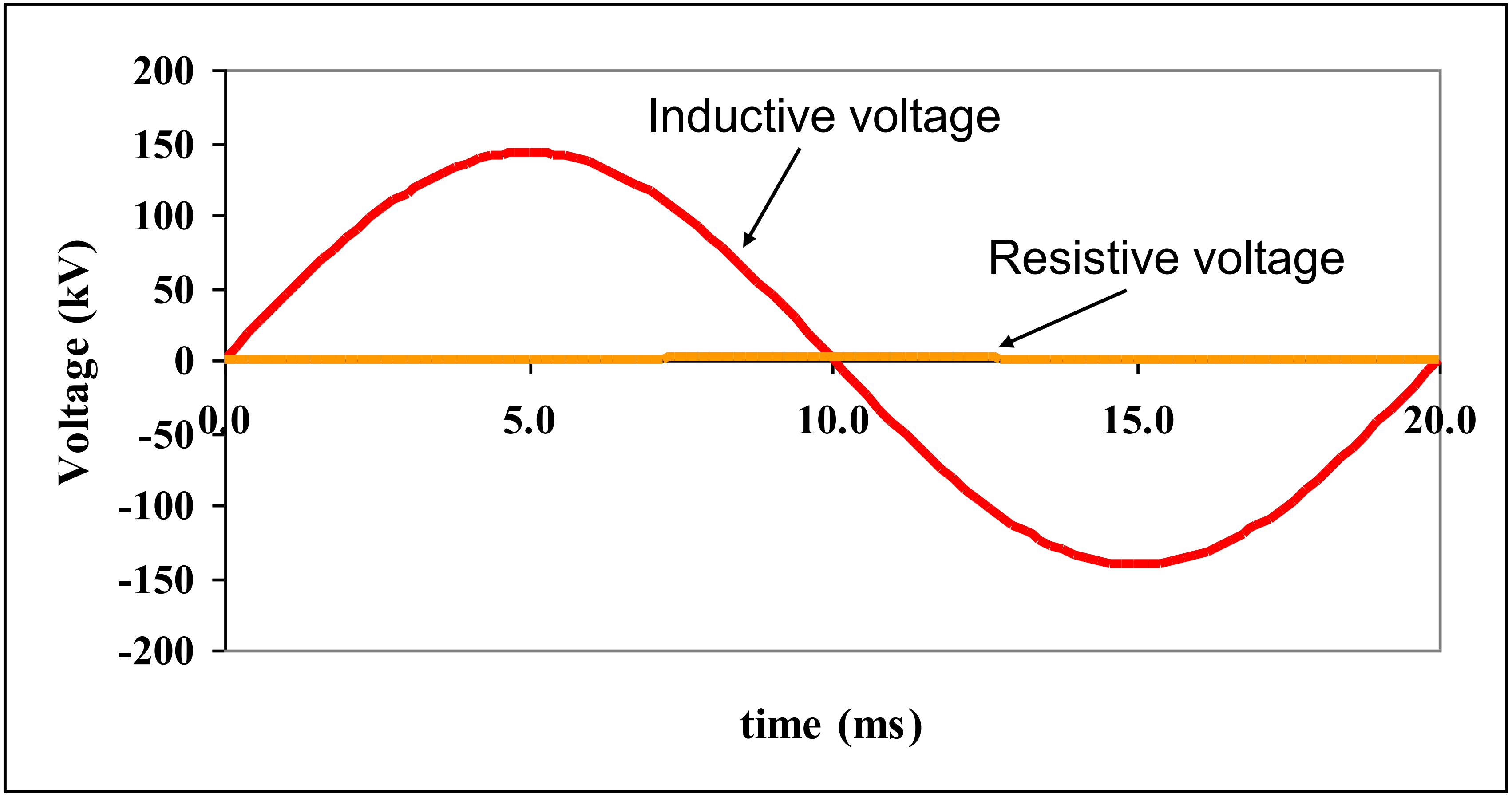
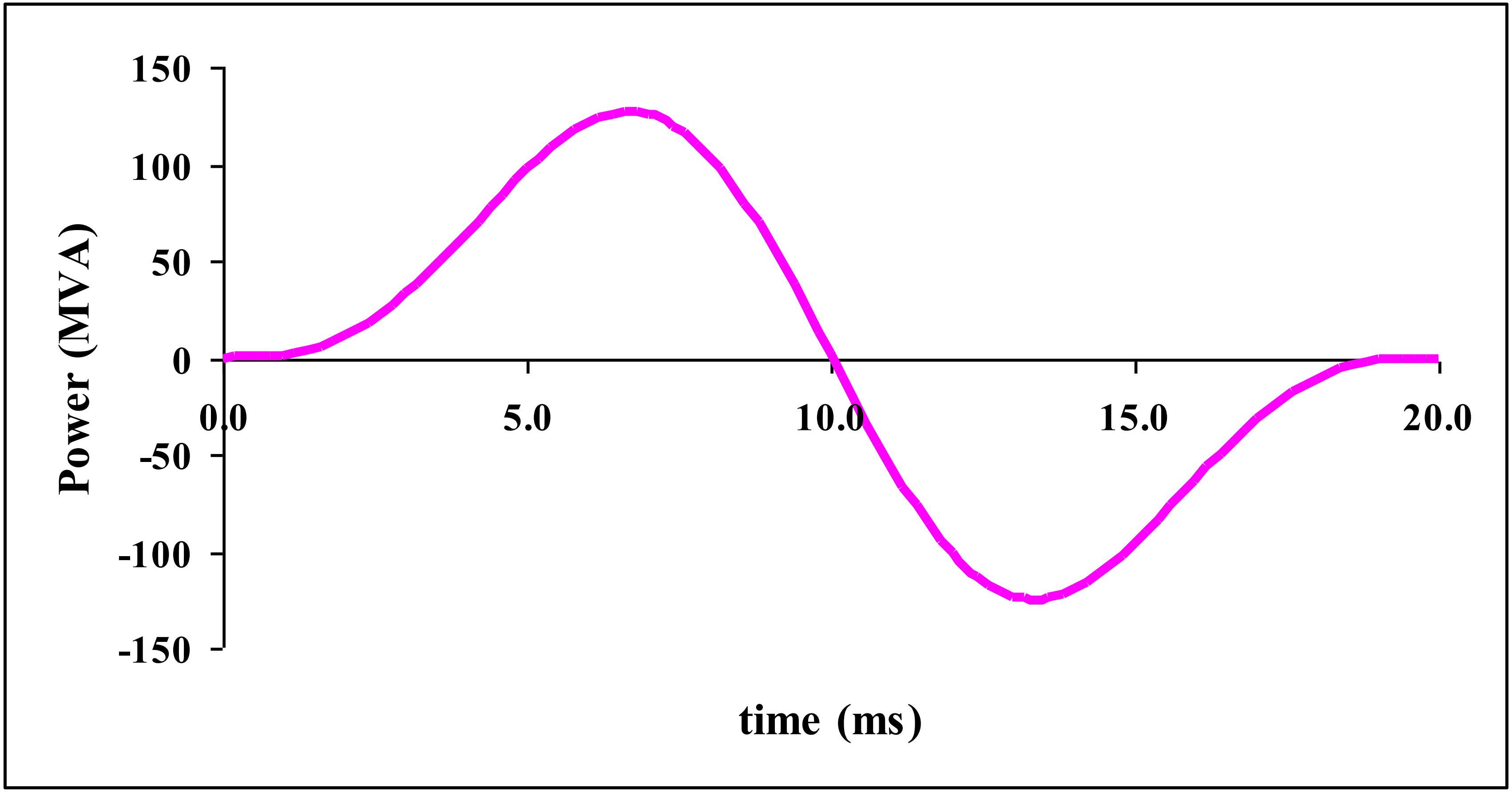
NINA Current waveform



