Converters for Cycling Machines

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Contents

- DC and AC accelerators;
- suitable waveforms in cycling machines;
- the magnet load;
- reactive power;
- slow and fast cycling accelerators;
- typical ratings – 3 examples (SPS, ESRF booster, NINA);
- mechanical energy storage;
- the 'White Circuit' (inductive energy storage);
- modern capacitative energy storage;
- the delay line mode of resonance.

DC and AC Accelerators

Some circular accelerators are d.c.:

- cyclotrons;
- storage rings (but only <u>accelerators</u> if d.c. is slowly ramped).

Constant radius machines that are true <u>accelerators</u> must be a.c. – magnetic field must increase as energy is raised:

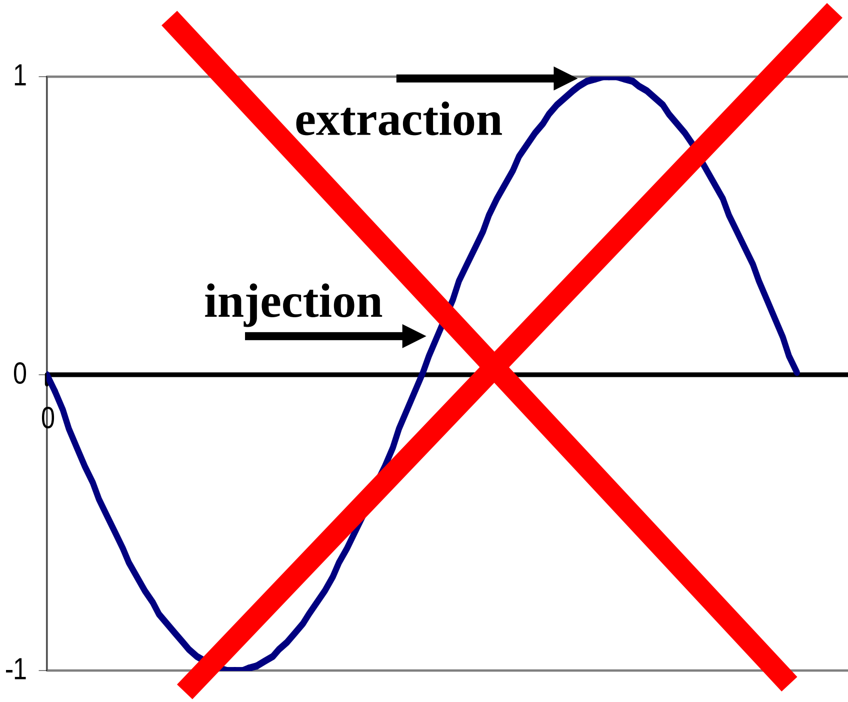
- the betatron;
- the synchrotron.

‘Simple’ A.C. Waveform

The required magnetic field (magnet current) is unidirectional –acceleration low to high energy:

- so ‘normal’ a.c. is <u>inappropriate</u>:

•only ¼ cycle used;
•excess rms current;
•high a.c. losses;
•high gradient at
injection.



Magnet Waveform criteria– r.f. system.

Acceleration:

particle momentum (rigidity) $= mv \propto B$;

r.f. accelerating voltage $V_{rf} \propto \partial B/\partial t$;

r.f. power $= k_1 \underset{\substack{\uparrow \\ \text{power into} \\ \text{beam}}}{V_{rf}} I_{beam} + k_2 (\underset{\substack{\uparrow \\ \text{cavity loss}}}{V_{rf}})^2$;

discontinuities in $\partial B/\partial t$ and r.f. voltage would generate synchrotron oscillations – possible beam loss.

Waveform criteria– synchrotron radiation.

Synchrotron radiation is only emitted by ultra relativistic particle beams (electrons at E ~ 1 GeV; protons at E ~ 1 TeV) when bent in a magnetic field !

synchrotron radiation loss	$\propto B^2 E^2$;
for a constant radius accelerator	$\propto B^4$;
r.f. voltage V_{rf} to maintain energy	$\propto B^4$;

Waveform criteria – eddy currents.

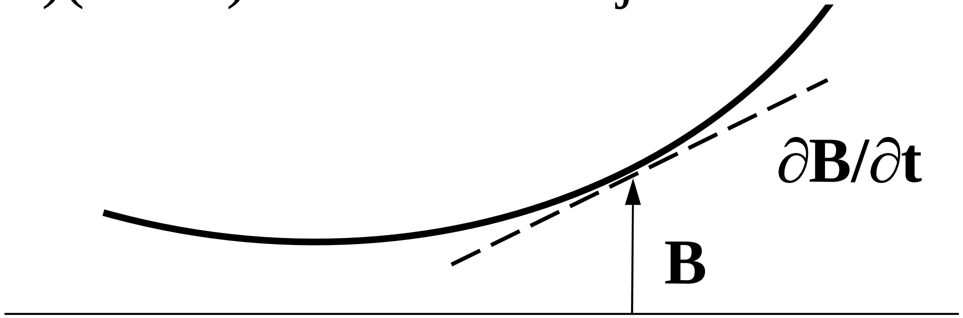
Generated by alternating magnetic field cutting a conducting surface:

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;

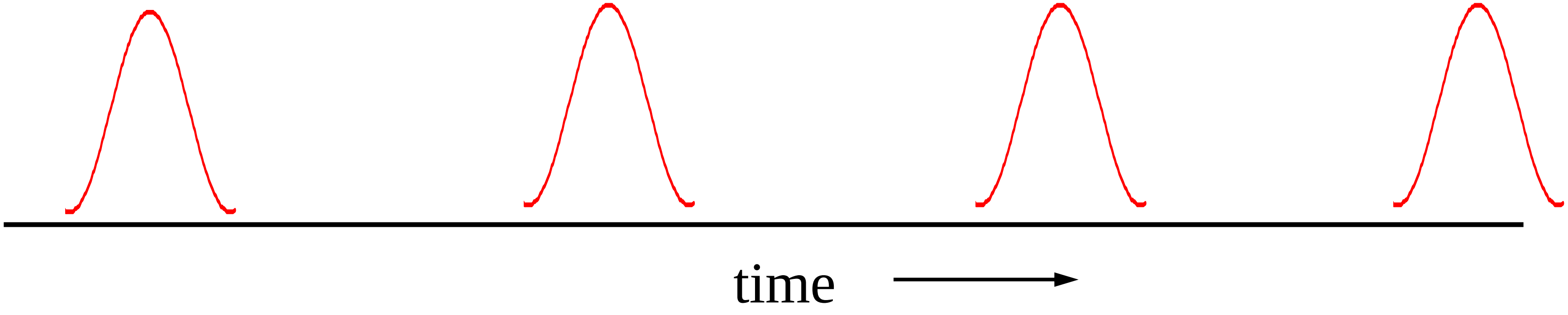
eddy effects proportional (1/B)(dB/dt) – critical at injection.



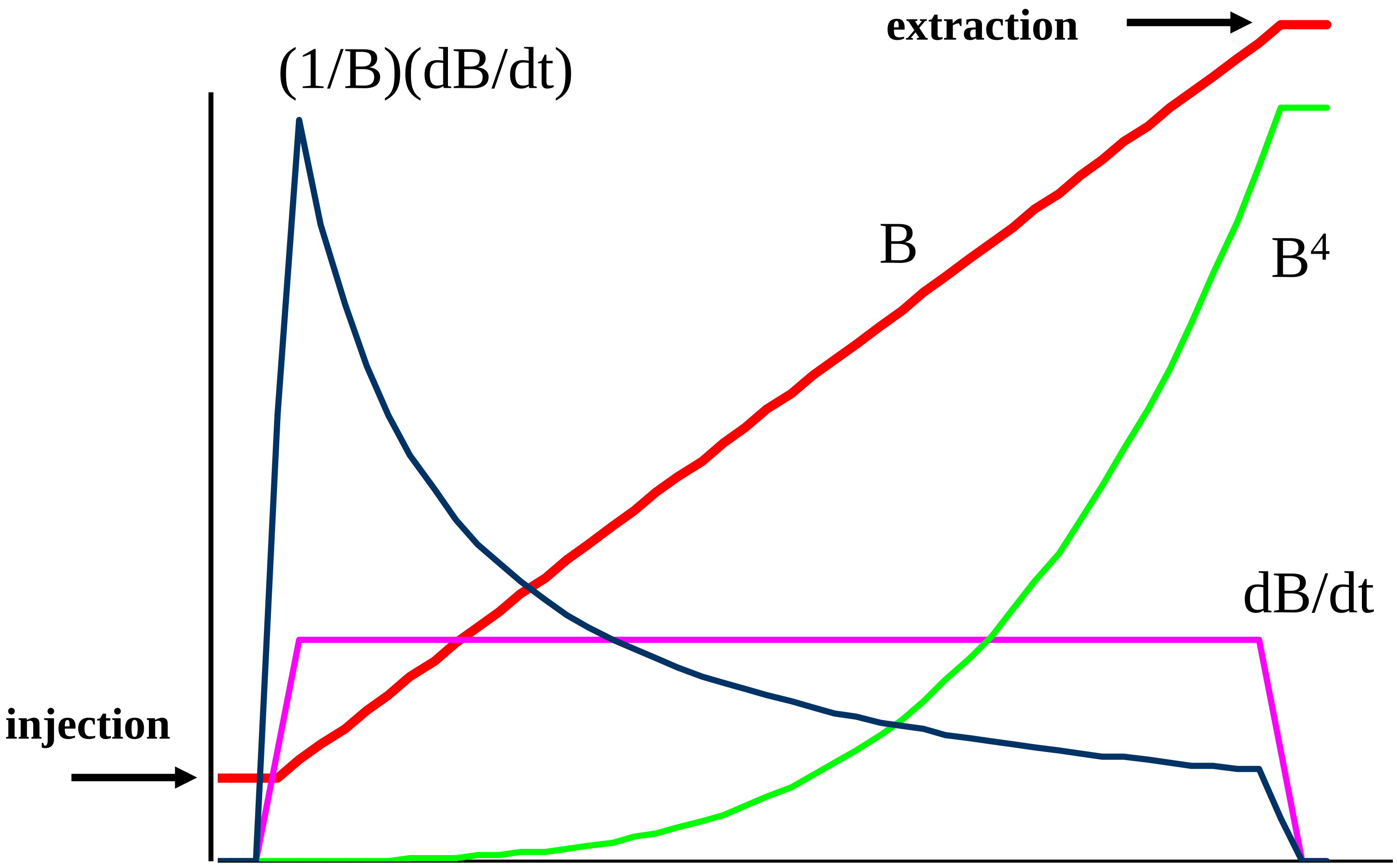
Waveform criteria – discontinuous operation

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

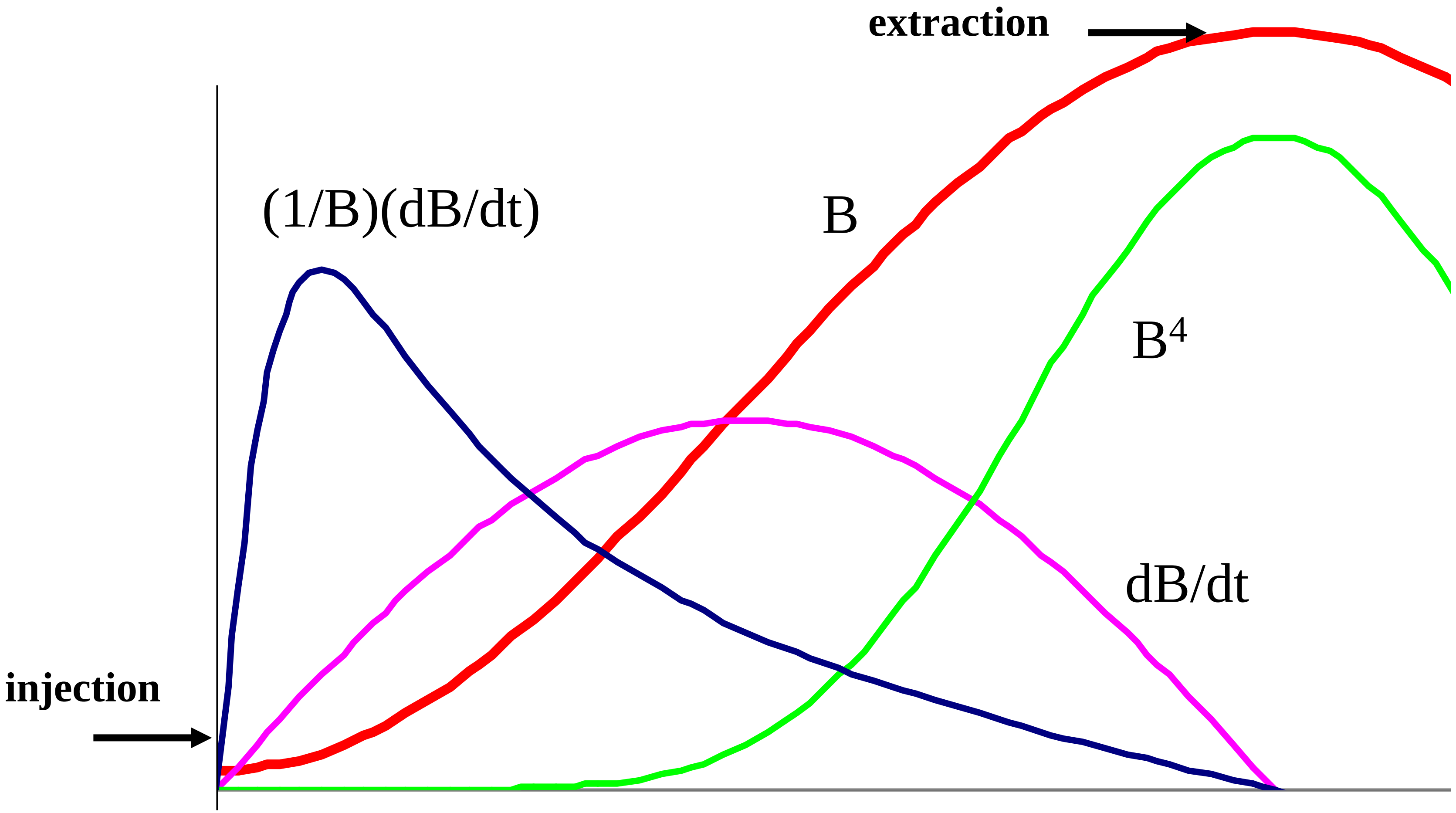
Solution – **'top up mode'** operation by the booster synchrotron – beam is only accelerated and injected once every n booster cycles, to maintain constant current in the main ring.



