Power converters for cycling accelerators

N. Marks
CCLRC Daresbury Laboratory, Warrington, UK

Abstract
Cycling accelerators require power converters which are capable of storing the energy which oscillates between lattice magnets and converter during the acceleration process. The paper presents the basic requirements for such systems and reviews the various electrical circuits that have been used for a variety of differing applications. The designs currently used for fast, medium, and slow cycling accelerators are presented.

1 Introduction

Some of the material presented in these proceedings is concerned with converters which supply direct current to the magnet loads. This is relevant to the storage ring, in which the particle momentum is fixed or where its variation with time is so slow that the energy increase in the magnets is smaller or of the same order as the resistive energy loss; in such circumstances, the converters can be regarded as variable amplitude d.c. systems. However, in most true synchrotrons, which accelerate the charged particle beam, the magnetic fields in the bending and focusing elements (if these be part of a separated function lattice) are required to be raised in a relatively short time, from the low amplitude required at beam injection, to a maximum value, corresponding to peak beam energy; the fields then need to be reduced in as short a time as possible, so as to be ready to accept the next pulse of injected beam. Thus, these cycling accelerators require power converters that are capable of delivering the appropriate cycling waveform.

As the accelerator magnets cycle from the injection to peak field, energy is transferred from the power converter to the magnet gap, whilst during the deceleration phase, this magnetic energy has to be removed from the magnet. In the case of a d.c. accelerator, this process occurs during switch-on and, later, during the power-down of the converters. The stored energy is small compared to the resistive loss in the magnet during any extended period of d.c. operation and hence, this ‘reactive power’ is not considered in the power supply specification. However, in a cycling accelerator, the largest component of energy supplied from the converter to the magnets is usually the magnetic energy associated with the field amplitude. It is therefore significantly more efficient to recover that energy during the deceleration phase and store it for the next acceleration cycle. Hence, a suitable energy storage system is an essential part of a converter for a cycling accelerator, and this requirement is central to the design and specification of such equipment. The nature of suitable engineering schemes depends on the cycling frequency specified for the accelerator; these can vary from less than 1 Hz for the large synchrotrons associated with particle physics, to 50 Hz for small- to medium-sized accelerators. The details of the most suitable circuits are discussed below.

2 The choice of waveform

2.1 Accelerator requirements

The simplest waveform that could be envisaged for a cycling system is ‘conventional’ alternating current. However, consideration of the requirements for particle acceleration indicate that this is highly inappropriate. This is explained in Fig. 1. Injection occurs at low field and the particles are then accelerated to peak energy, at the maximum of the sine wave; the acceleration occurs only during the positive part of the cycle. The simple a.c. waveform shown in the figure produces major disadvantages:

- only a quarter of the cycle is used for acceleration;
- there is an unnecessarily large r.m.s. current, as the negative part of the wave is superfluous;
- therefore there are high resistive and a.c. losses;
- there is a high magnetic field variation with time at injection (see below).

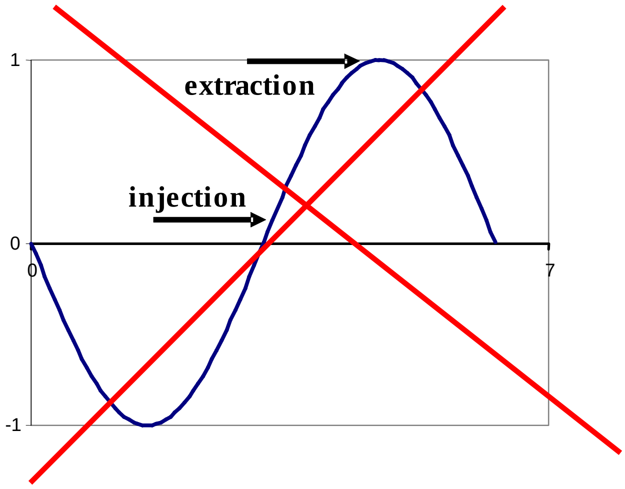

Fig. 1: Simple a.c. is an inappropriate waveform for a cycling accelerator

Before examining other possible waveforms in detail, it is worth while examining the detailed waveform requirements of the cyclic particle accelerator.

2.1.1 RF system

The radio frequency system provides the voltage necessary to accelerate the particles, or, where the particles are losing energy due to synchrotron radiation, to replace that loss and maintain the beam at the required momentum.