NINA Voltage waveform



NINA Power waveform



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;

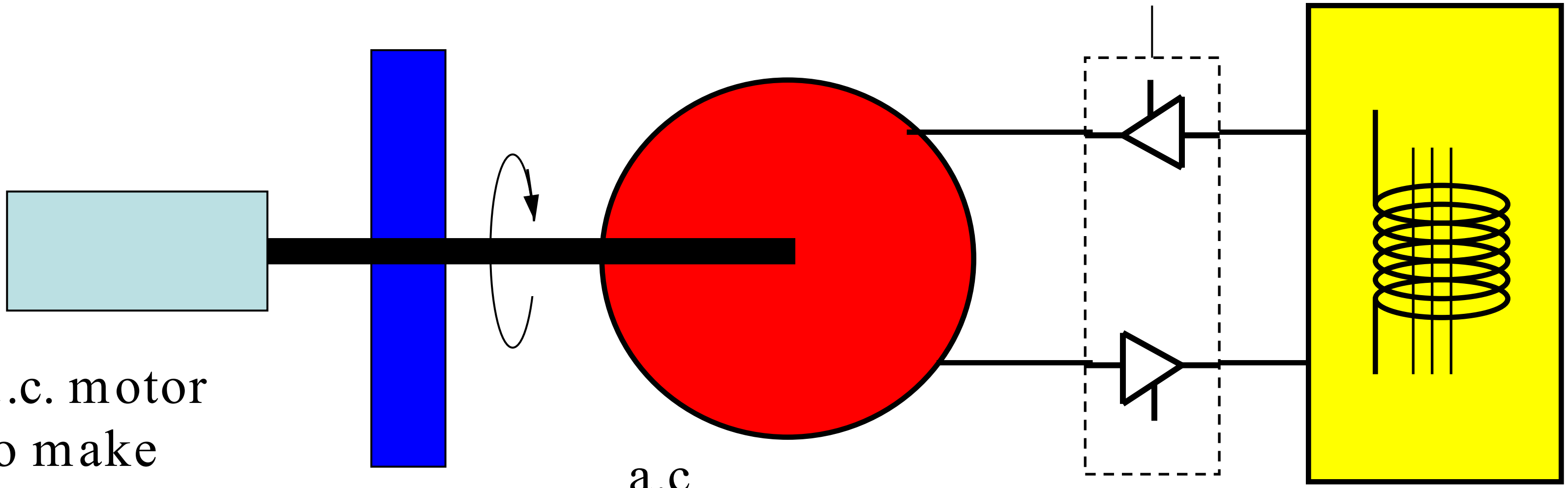
Medium; or

Fast;

cycling accelerators.