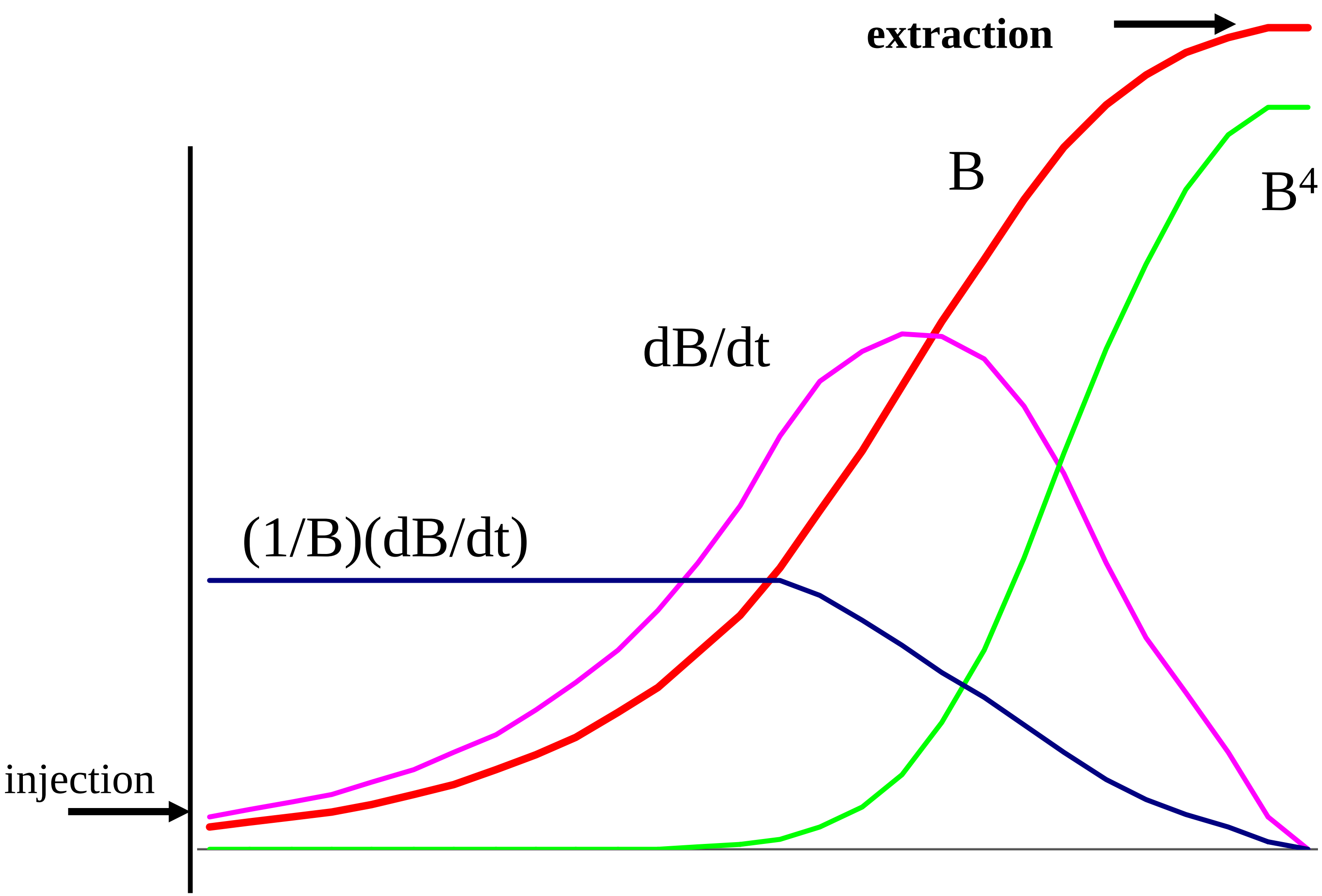
Possible waveform – linear ramp.



Possible waveform – biased sinewave.



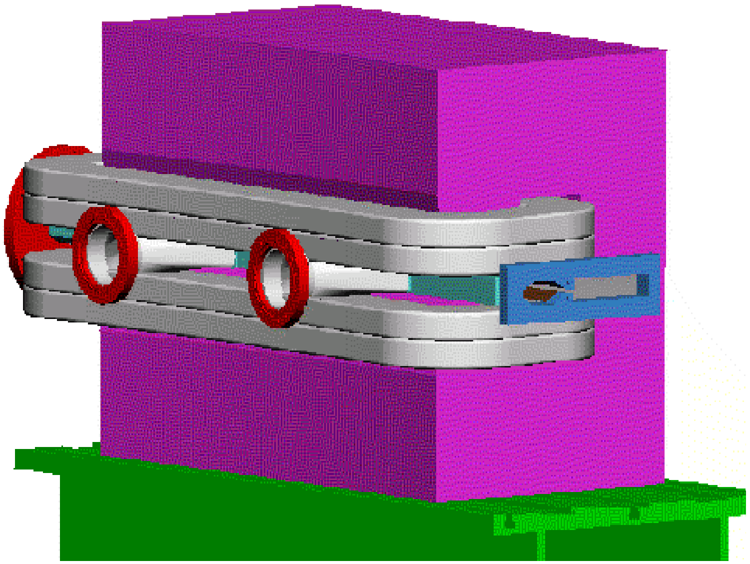
Possible waveform – ‘specified’ shape.

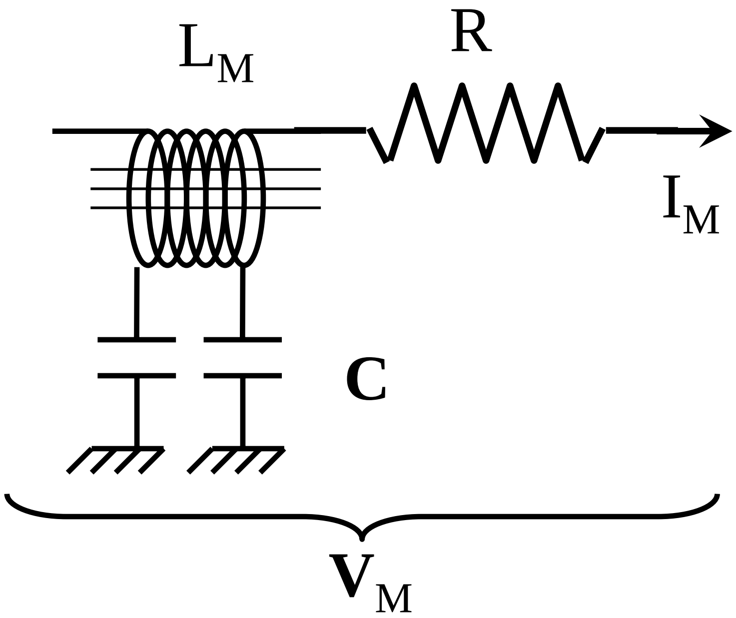


Waveform suitability

Waveform	Suitability
Linear ramp	**Gradient constant during acceleration;** **(∂ B/∂t)/B very high at injection;** **control of waveform during acceleration?**
Biased sinewave	**(∂ B/∂t)/B maximum soon after injection but lower than linear ramp;** **no control of waveform during acceleration.**
Specified waveform	**Provides for low (∂ B/∂t)/B at injection and full waveform control during acceleration; presents engineering design challenge.**

Magnet Load





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

‘Reactive’ Power

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.

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 01 to 5 Hz;
- separated function electron accelerators;

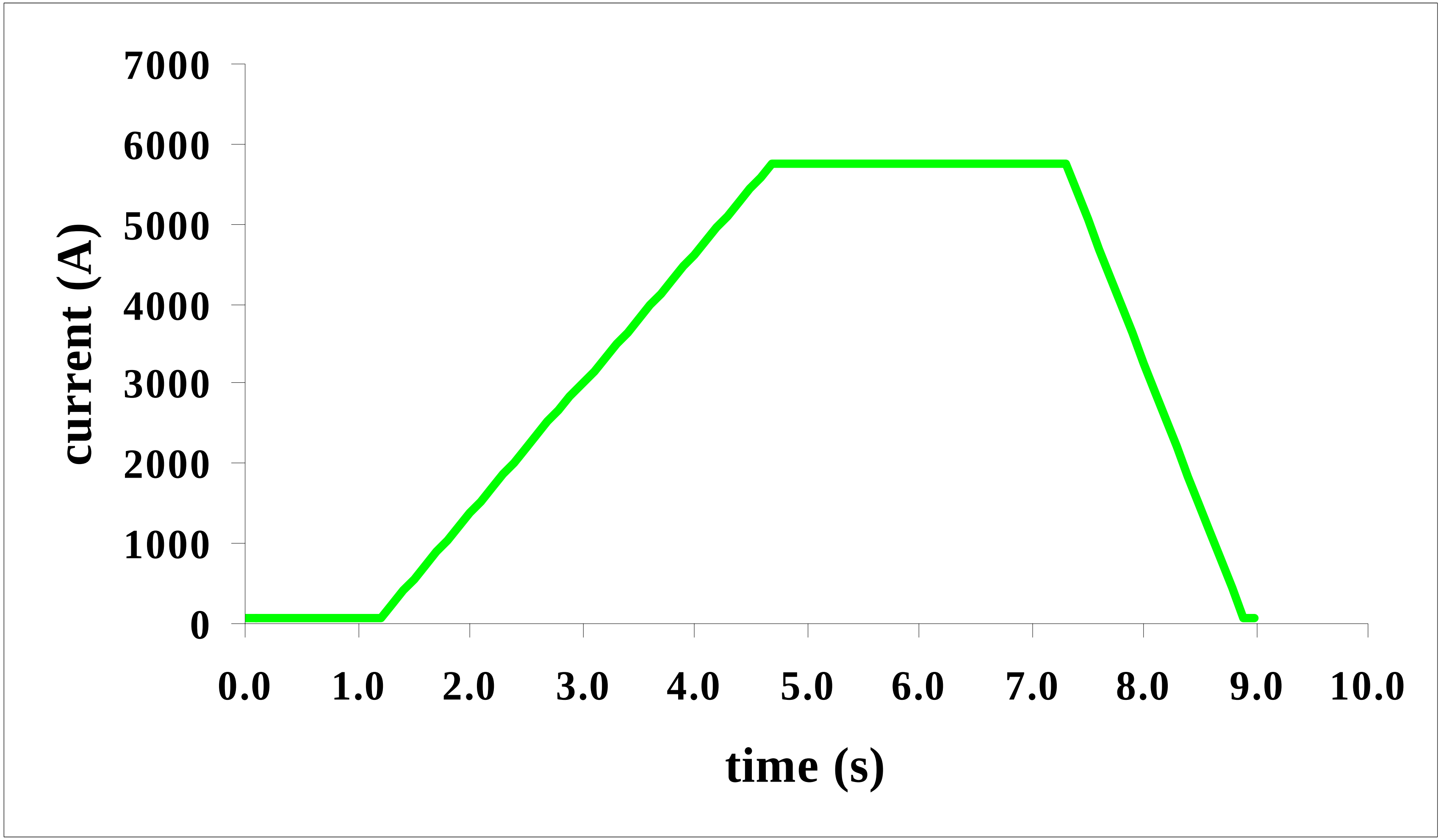
Examples – 1 the CERN SPS

A slow cycling synchrotron.

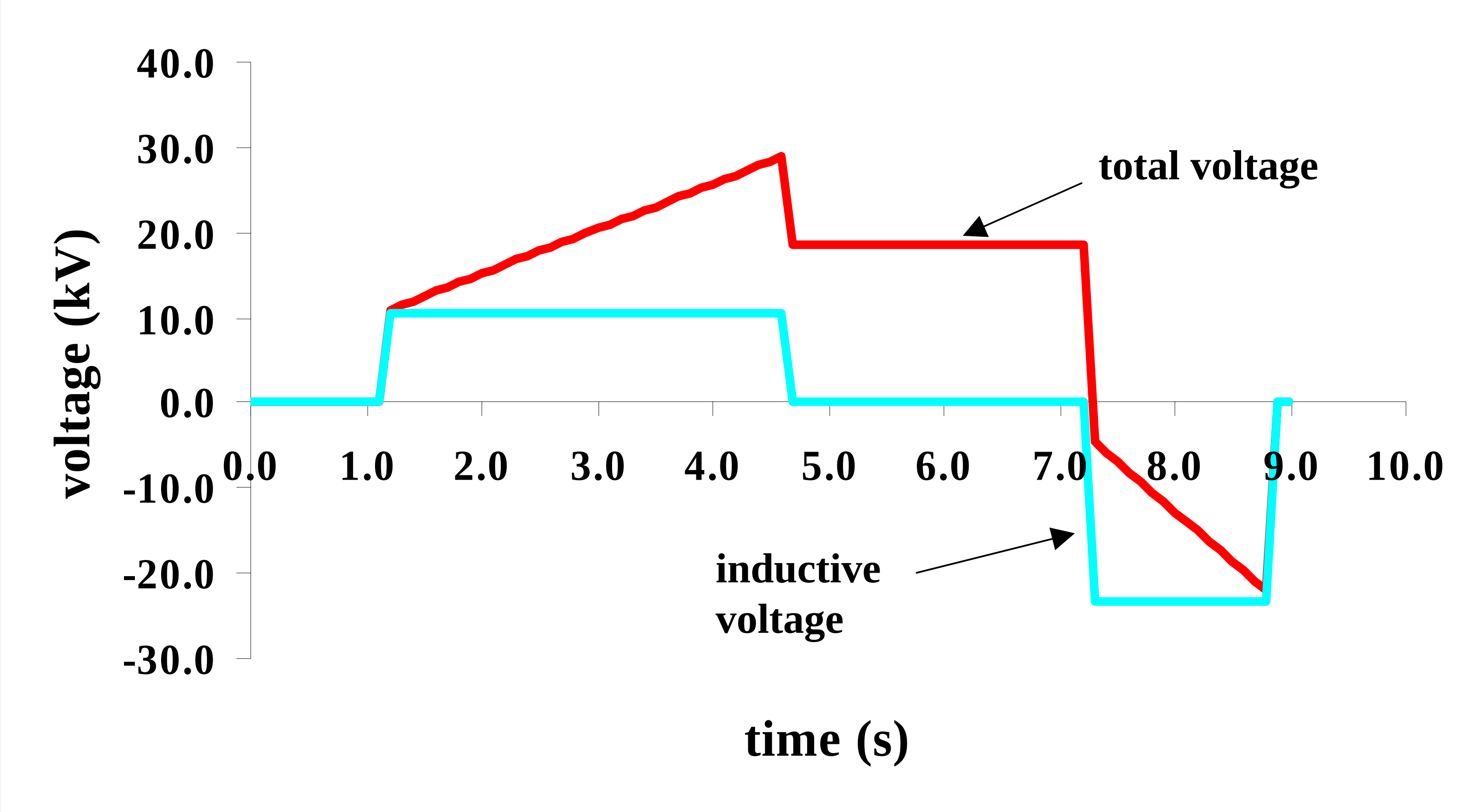
Dipole power supply parameters (744 magnets):

• 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;