Acceleration:

- particle momentum (rigidity) = $mv \propto B$;
- r.f. accelerating voltage $V_{rf} \propto dB/dt$;
- r.f. power $$P = \underbrace{k_1 V_{rf} I_{beam}}_{\text{power transferred to beam}} + \underbrace{k_2 (V_{rf})^2}_{\text{loss into cavities}};$$

where:

- mv is the momentum of a particle mass m;
- B is the flux density in the bending magnets;
- I_{beam} is the beam current;
- k_1 and k_2 are constants fixed by the r.f system and accelerator design.

Any discontinuity in d*B*/d*t* would call for a step change in r.f. voltage and power and could generate beam instabilities, leading to possible beam loss.

Additionally, the particle beam is held in a potential well, created by the r.f. voltage, in a mechanism known as 'phase stability'. The trapped particles move within that potential well, executing 'synchrotron oscillations'. The frequency of these oscillations (the 'synchrotron frequency') is one of the fundamental parameters of the accelerator and is proportional to d*B*/d*t*. Large values of this frequency can also cause resonant beam loss, and this places a further constraint on the field gradient, particularly at injection (see below).

Synchrotron radiation

This radiation is emitted by ultra relativistic particle beams (electrons at $E \sim 1$ GeV; protons at $E \sim 1$ TeV) when bent in a magnetic field.

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

where:

- E is the energy of the circulating beam.

The magnet waveform therefore needs to have no discontinuities in amplitude (effectively impossible with an inductive load), or gradient. To limit the maximum r.f. voltage that needs to be generated by the r.f. amplifier (and therefore to limit its power ratings), the maximum value of d*B*/d*t* should not greatly exceed the average required over the acceleration cycle.

2.1.2 Field gradient at injection

The variation of magnetic flux density with time generates eddy currents in any conducting material located within the field. In a cycling accelerator, eddy currents will occur predominantly in the walls of a metallic vacuum vessel, with smaller eddy currents present in the magnet poles themselves. These currents generate magnetic field disturbances:

- negative dipole field — reduces main field magnitude;
- negative sextupole field — generates negative chromaticity and could drive resonances.

The magnitude of these unwanted disturbances is inversely proportional to the beam momentum, which is, of course, determined by the dipole field, *B*. Hence the effect of eddy currents is proportional to

$$(1/B)(\mathrm{d}B/\mathrm{d}t), \quad \text{expressed as } \dot{B}/B\,.$$

It should be noted that the synchrotron frequency is determined by the same ratio.

This parameter, the ratio of the field gradient to the field magnitude, is most critical at injection, when field and beam momentum are low and when the beam is being 'captured' into its correct synchronous phase. This situation is illustrated in Fig. 2.

It will be seen that the value of (1/*B*)(d*B*/d*t*) will be one of the determining factors on which waveform suitability is judged.

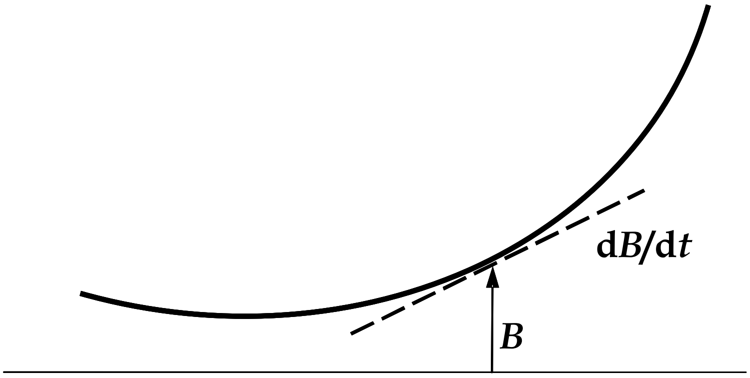

Fig. 2: Field gradient and magnitude at injection

2.1.3 Discontinuous operation

In some situations, the accelerator may only be required to undertake an acceleration cycle at time intervals that are much longer than the normal cycle time. For example, the circulating beam in a storage ring may decay very slowly with time. To maintain constant beam current, which is very valuable to experimenters, the booster synchrotron which feeds the main ring is needed to operate in **'top up mode'**, in which beam is only accelerated and injected once every '*n*' booster cycles, with the value of *n* varying according to the operational details of the storage ring. The booster could be operated continuously whatever time delay is required between injection pulses but this results in unnecessary power consumption. Hence it is most efficient if the power converter can deliver an excitation waveform can that allows discontinuous operation at intervals determined by the rate of loss of stored beam, as illustrated in Fig. 3.