'Slow Cycling' Mechanical Storage

Thryistor 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

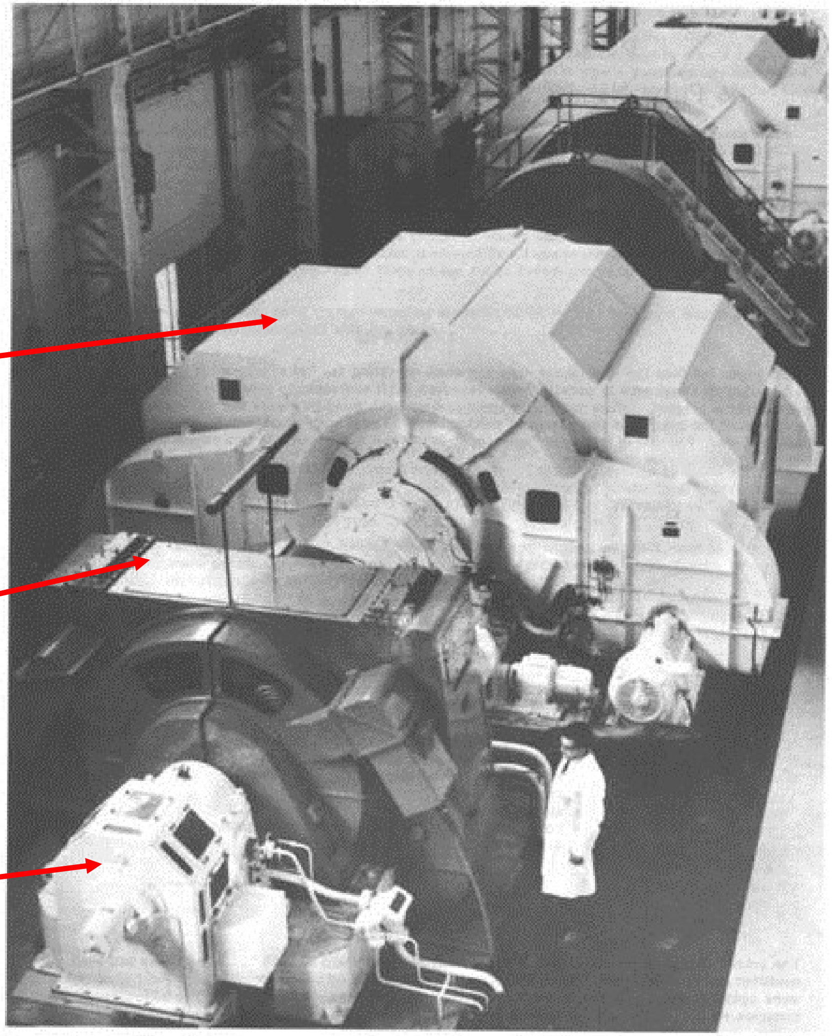
rectifier/ inverter

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.

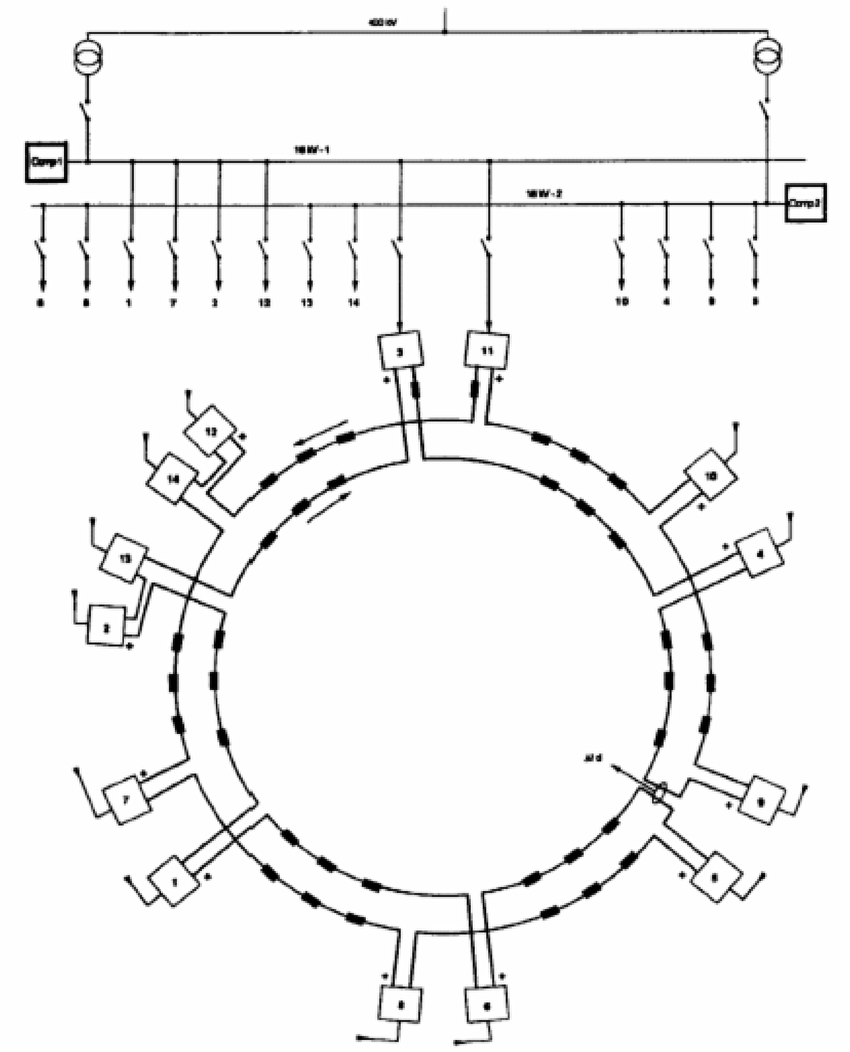
A 'rigid' high voltage line in is necessary.

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.