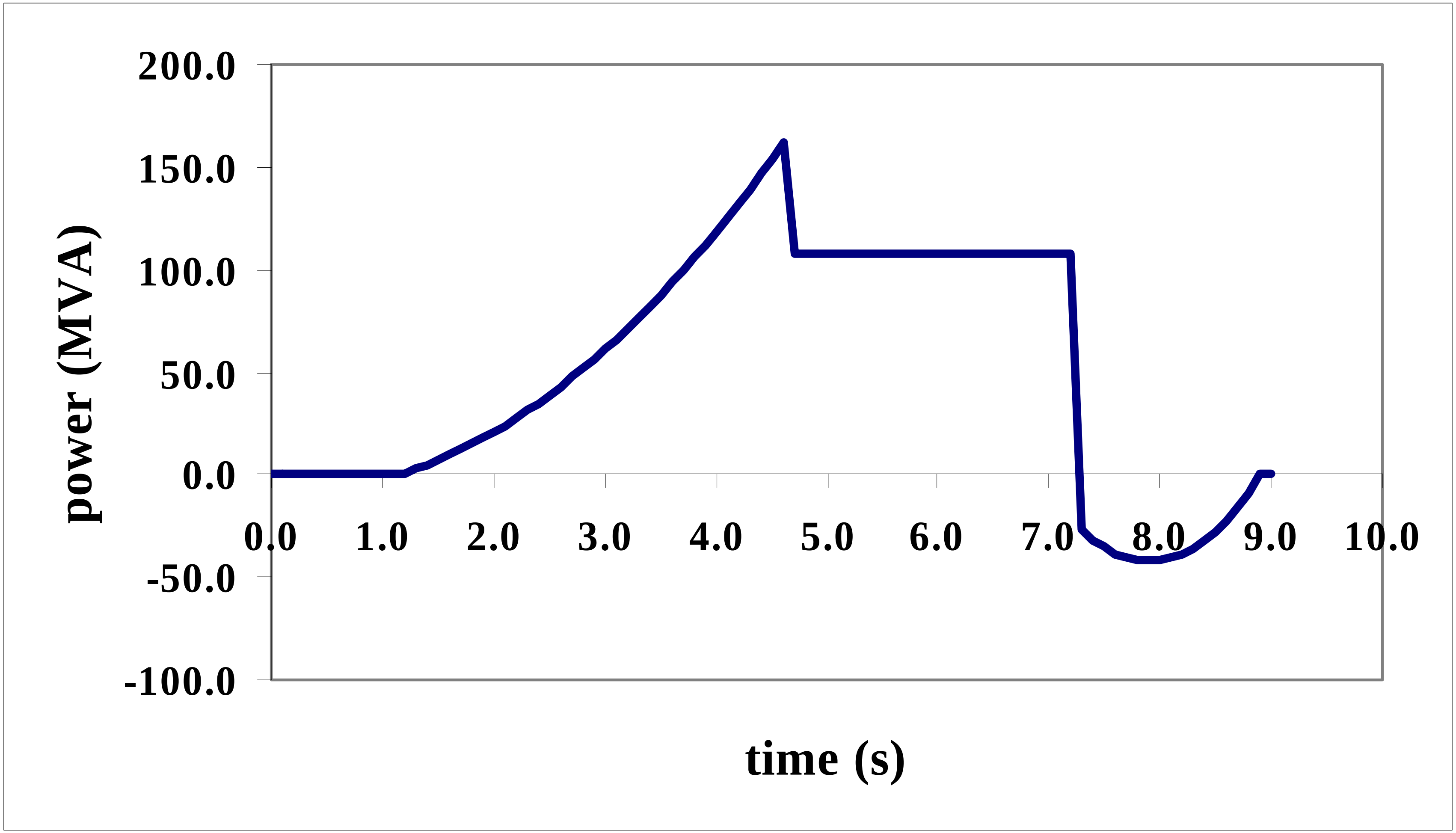
SPS Current waveform



SPS Voltage waveforms



SPS Magnet Power



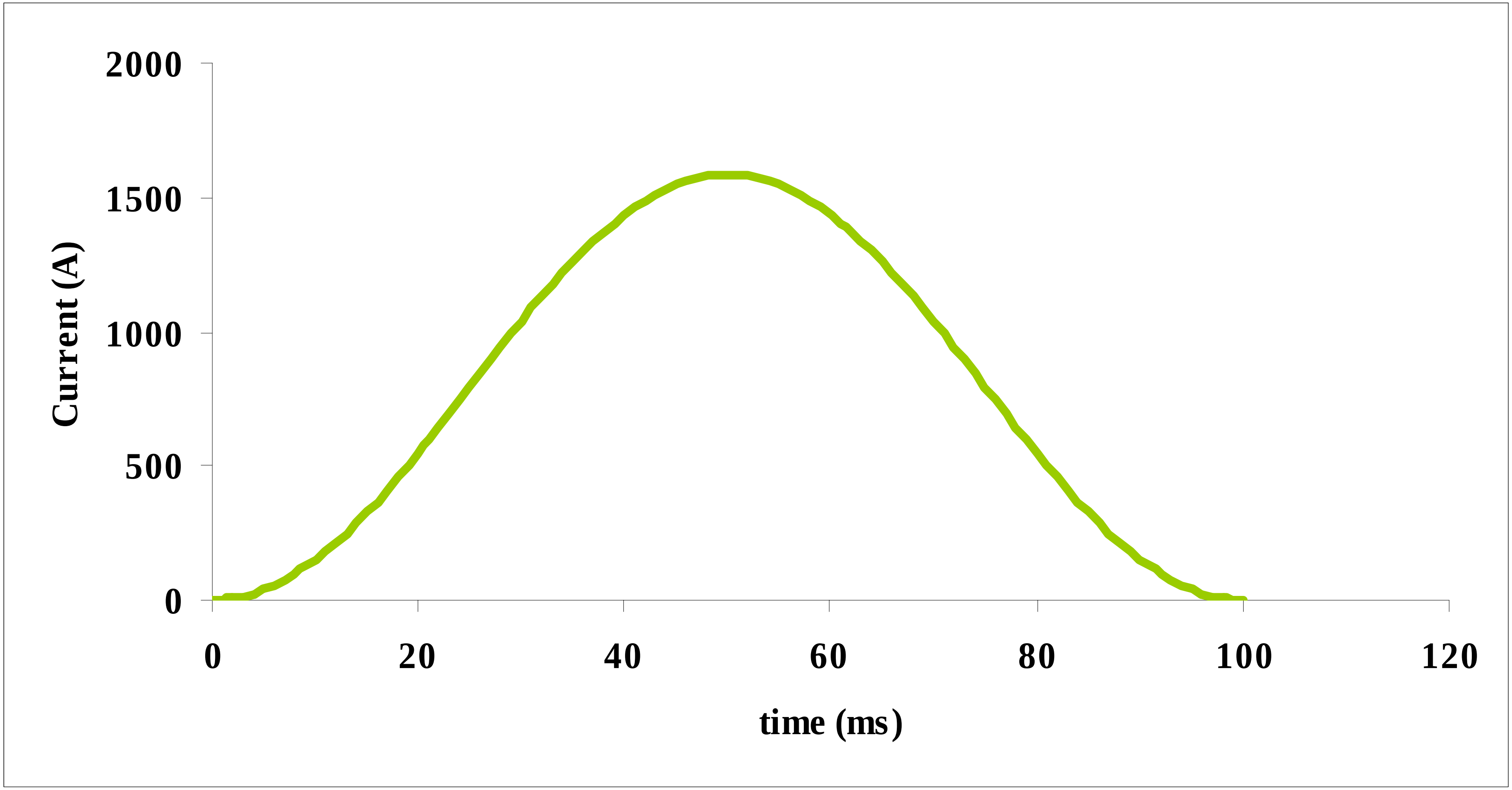
Example 2 – ESRF Booster

A 'medium' cycling synchrotron

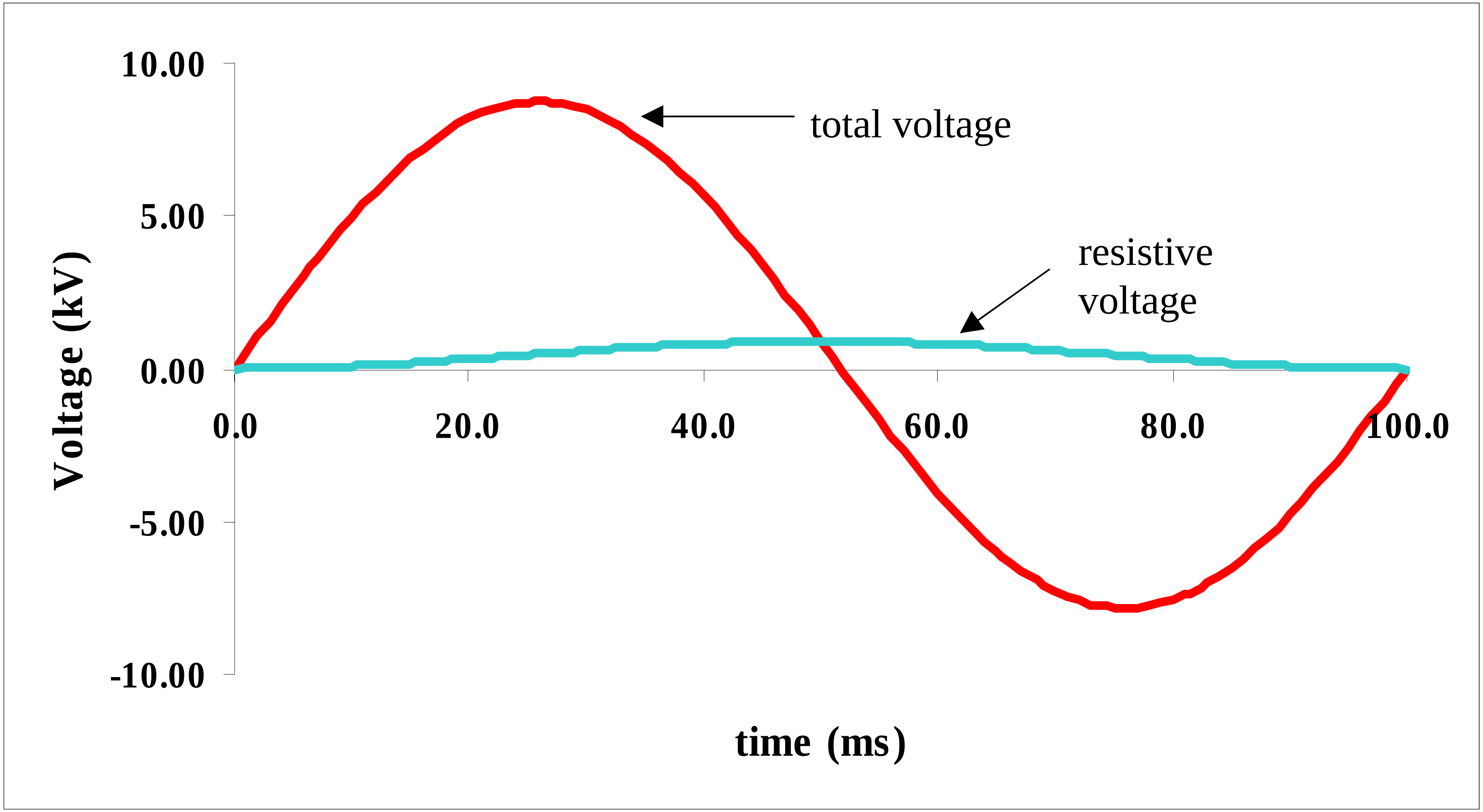
magnet power supply parameters;

• peak electron energy	3.0	GeV;
• cycle time	100	msecs;
• cycle frequency	10	Hz
• peak dipole current	1588	A;
• magnet resistance	565	mΩ;
• magnet inductance	166	mH;
• magnet stored energy	209	kJ;

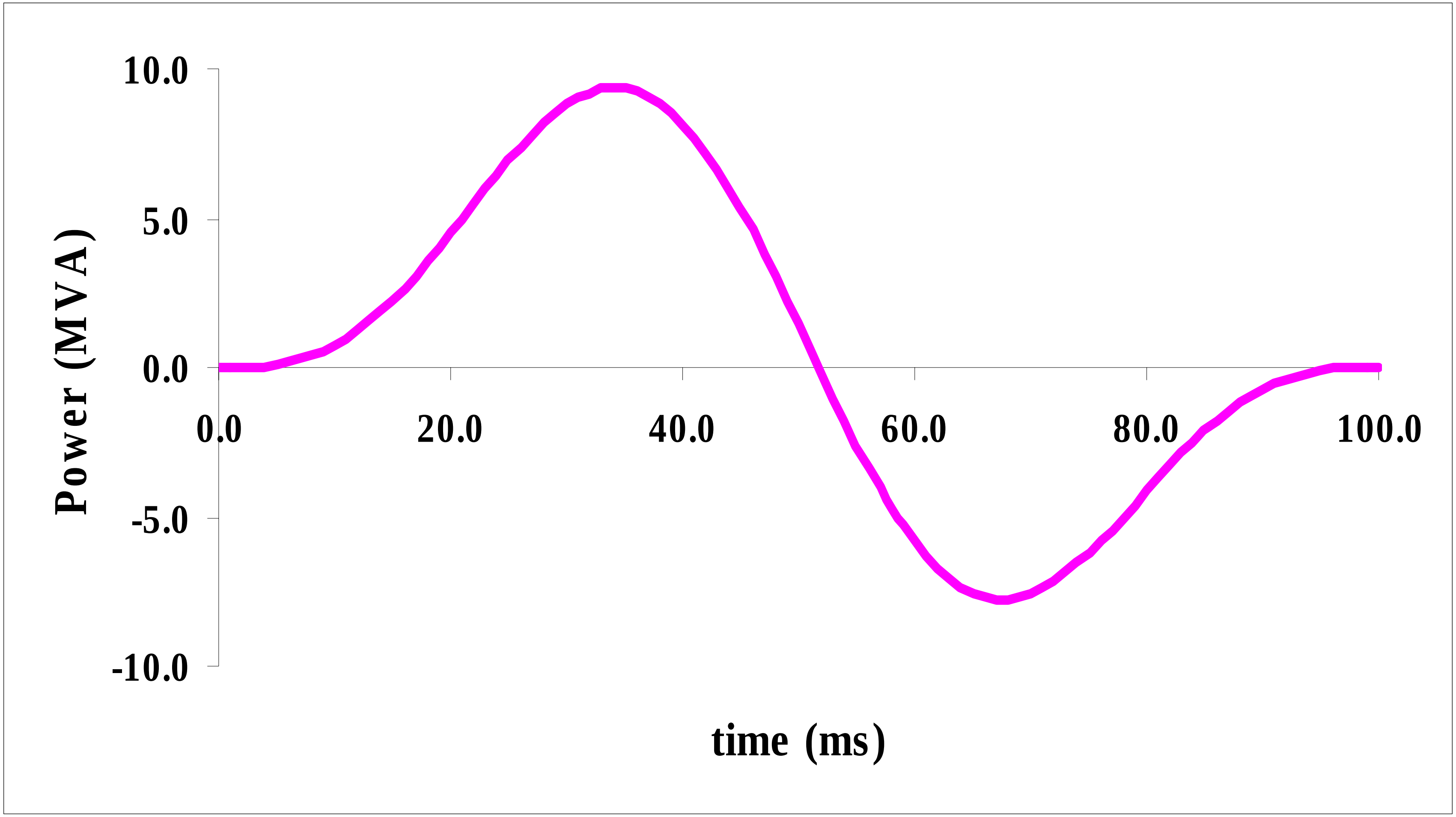
ESRF Booster Dipole Current waveform



ESRF Booster Voltage waveform



ESRF Booster Power waveform



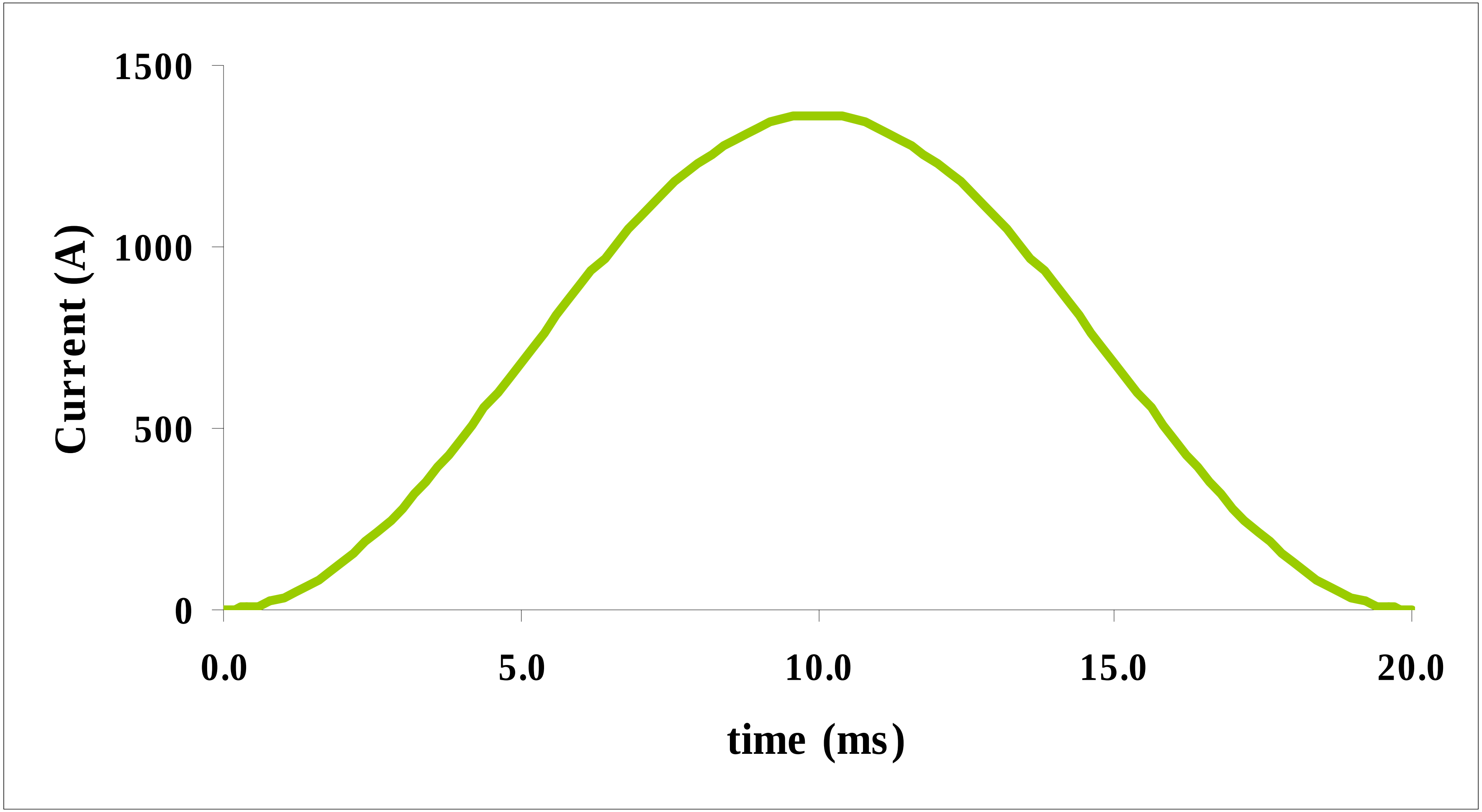
Example 3 – NINA (D.L.)