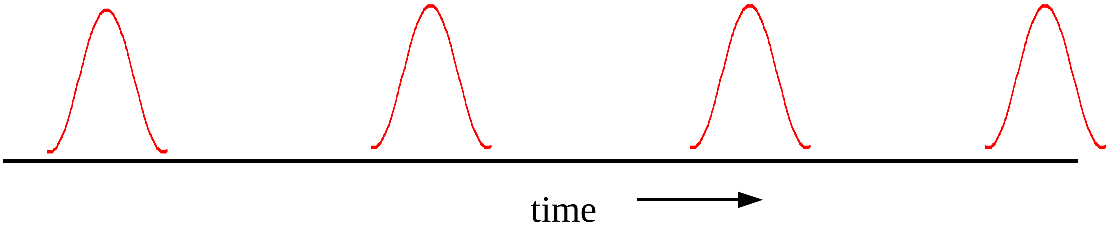

Fig. 3: Discontinuous acceleration cycles as used for 'top-up' injection; note that the delay between cycles is much in excess of the actual cycle time

2.2 Possible waveforms

Having established that a normal alternating current is not suitable for powering a cyclic accelerator and having examined the criteria against which waveforms should be judged, a number of more suitable waveforms can be considered.

2.2.1 Linear ramp

A linear field ramp and associated waveforms are shown in Fig. 4.

It can be seen that the uniform gradient throughout the cycle results in a very high value of $(1/B)(\mathrm{d}B/\mathrm{d}t)$ at injection when the field magnitude is low, and some form of smooth transition into the ramp (the 'front porch') would be necessary.

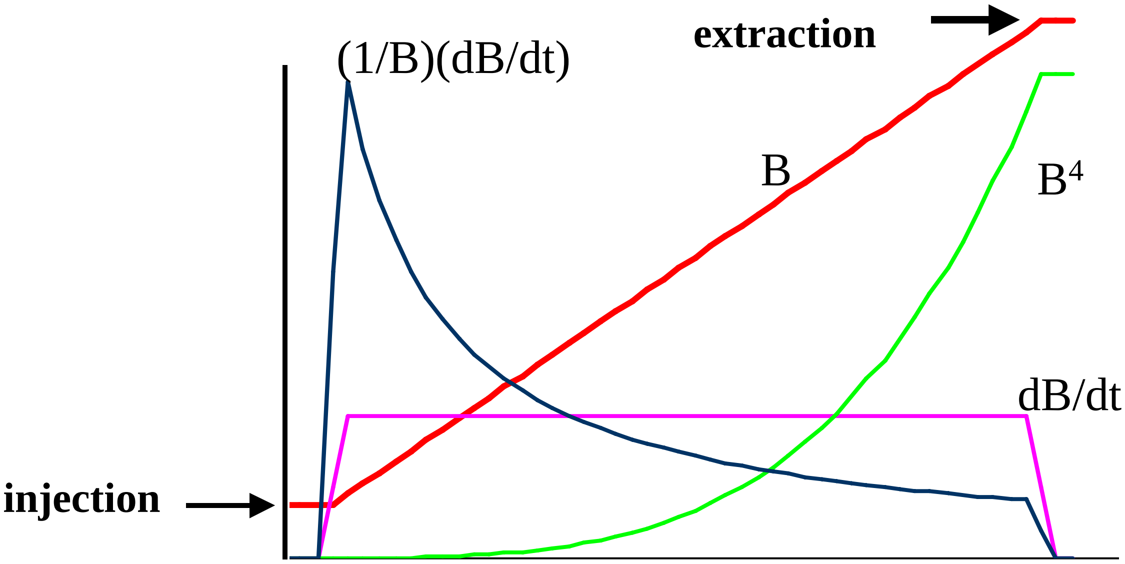

Fig. 4: A linear field ramp between injection and high energy (extraction) (*B*); also shown is the gradient (d*B*/d*t*), *B* dot over B [(1/*B*)(d*B*/d*t*)] and the function determining synchrotron radiation loss (B^4)

2.2.2 *Biased sine-wave*

This waveform, shown in Fig. 5, is based on the use of a half sine-wave with a direct current bias of equal magnitude to the sine-wave's peak value.