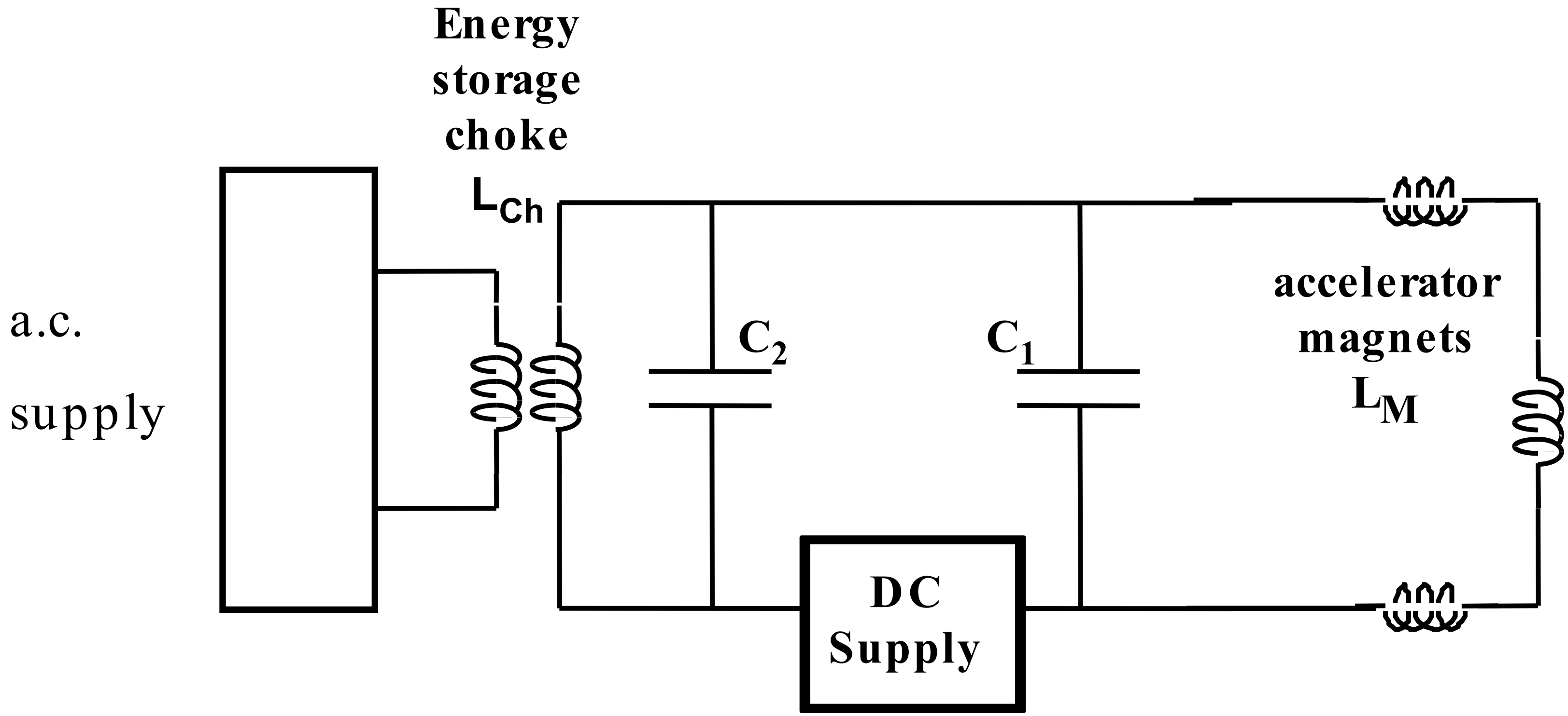
Medium & fast cycling inductive storage.

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

inductive storage <u>was</u> 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.)

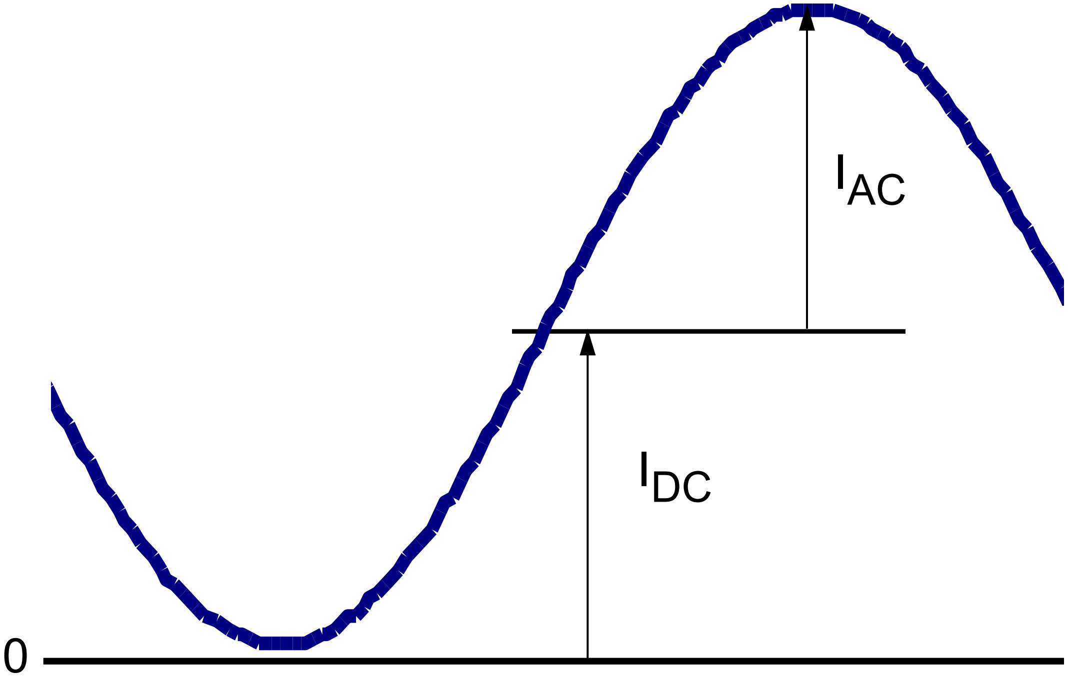
Single cell circuit:

- magnets are all in series (L_M);
- circuit oscillation frequency ω;
- C_1 resonates magnet in parallel: $C_1 = \omega^2 / L_M$;
- C_2 resonates energy storage choke: $C_2 = \omega^2 / L_{Ch}$;
- 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