A fast cycling synchrotron

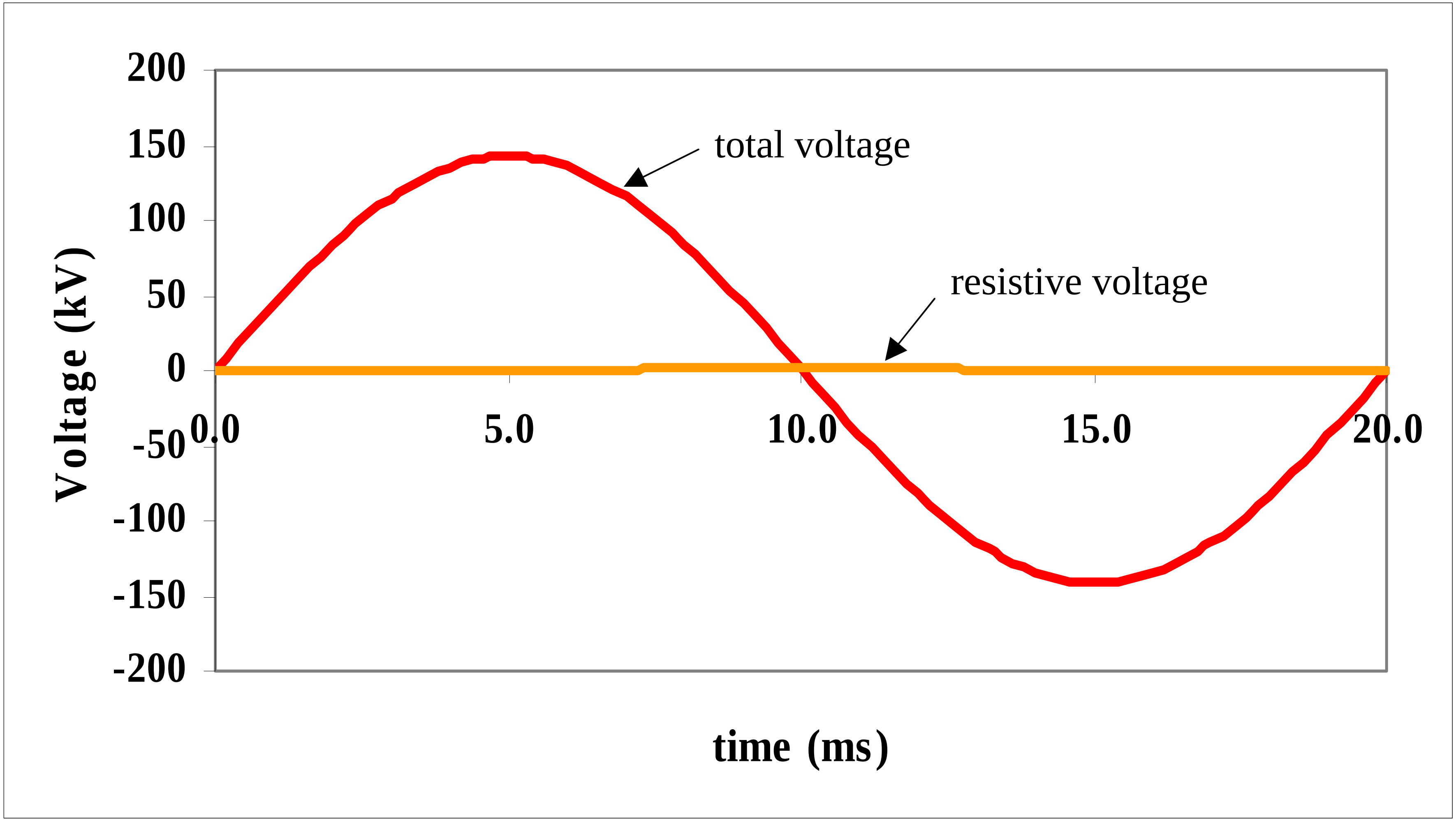
magnet power supply parameters;

peak electron energy	5.0	GeV;
cycle time	20	msecs;
cycle frequency	50	Hz
peak current	1362	A;
magnet resistance	900	mΩ;
magnet inductance	654	mH;
magnet stored energy	606	kJ;

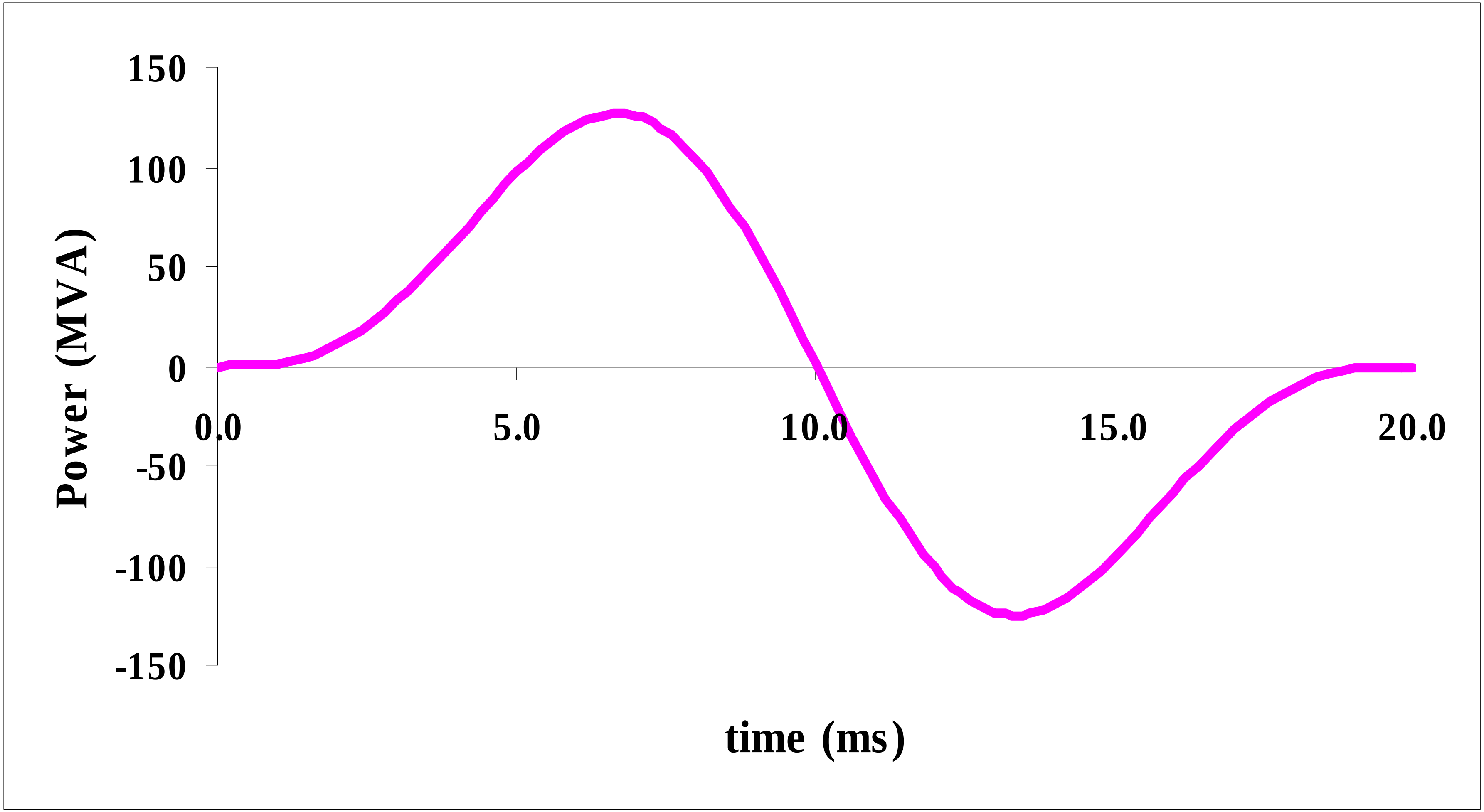
NINA Current waveform



NINA Voltage waveform



NINA Power waveform

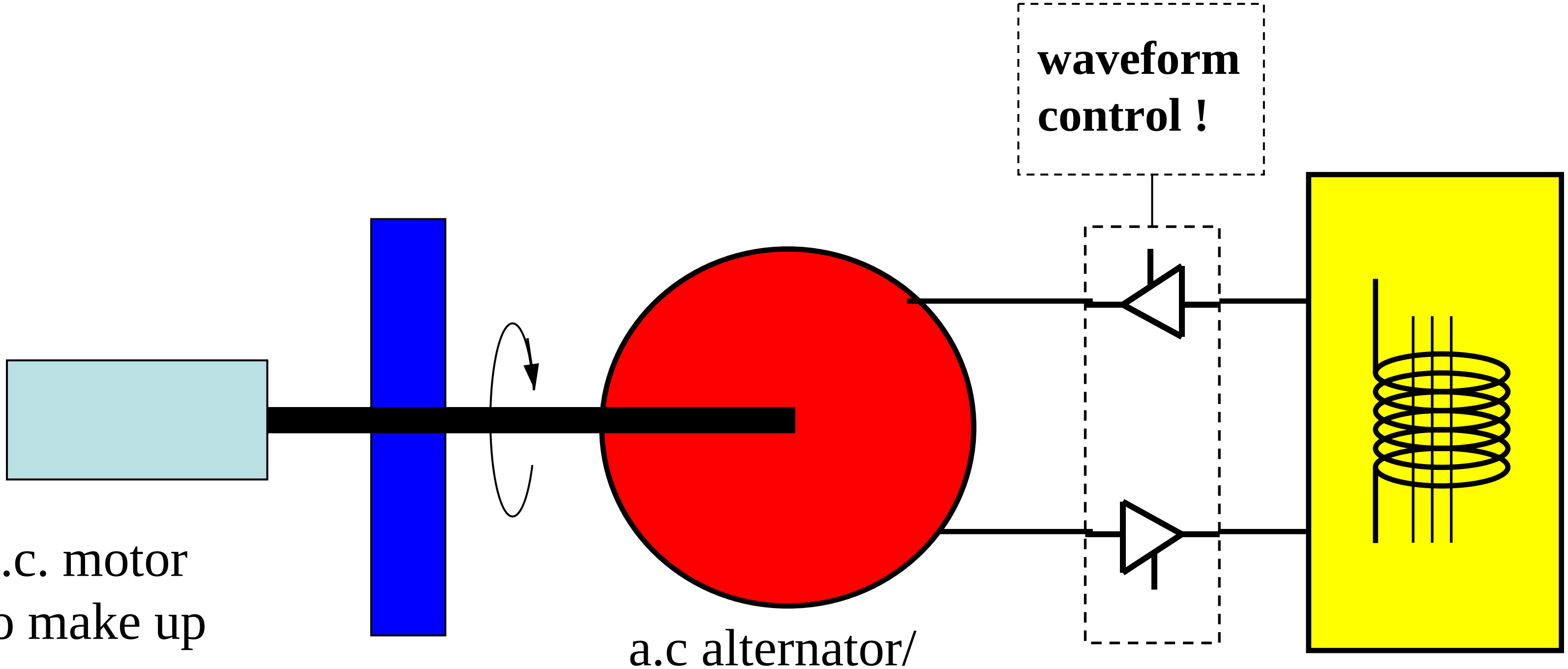


Cycling converter requirements

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 possible) discontinuous operation for ‘top up mode’.

‘Slow Cycling’ Mechanical Storage



waveform control !