It can be seen that the biased sine-wave provides a lower maximum value of (1/*B*)(d*B*/d*t*) at injection compared to the linear ramp. However, the variation of gradient during the cycle has a higher maximum value than that produced by the linear variation and hence, higher r.f. voltage would be required. Additionally, higher r.f. power would be needed if the beam was emitting synchrotron radiation, as the integrated value of the B^4 curve is higher.

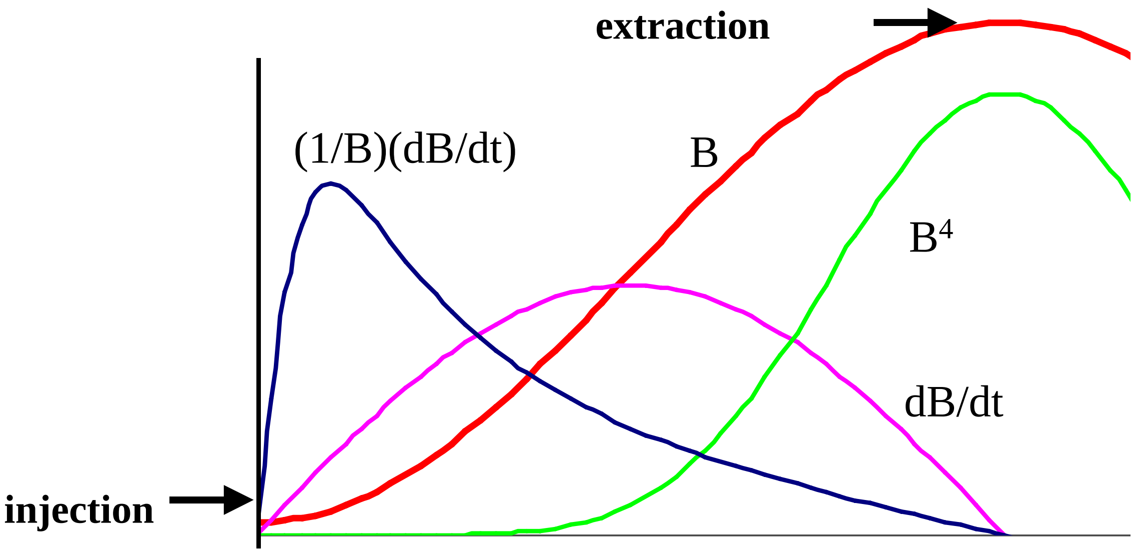

Fig. 5: A biased sine-wave field variation between injection and high energy (extraction) (*B*); also shown is the gradient (d*B*/d*t*), *B* dot over *B* [(1/*B*)(d*B*/d*t*)] and the function determining synchrotron radiation loss (B^4)

2.2.3 *'Custom specified' waveform*

A better alternative to either of the two waveforms presented above would be to have a variation with time that could be specified by the accelerator operator — i.e., a custom specified waveform. A possible example is shown in Fig. 6.