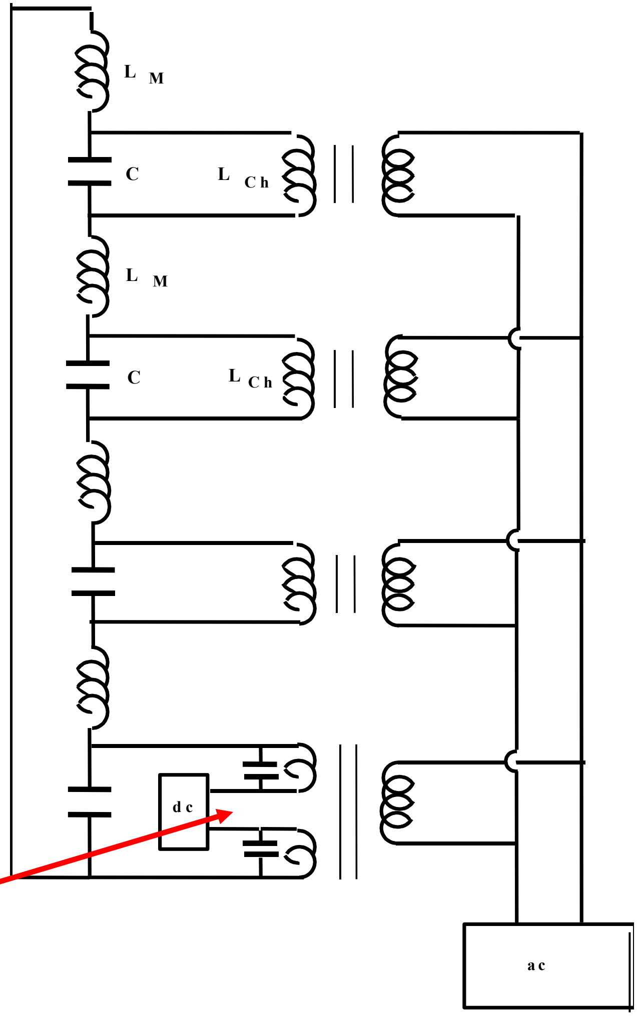
Magnet current is biased sin wave – amplitude of I_{AC} and I_{DC} independently controlled.

Usually fully biased,
so $I_{DC} \sim I_{AC}$



Multi-cell White Circuit (NINA, DESY, CEA & others)

For high voltage circuits, the magnets are segmented into a number of separate groups.



earth point

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:

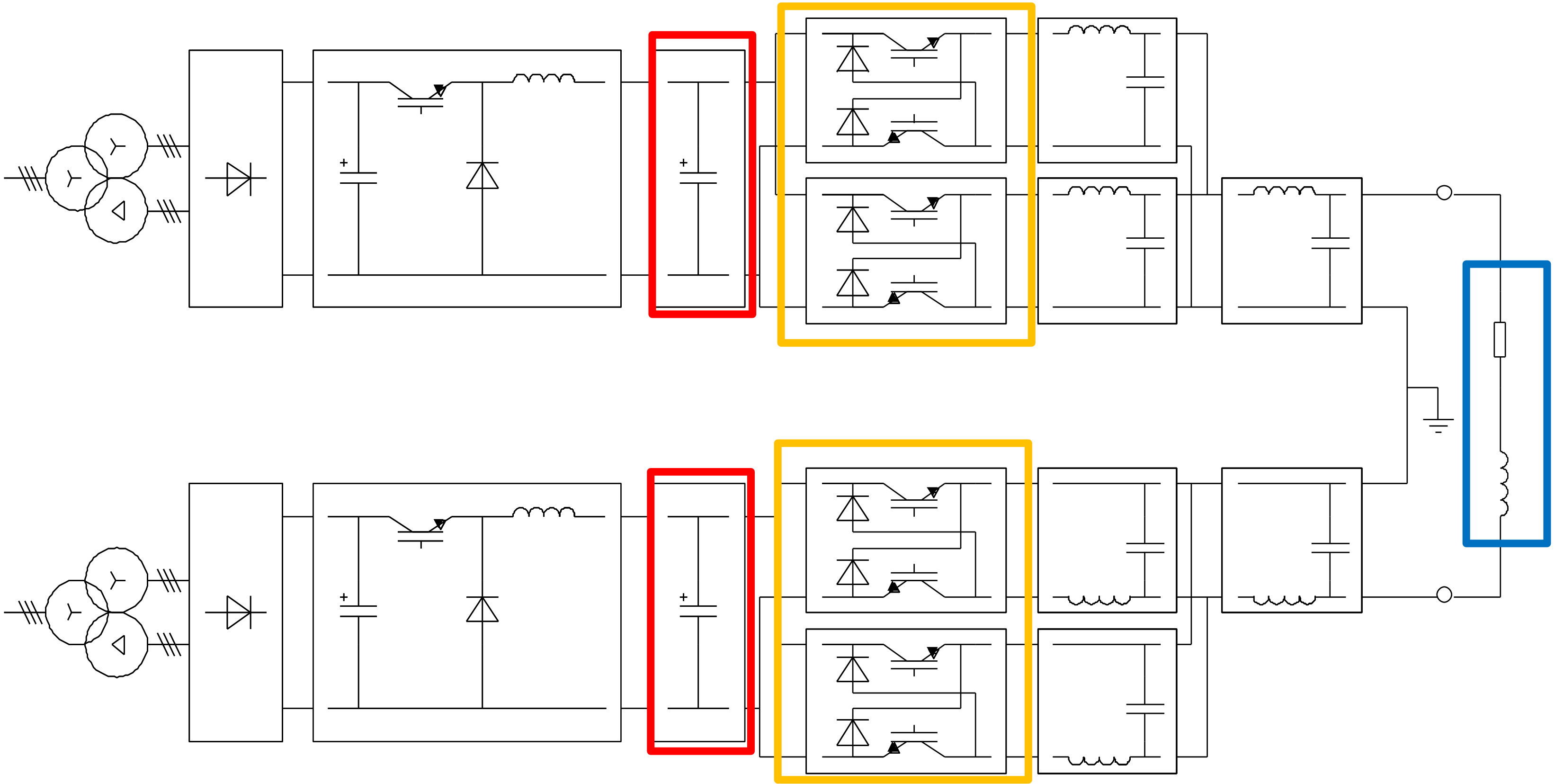
Technical and economic developments in electrolytic capacitors manufacture now result in capacitiative storage being lower cost than inductive energy storage (providing voltage reversal is not needed).