d.c. motor to make up losses

high inertia fly-wheel to store energy

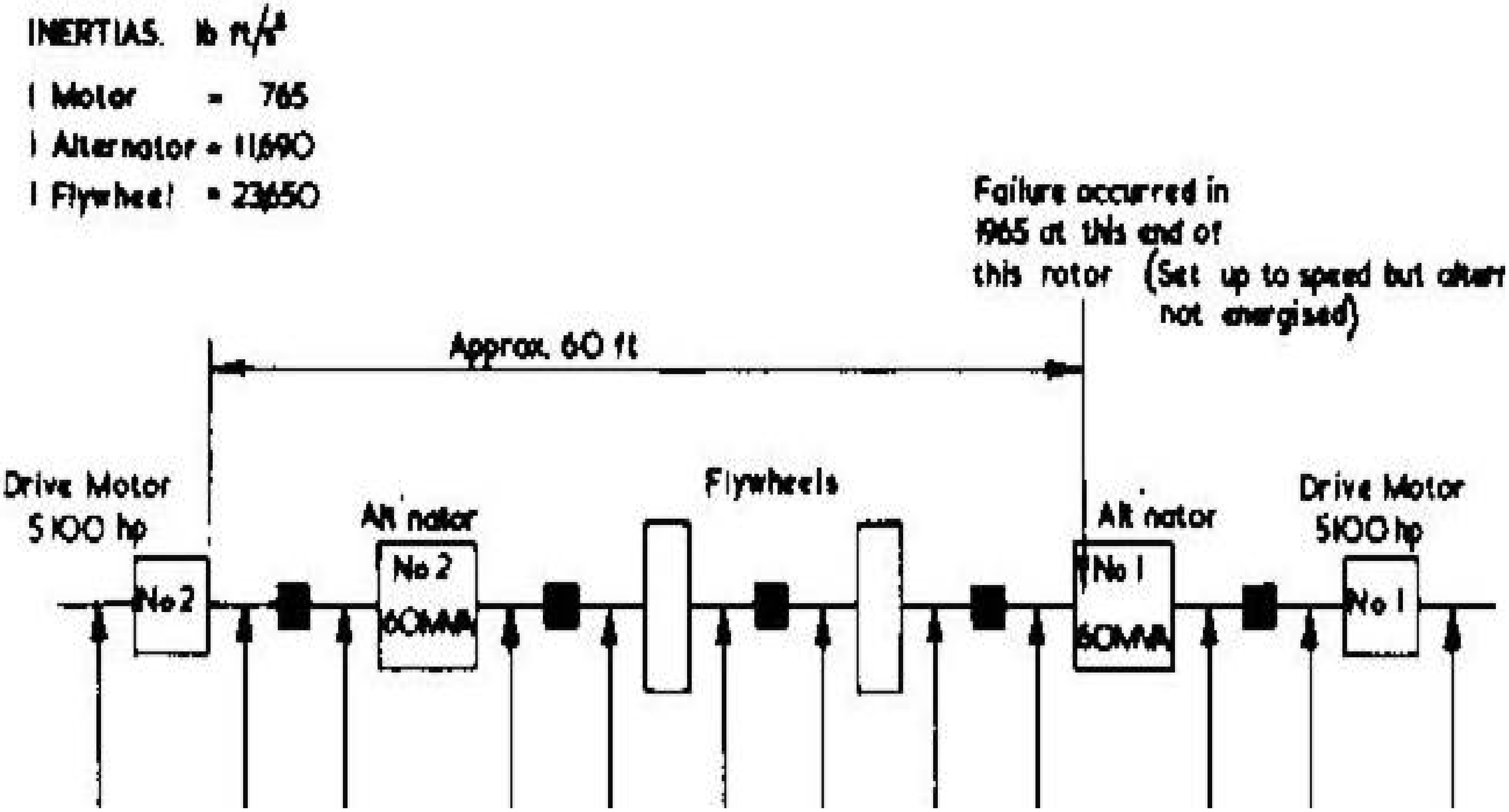
a.c alternator/ synchronous motor

rectifier/ inverter

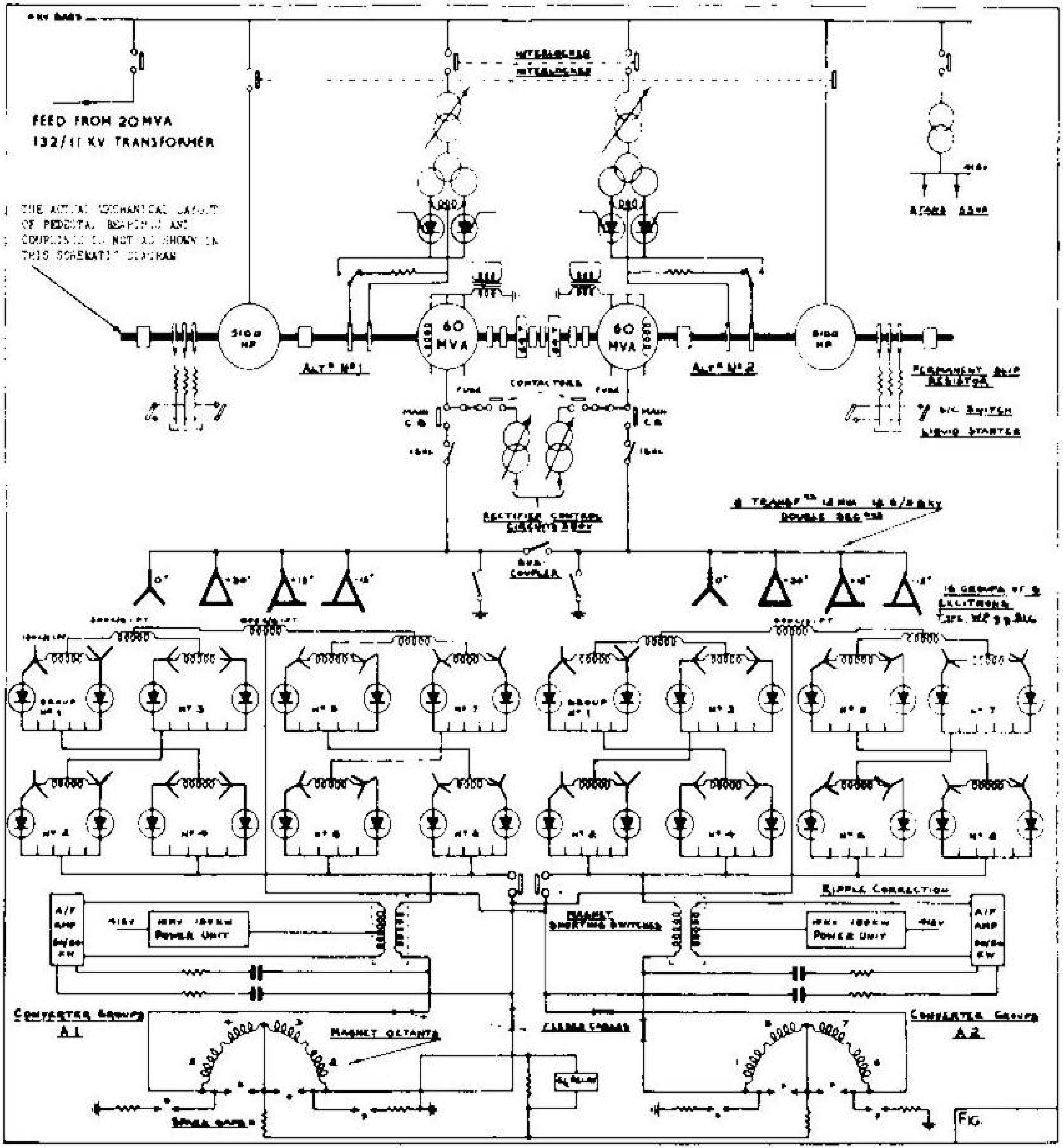
magnet

Examples: all large proton accelerators built in 1950/60s.

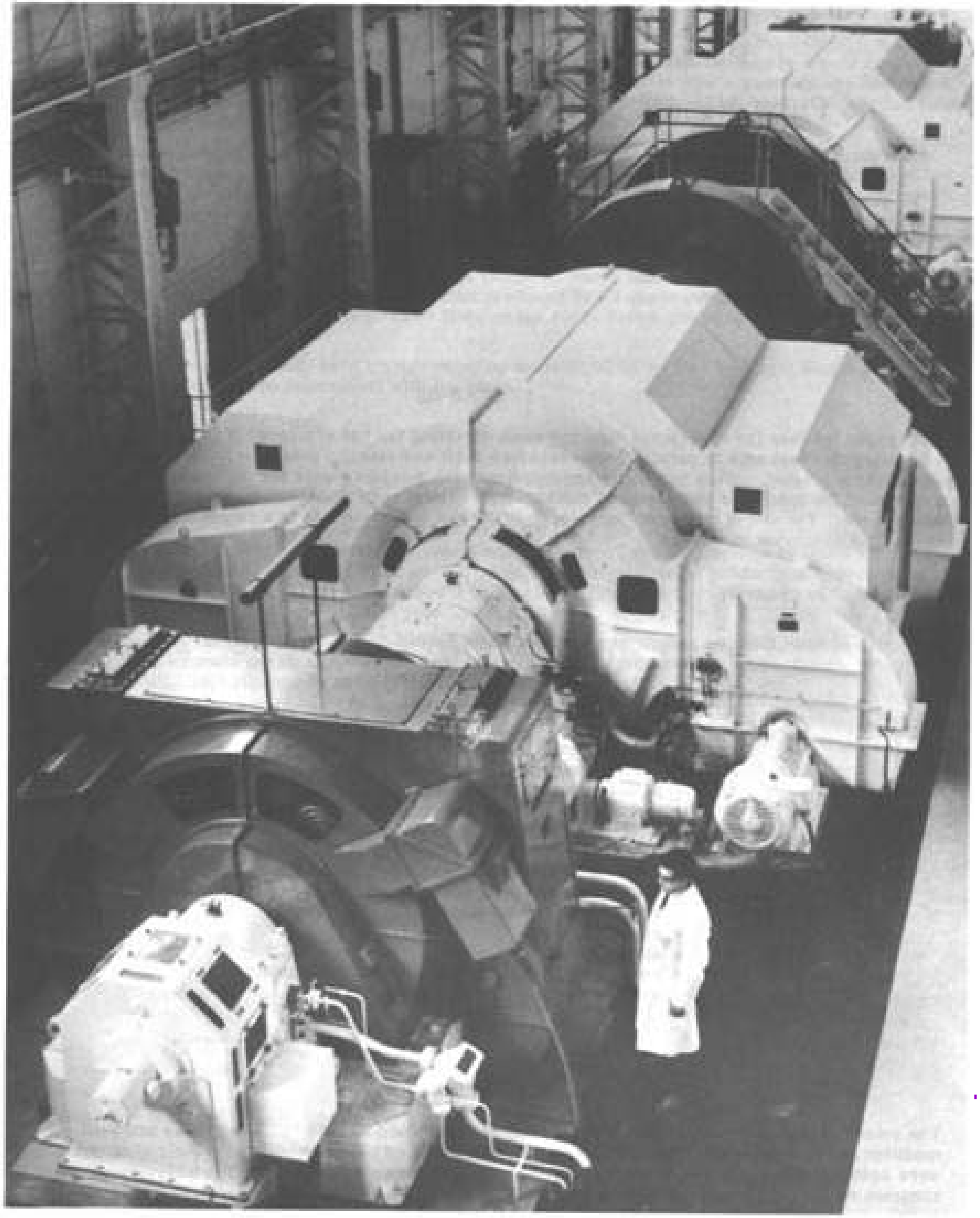
System/circuit for 7 GeV ‘Nimrod’



Nimrod circuit



Nimrod motor, alternators and fly-wheels



‘Slow cycling’ direct connection to supply network

National supply networks have large stored (inductive) energy; given 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.

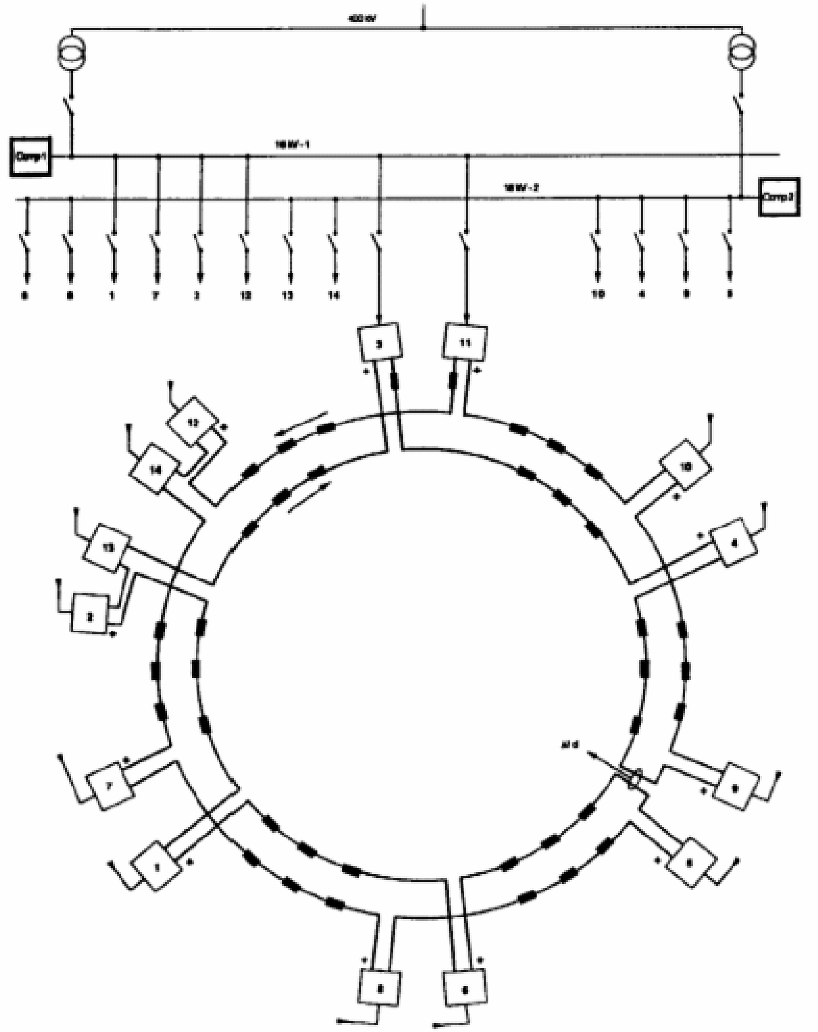
A ‘rigid’ high voltage line in is necessary.

Example - Dipole supply for the SPS

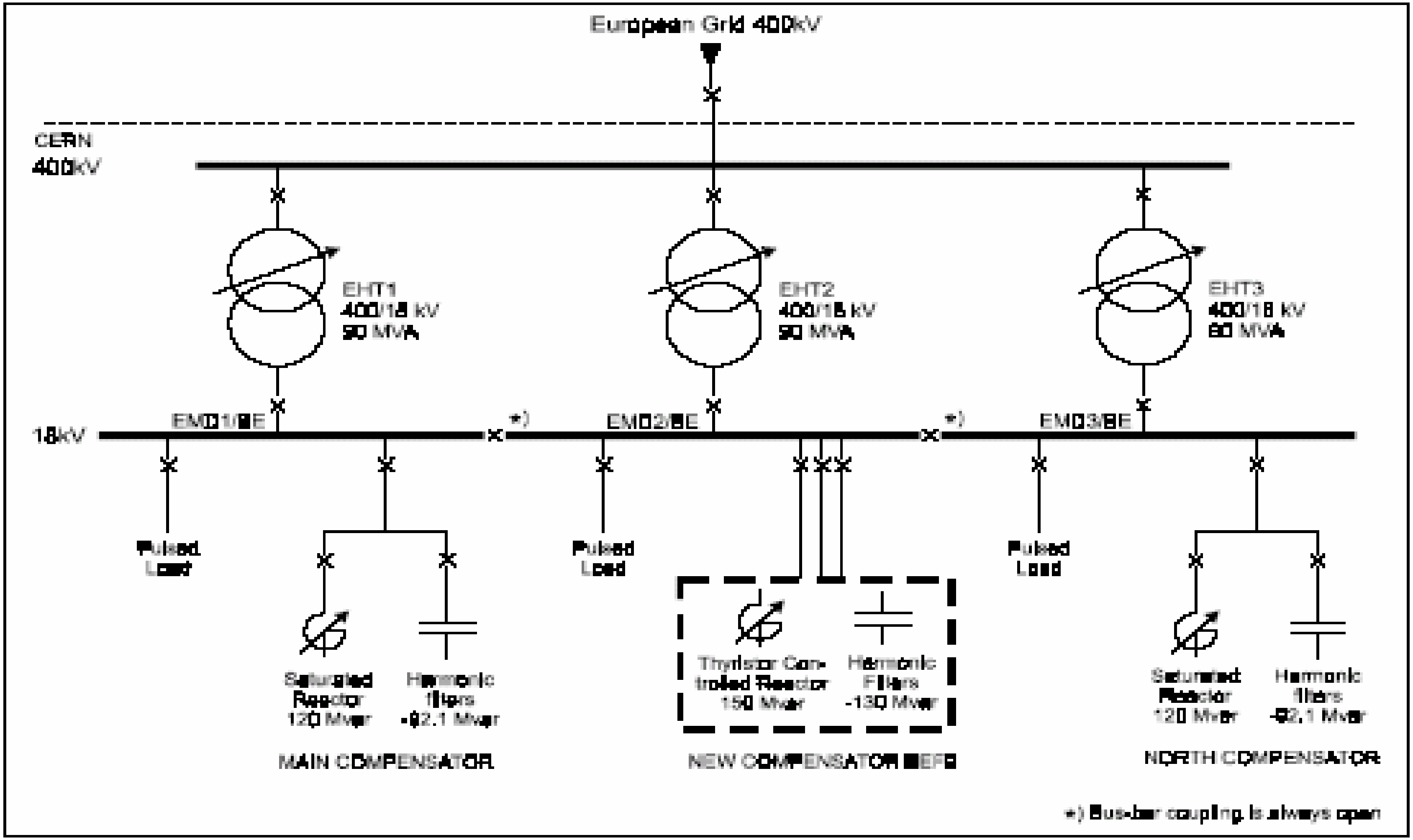
14 converter modules (each 2 sets of 12 pulse phase controlled thyristor rectifiers) supply the ring dipoles in series; waveform control!