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.



DC
CHARGING

STORAGE
CAPACITOR

TWO
QUADRANT
CHOPPER

FILTER

MAGNET

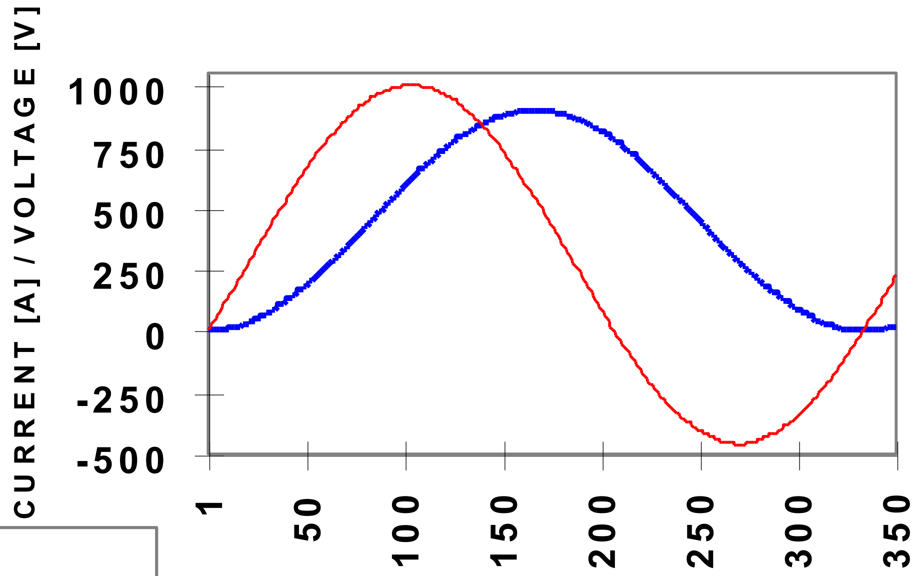
acknowledgment :Irminger, Horvat, Jenni, Boksberger, SLS

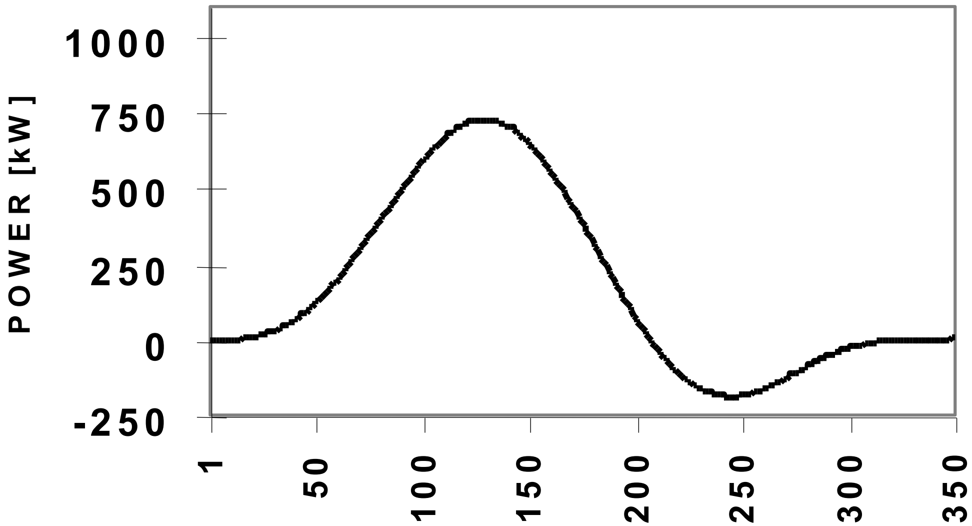
SLS Booster parameters

Combined function dipoles	48 BD 45 BF	
Resistance	600	mΩ
Inductance	80	mH
Max current	950	A
Stored energy	28	kJ
Cycling frequency	3	Hz

acknowledgment :Irminger, Horvat, Jenni, Boksberger, SLS

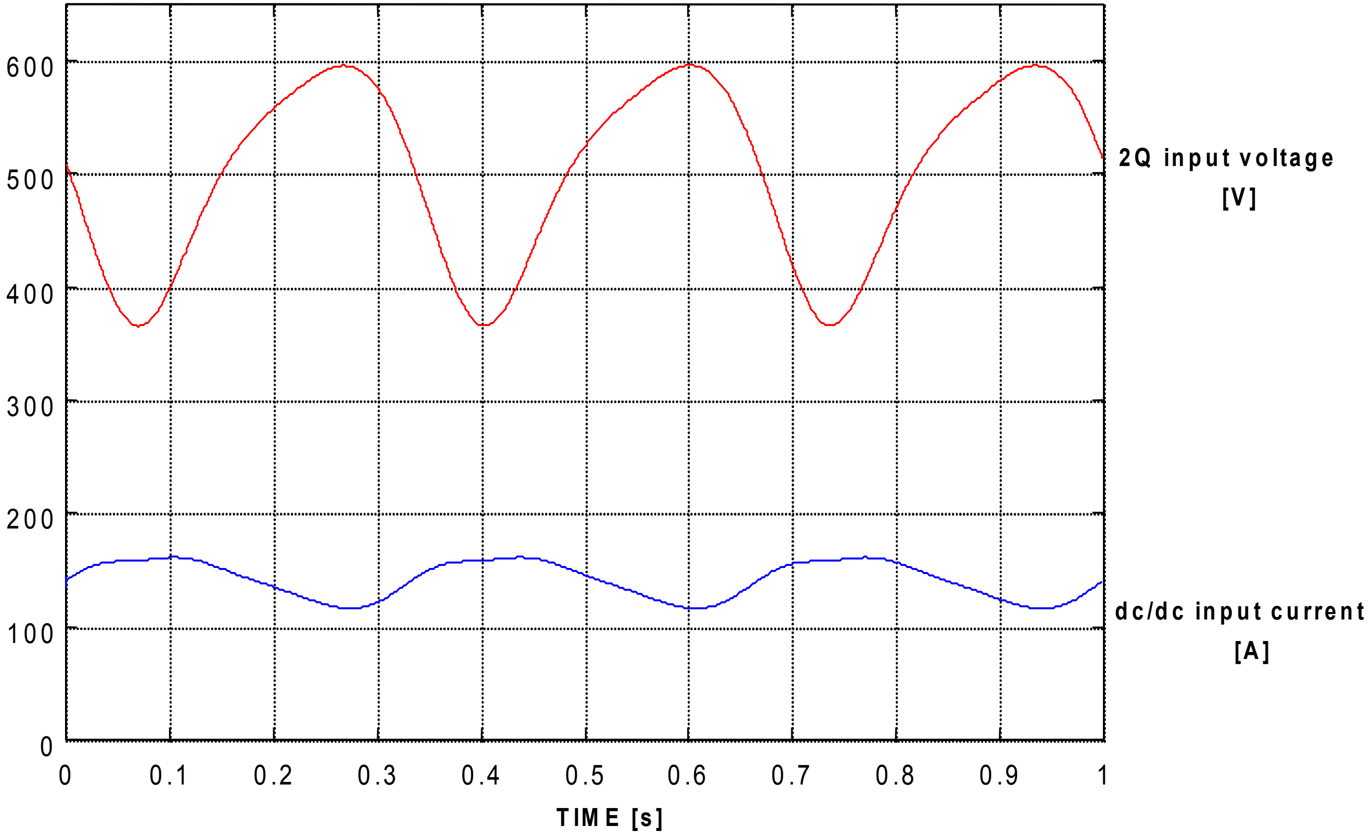
SLS Booster Waveforms





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

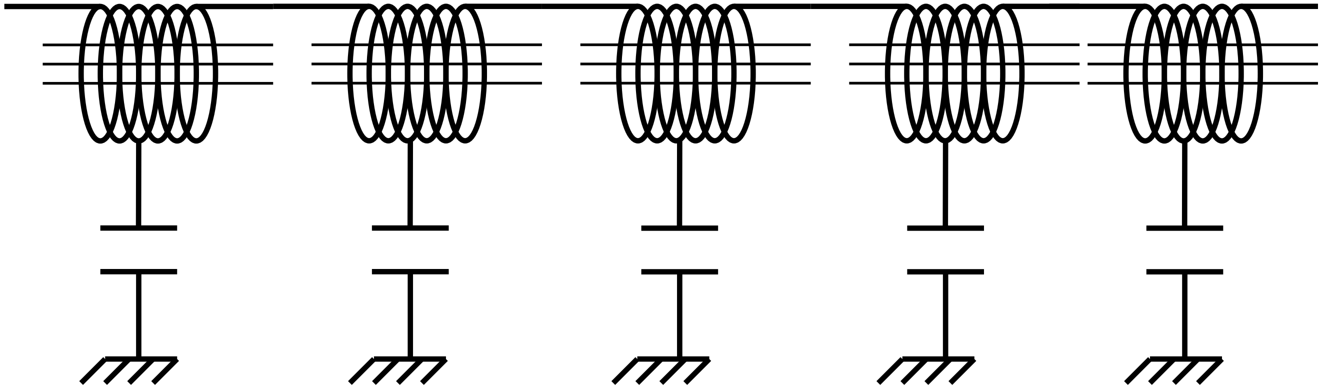
Parameter	low turns	high turns	
Number of turns per dipole:	16	20	
Peak current:	1271	1016	A
Total RMS current (for fully biased sine-wave):	778	622	A
Conductor cross section:	195	156	mm^2
Total ohmic loss:	188	188	kW
Inductance all dipoles in series:	0.091	0.142	H
Peak stored energy all dipoles:	73.3	73.3	kJ
Cycling frequency:	5	5	Hz
Peak reactive alternating volts across circuit:	1.81	2.26	kV