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.

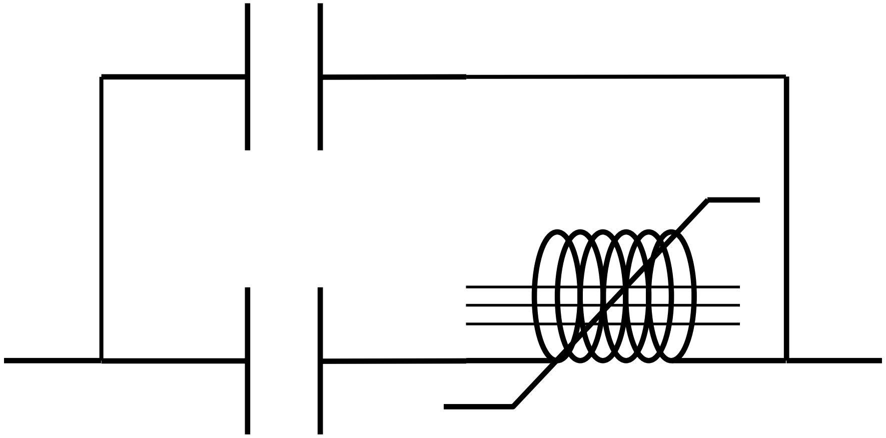


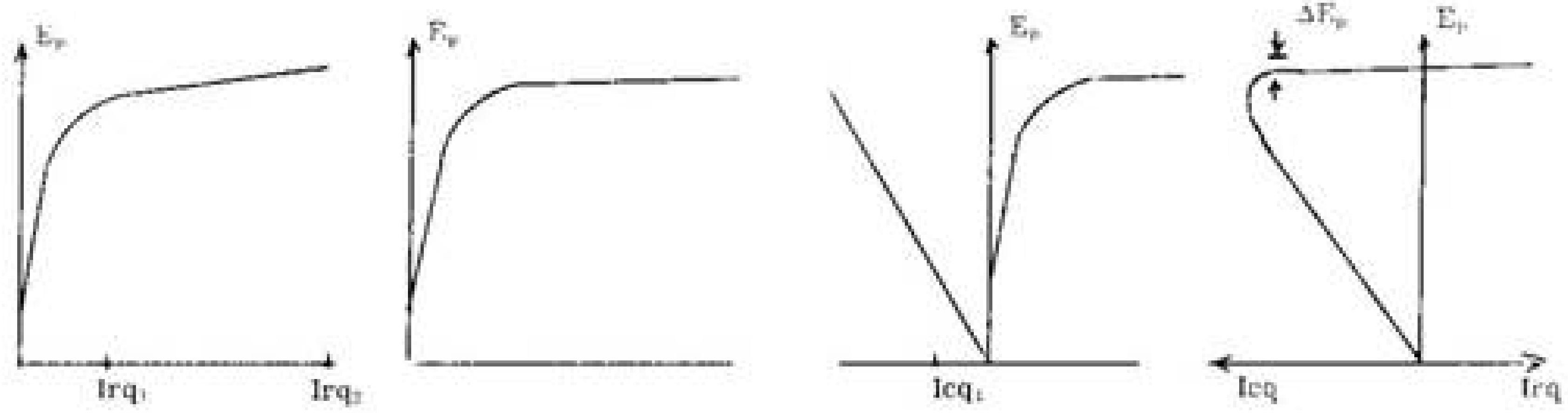
Reactive power compensation.



Saturable reactor compensation

J. Fox's original diagrams (1967) for the capacitor/inductor parallel circuit:





Reactor
(a)

+ series capacitor
(b)

+ shunt capacitor
(c)

combined
(d)

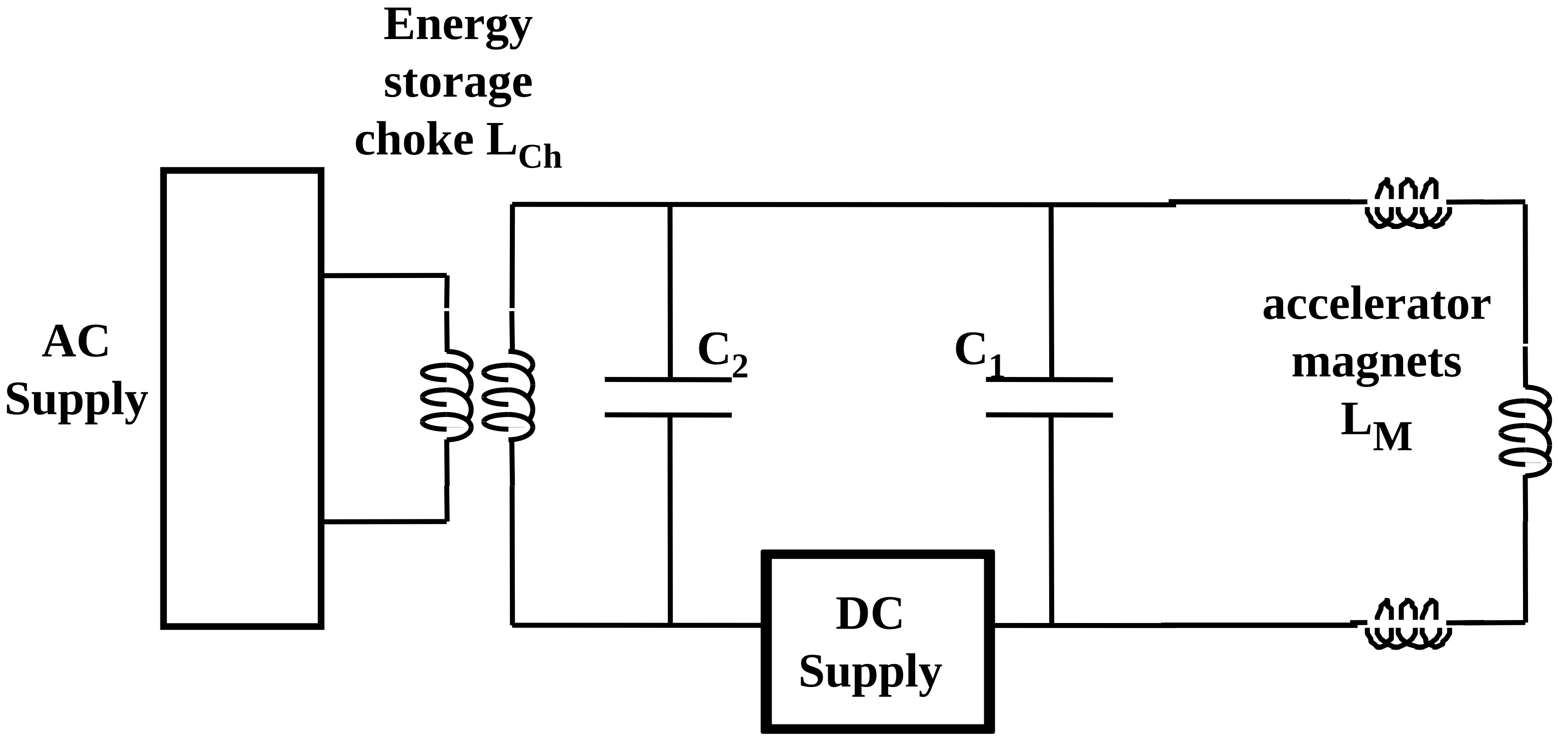
Medium & fast cycling inductive storage.

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

inductive storage was roughly half the cost per 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.)

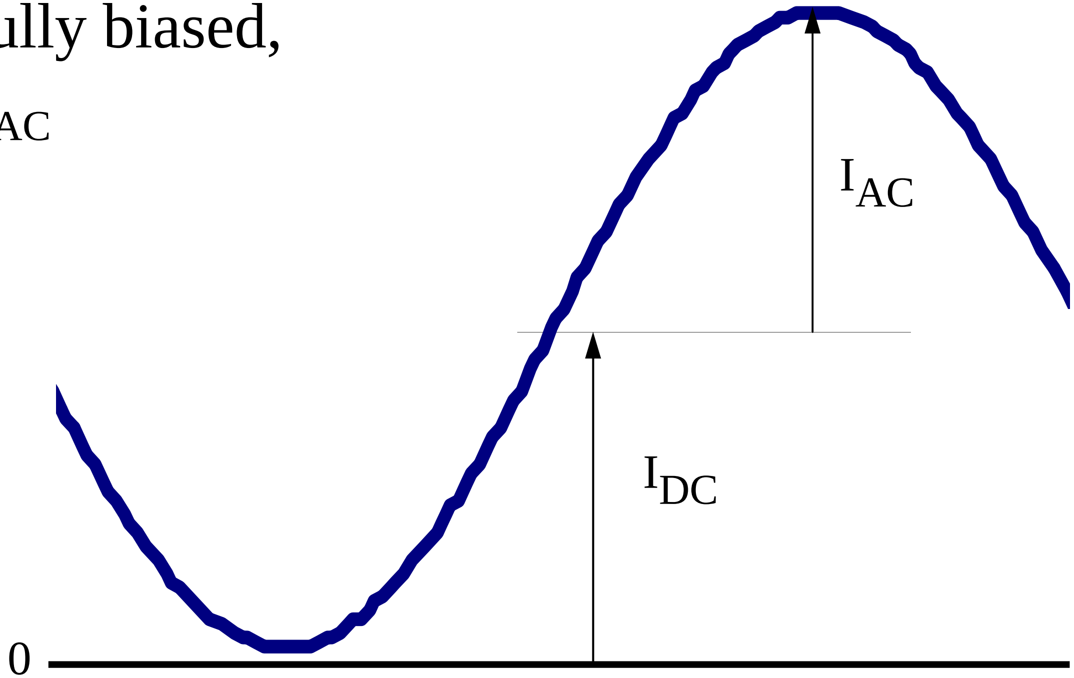
Single cell circuit:

- 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 $I_{DC} \sim I_{AC}$



White circuit parameters

Magnet current: $I_M = I_{DC} + I_{AC} \sin(\omega t);$

Magnet voltage: $V_M = R_M I_M + \omega I_{AC} L_M \cos(\omega t)$

Choke inductance: $L_{Ch} = \alpha L_M$

(α is determined by inductor/capacitor economics)

Choke current: $I_{Ch} = I_{DC} - (1/\alpha) I_{AC} \sin(\omega t);$

Peak magnet energy: $E_M = (1/2) L_M (I_{DC} + I_{AC})^2;$

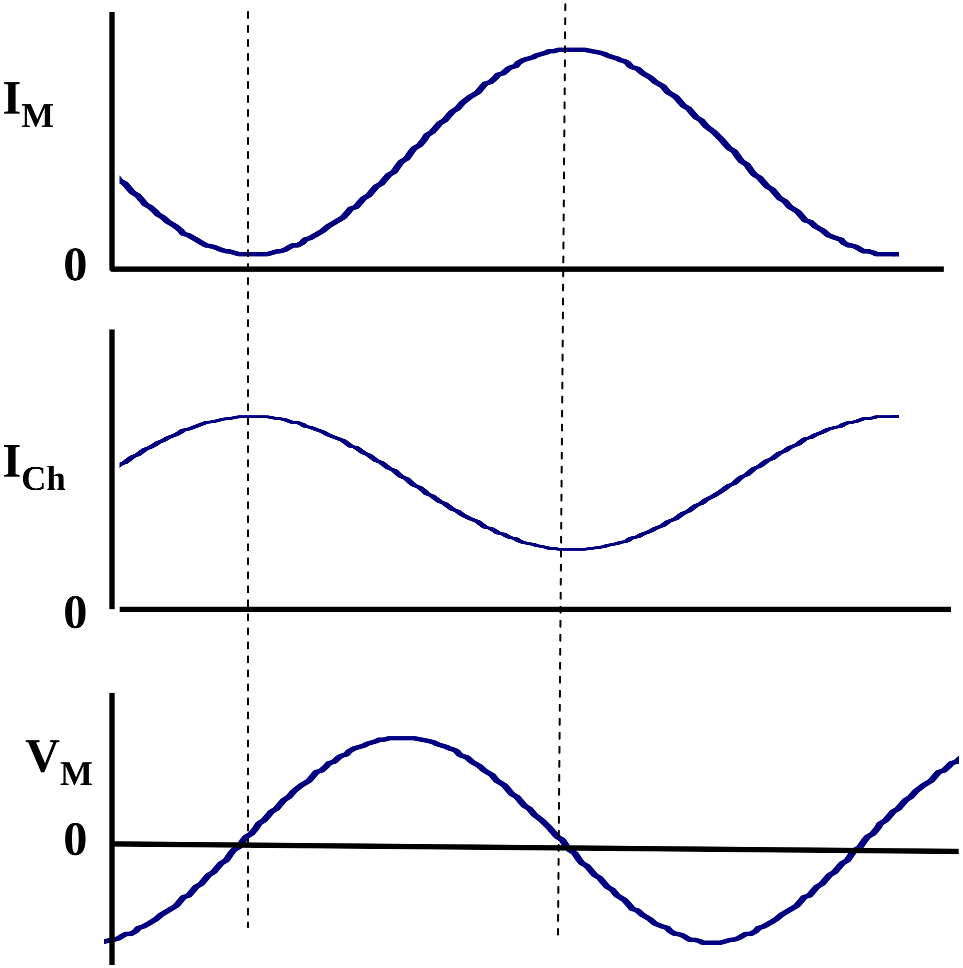
Peak choke energy: $E_{Ch} = (1/2) \alpha L_M (I_{DC} + I_{AC}/\alpha)^2;$

Typical values: $I_{DC} \sim I_{AC}; \alpha \sim 2;$

Then $E_M \sim 2 L_M (I_{DC})^2;$

$E_{Ch} \sim (9/4) L_M (I_{DC})^2;$

White Circuit waveforms

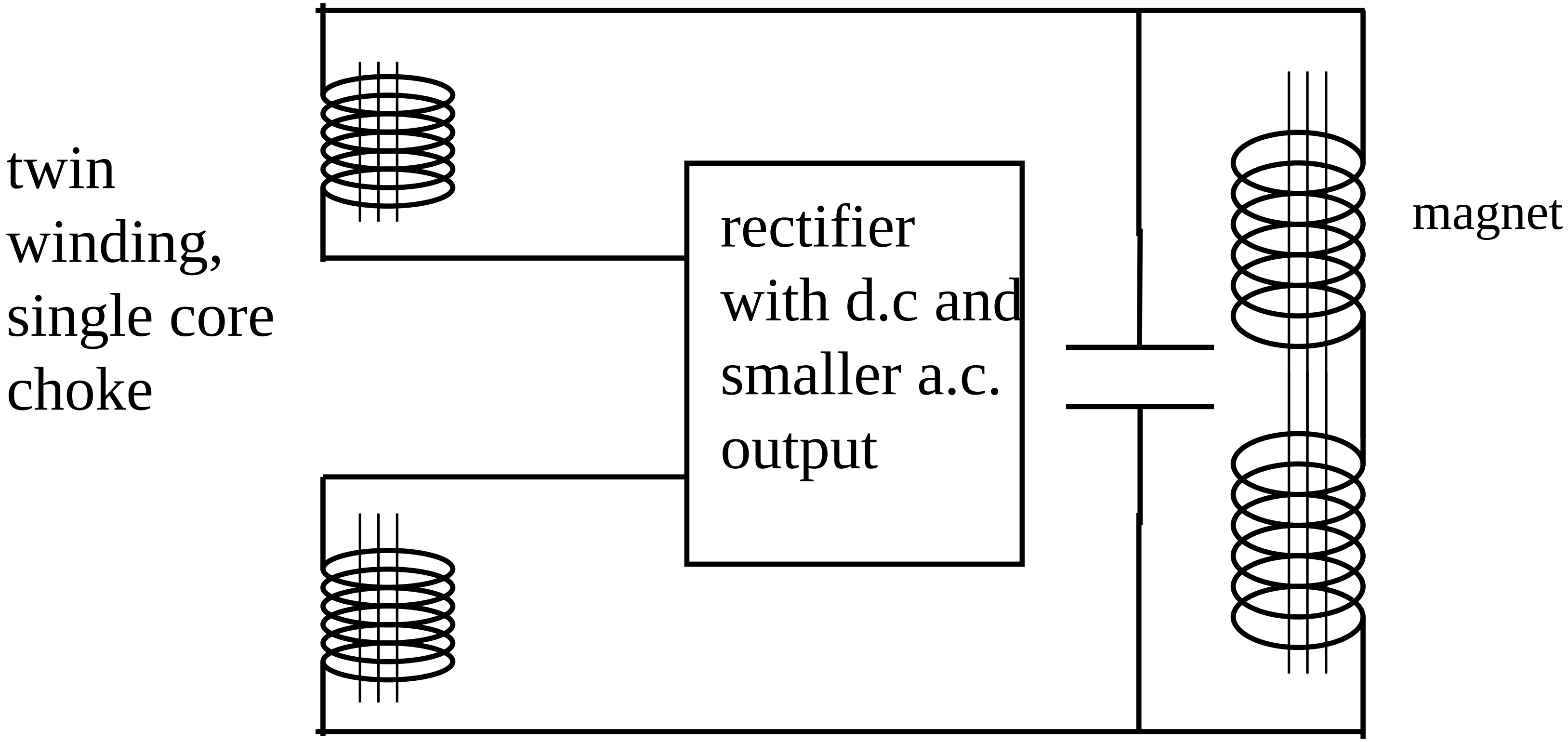


Magnet current:

Choke current:

Magnet voltage:

Single power supply alternative



Single supply alternative (cont.)