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

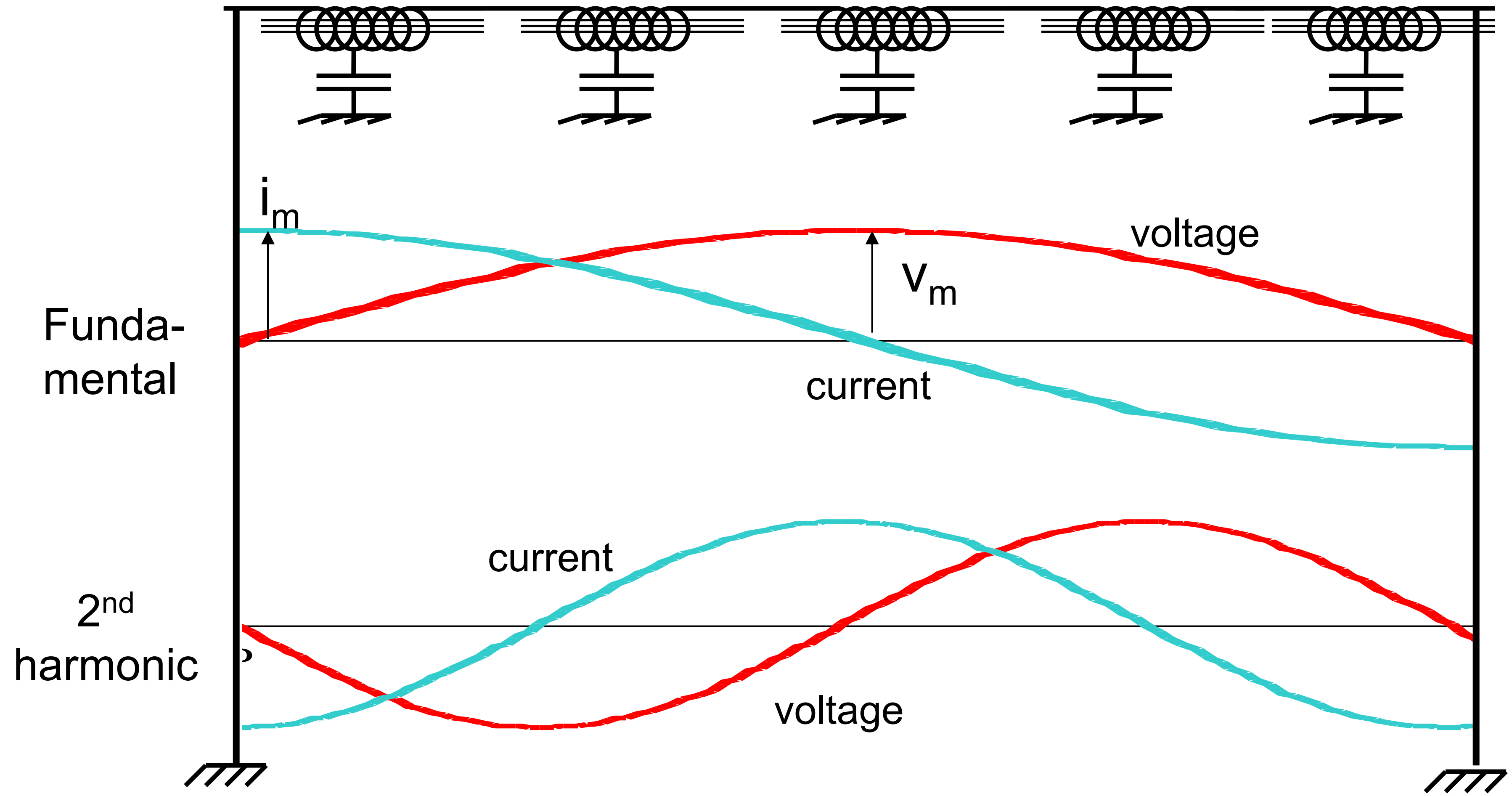
Most often seen in cycling circuits (high field disturbances produce disturbance at next injection); but can be present in any system.

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!**

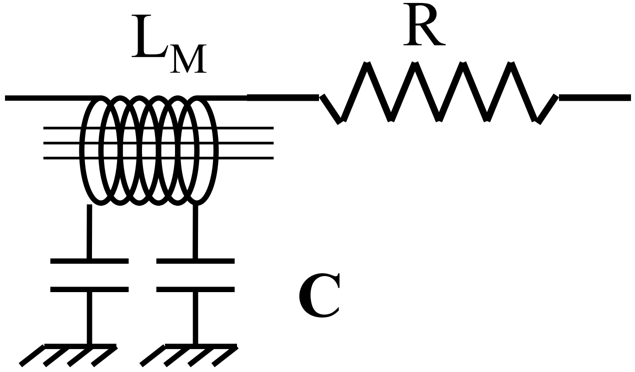


BAD ☹☹☹!

Standing waves in magnets chain.



Delay-line mode equations



L_M is total magnet inductance;
C is total stray capacitance;

Then:

surge impedance:

$$Z = v_m / i_m = \sqrt{(L_M / C)};$$

transmission time:

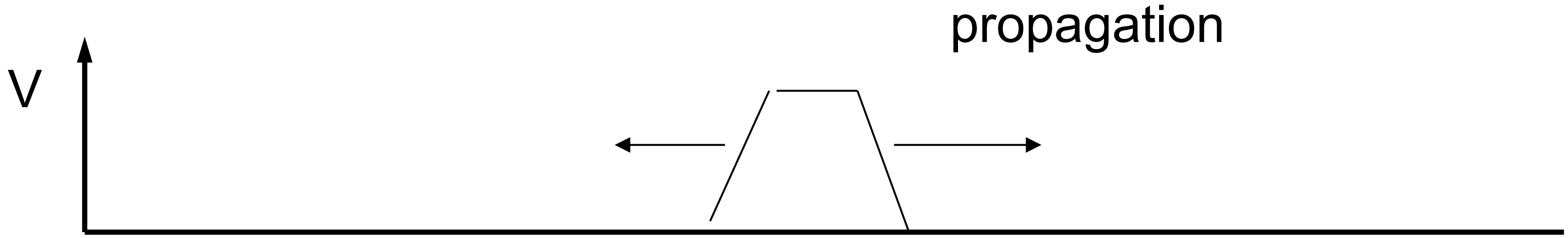
$$\tau = \sqrt{(L_M C)};$$

fundamental frequency:

$$\omega_1 = 1/\ \{2\sqrt{(L_M C)}\}$$

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!