Benefits:

- single power supply (some economic advantage).

Features:

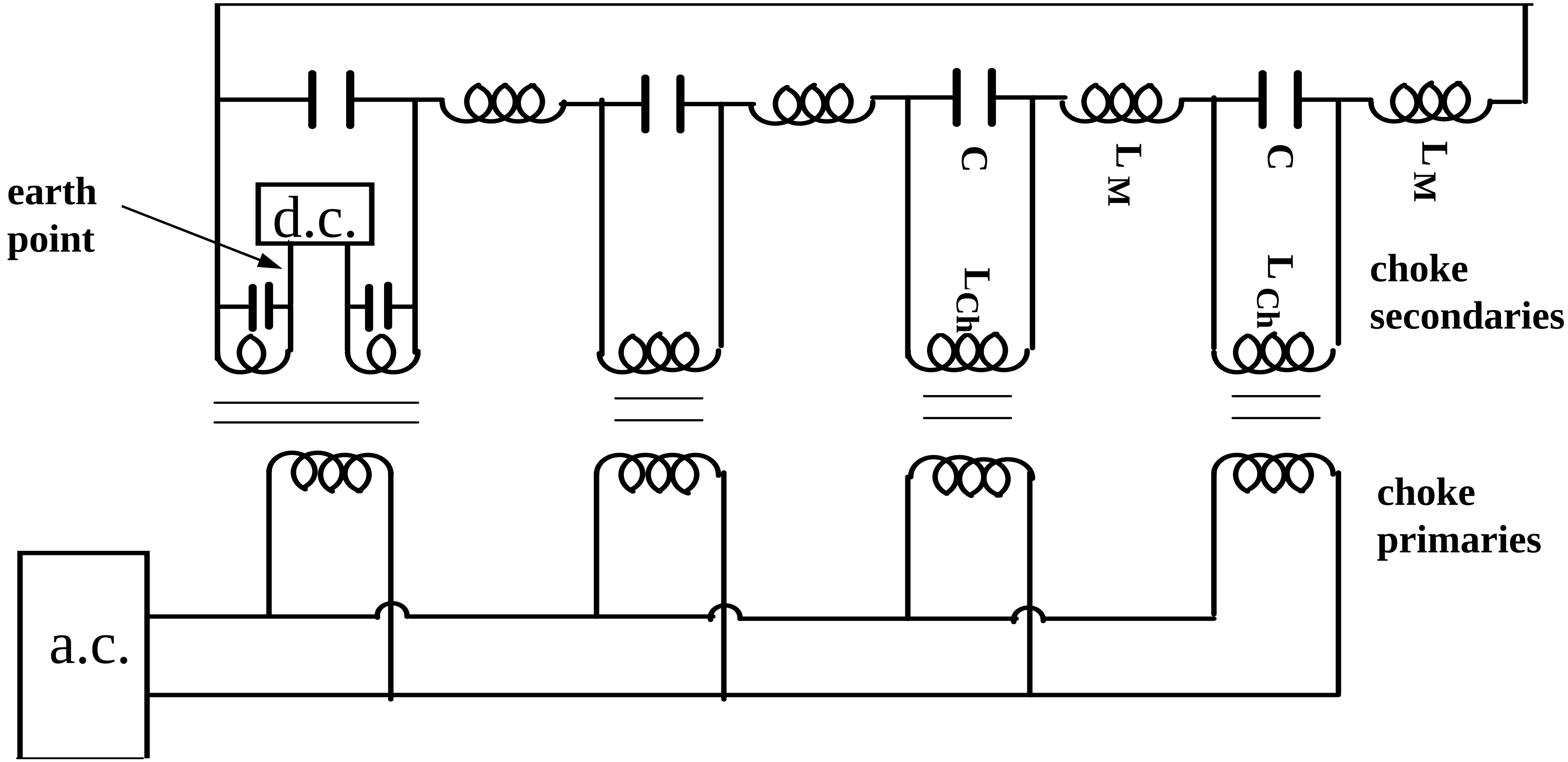
- rectifier generates voltage waveform with d.c. and large a.c. component (in inversion);
- choke inductance must be ~ x 2 magnet inductance to prevent current reversal in rectifier.

Problems:

- large fluctuating power demand on mains supply.

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

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

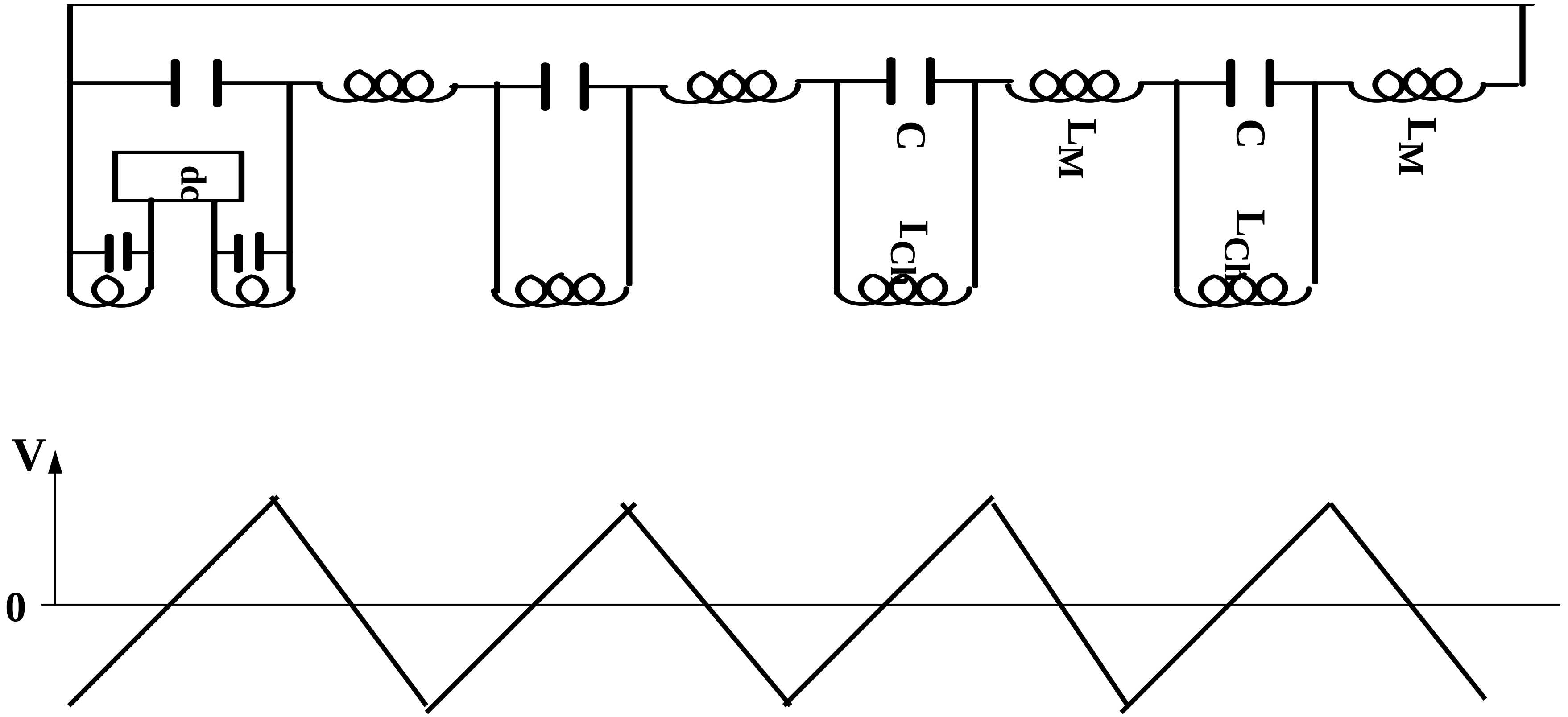


Multi-cell White circuit (cont.)

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.

Voltage distribution at fundamental frequency.



‘Spurious Modes’ of resonance

For a 4 cell network (example) , resonance frequencies **<u>with primary windings absent</u>** are 4 eigen-values of:

$$\left| \begin{pmatrix} 1 \\ 1 \\ 1 \\ 1 \end{pmatrix} - \omega_n^2 L_{ch} \begin{pmatrix} K_{1,1} & K_{1,2} & K_{1,3} & K_{1,4} \\ K_{2,1} & K_{2,2} & K_{2,3} & K_{2,4} \\ K_{3,1} & K_{3,2} & K_{3,3} & K_{3,4} \\ K_{4,1} & K_{4,2} & K_{4,3} & K_{4,4} \end{pmatrix} \begin{pmatrix} C_1 & 0 & 0 & 0 \\ 0 & C_2 & 0 & 0 \\ 0 & 0 & C_3 & 0 \\ 0 & 0 & 0 & C_4 \end{pmatrix} \right| = 0$$

Where: K_{nm} are coupling coefficients between windings n,m;
C_n is capacitance n
L_{ch} is self inductance of each secondary;
ω_n are frequencies of spurious modes.

The spurious modes do not induce magnet currents; they are eliminated by closely coupled paralleled primary windings.

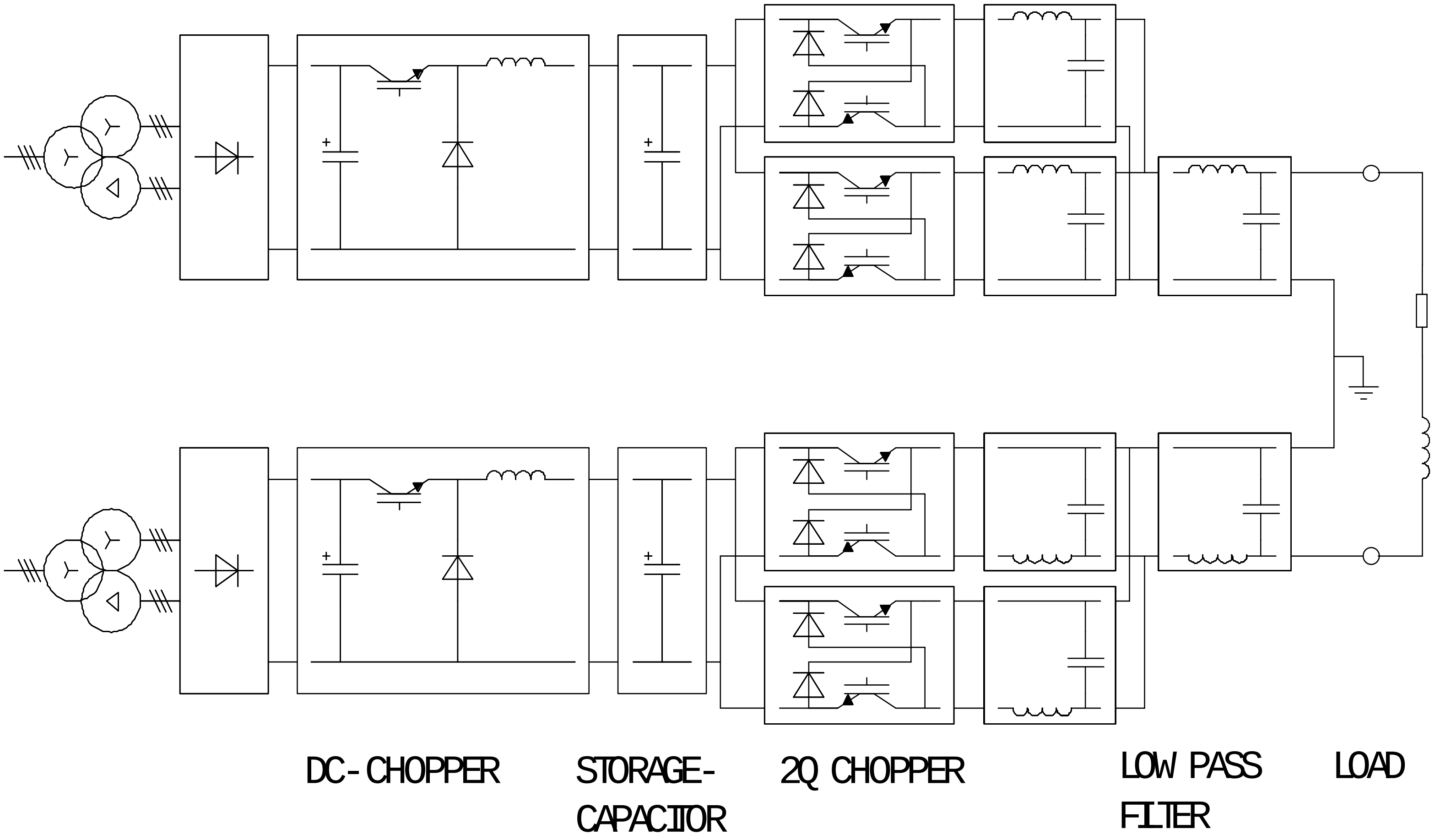
Modern Capacitative Storage

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).

Also semi-conductor technology now allows the use of fully controlled devices (IGBTs) giving waveform control at medium current and voltages.

Medium sized synchrotrons with cycling times of 1 to 5 Hz can now take advantage of these developments for cheaper and dynamically controllable power magnet converters – WAVEFORM CONTROL!

Example: Swiss Light Source Booster dipole circuit.



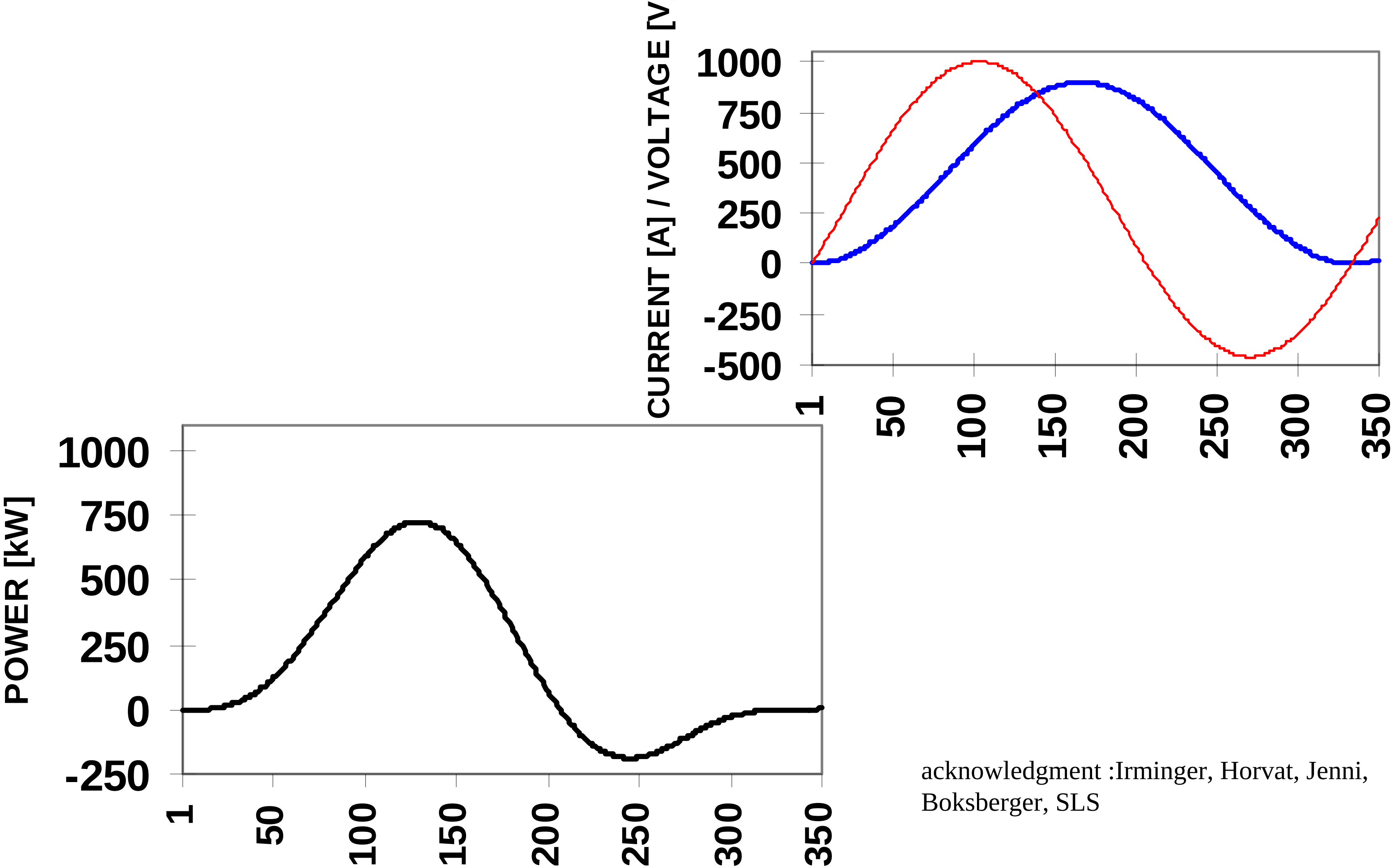
acknowledgment :Irminger, Horvat, Jenni, Boksberger, SLS

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



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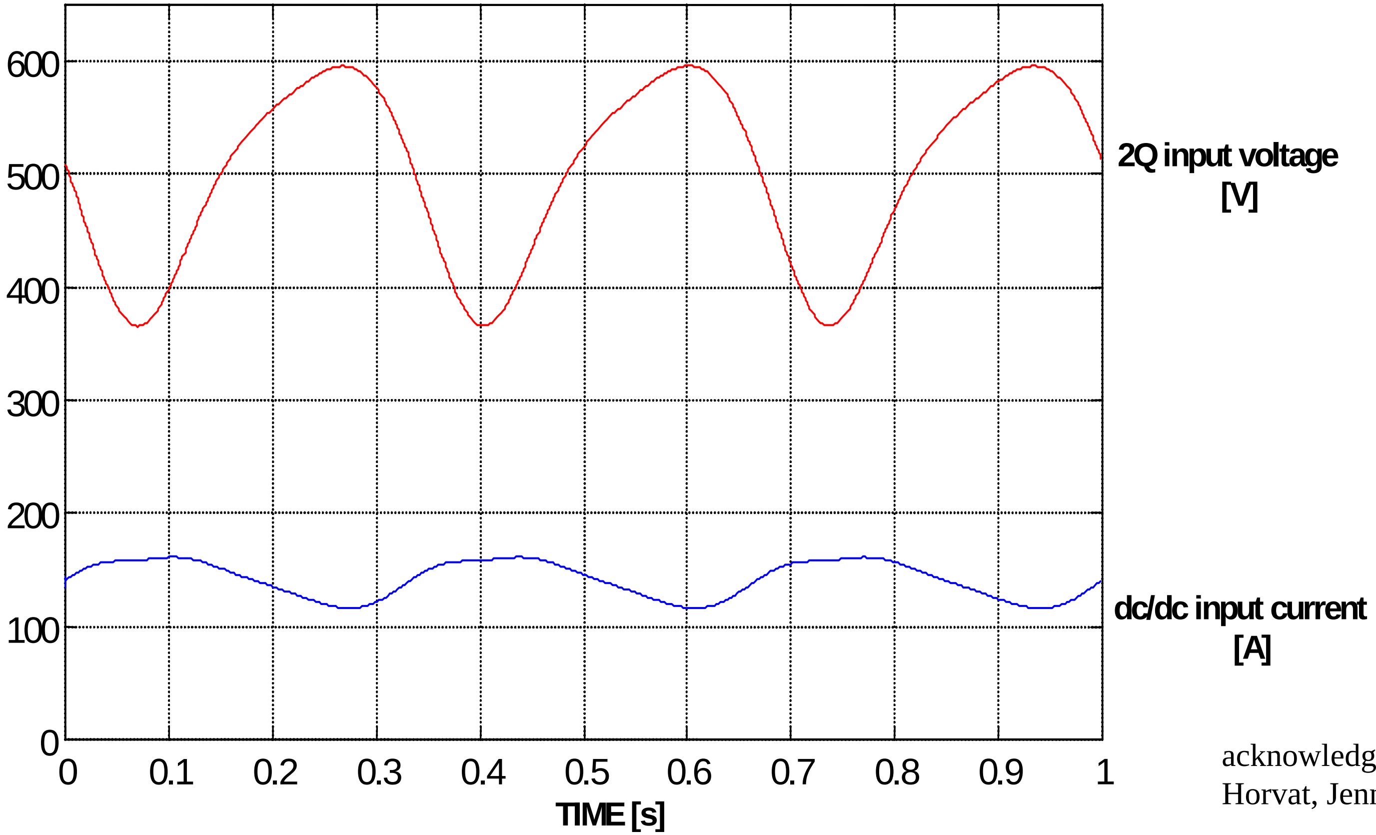
SLS Booster Waveforms

The storage capacitor only discharges a fraction of its stored energy during each acceleration cycle:



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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 ‘top up mode’).

However:

- the current and voltages possible in switched circuits are restricted by component ratings.

Diamond Booster parameters for SLS type circuit

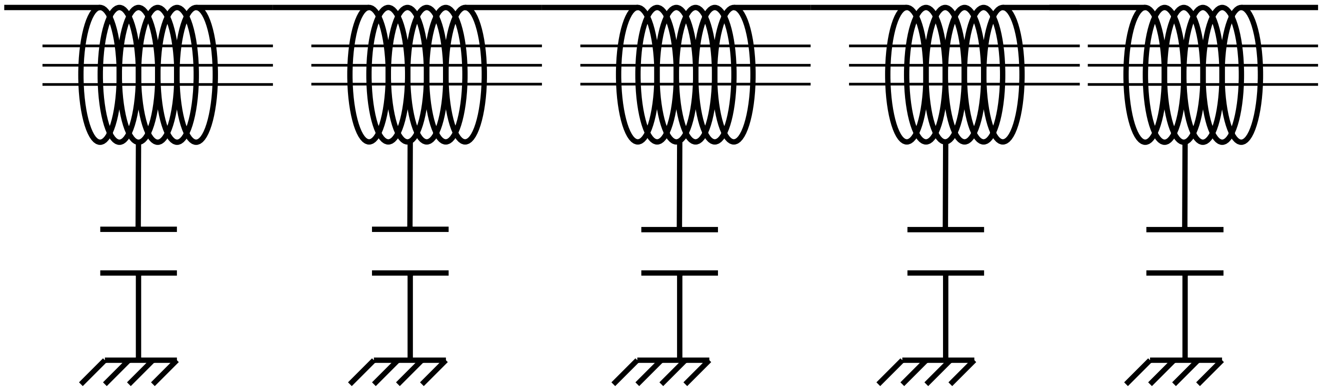
Parameter	low turns	high turns	
Number of turns per dipole:	16	20	
Peak current:	1271	1016	A
Total RMS current (for fully biased sine-wave):	778	622	A
Conductor cross section:	195	156	mm^2
Total ohmic loss:	188	188	kW
Inductance all dipoles in series:	0.091	0.142	H
Peak stored energy all dipoles:	73.3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

Note: the higher operating frequency; the 16 or 20 turn options were considered to adjust to the current/voltage ratings available from capacitors and semi-conductors; the low turns option was chosen and is now being constructed.

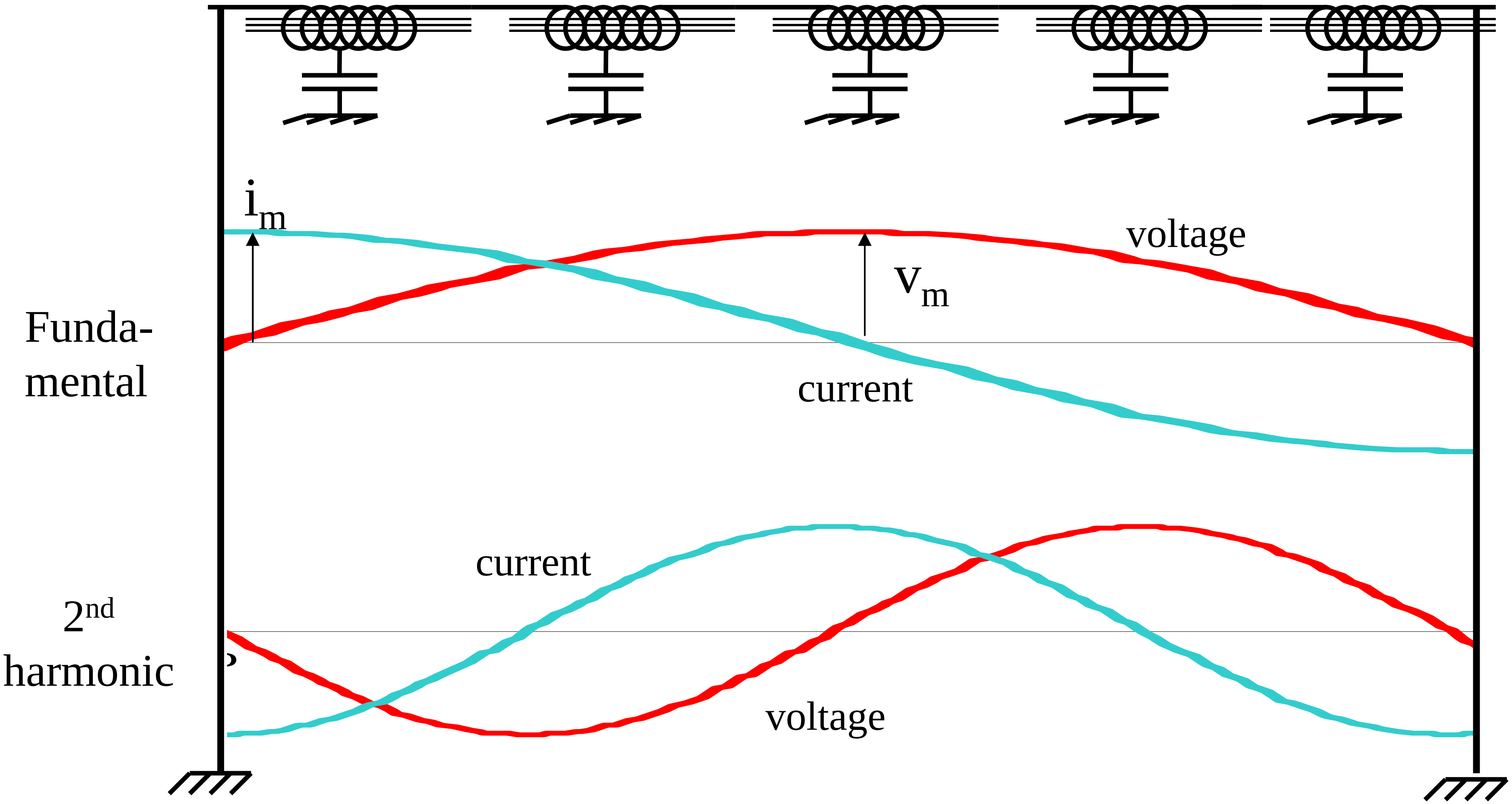
Delay-line mode of resonance

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!**



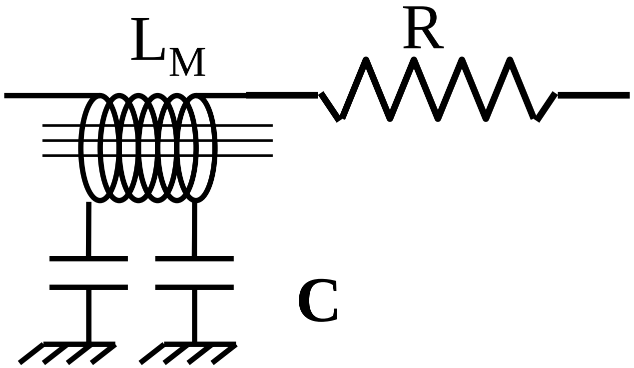
Standing waves on magnets series



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:

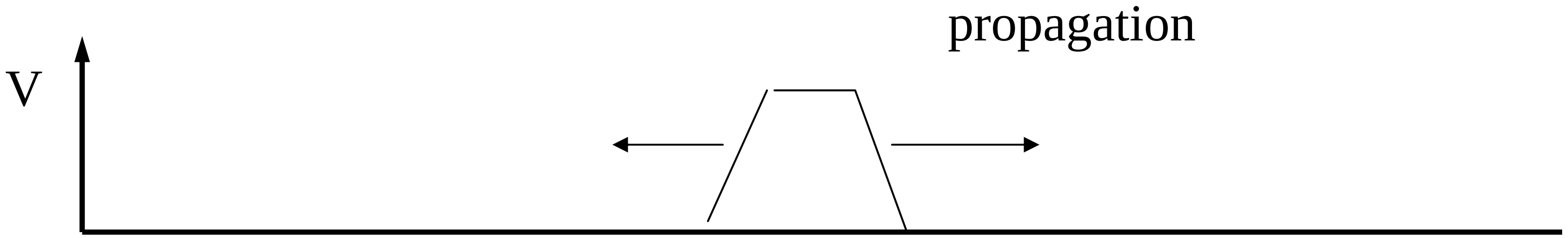
$$\tau = \sqrt{(L_M C)};$$

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.