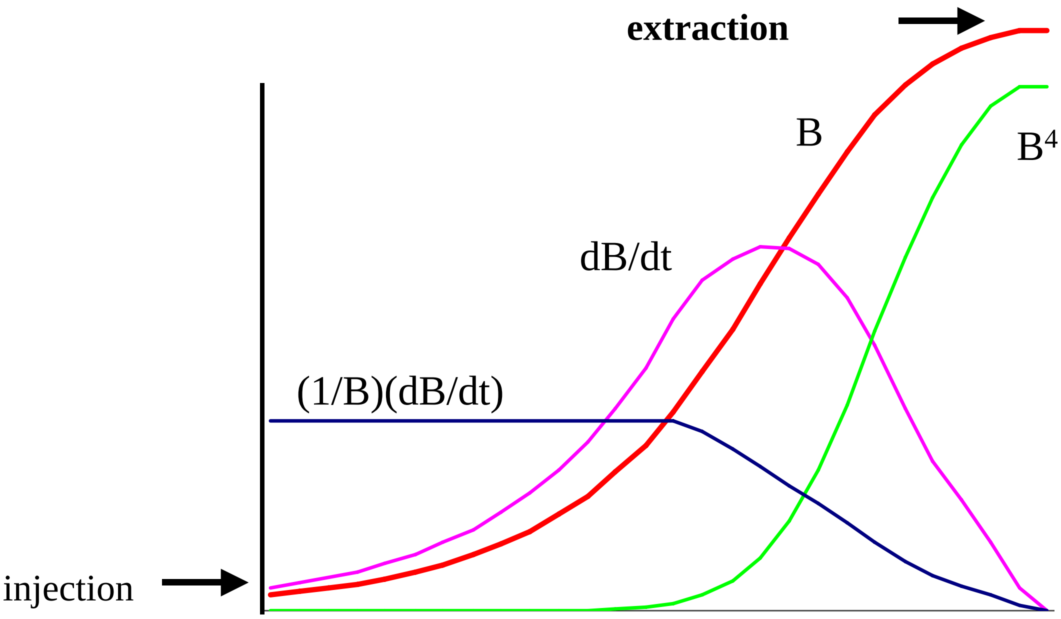

Fig. 6: A 'custom specified' field variation between injection and high energy (extraction) (B), designed to provide a low gradient during and just after injection; shown is the gradient (dB/dt), B dot over B [(1/B)(dB/dt)] and the function determining synchrotron radiation loss (B^4)

The waveform is based on a constant value of (1/B)(dB/dt) during and for a significant time after injection, which subsequently declines to zero at peak field. If the accelerated beam were to be emitting synchrotron radiation, the late increase in the B^4 term would result in a significant reduction in r.f. power, though the peak r.f. volts is increased as maximum in the dB/dt term is higher.

2.2.4 *Waveform comparison*

A comparison of three different waveforms presented above is shown in Table 1.

Table 1: Comparison of suitability of three possible magnet waveforms

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

It can be seen that the choice of waveform is usually a compromise between different criteria and is often predicated by the electrical engineering circuits that are available, this issue will be discussed later in the paper.

3 Power ratings in cycling systems

3.1 Electrical parameters

Figure 7 shows a typical bending magnet with its equivalent circuit.

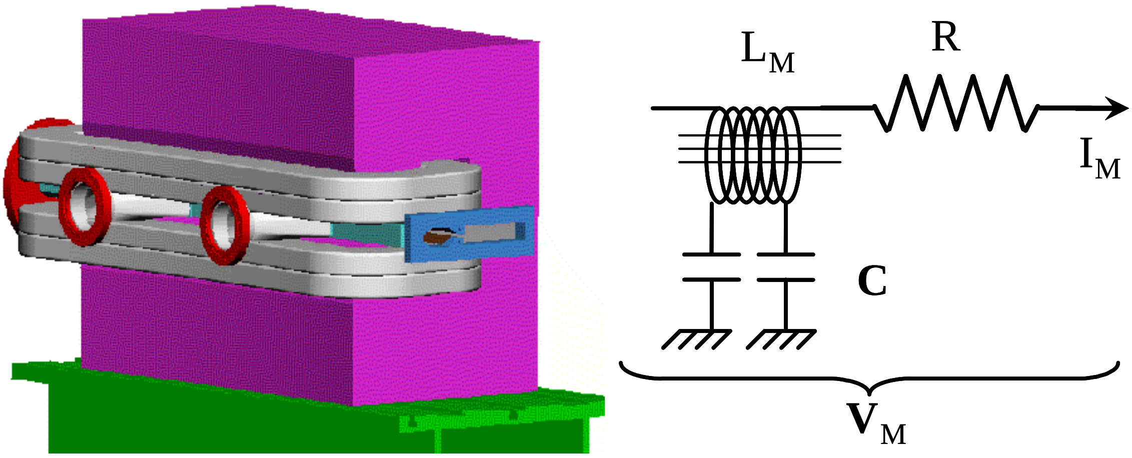

Fig. 7: A typical dipole bending magnet shown with its equivalent circuit

The symbols used in the equivalent circuit are defined below:

– magnet current: I_M;

– magnet voltage: V_M

– series self inductance: L_M;

– series resistance: R;

– distributed capacitance to earth: C.

Then:

– magnet voltage: $V_M = RI_M + L(\mathrm{d}I_M/\mathrm{d}t)$;

– instantanious power: $V_M I_M = R(I_M)^2 + L\, I_M(\mathrm{d}I_M/\mathrm{d}t)$;

– stored energy: $E_M = 1/2 L_M (I_M)^2$;

– $\mathrm{d}E_M/\mathrm{d}t = L(I_M)(\mathrm{d}I_M/\mathrm{d}t)$;

– therefore power: $V_M\, I_M = R\,(I_M\,)^2 + \mathrm{d}E_M/\mathrm{d}t$;

resistive power loss

'reactive' power — alternates
between +ve and –ve as field rises
and falls.

The first term above will be recognized as the resistive loss in the magnet; the second is the rate of change of energy stored in the magnet as the field cycles between injection and peak field. This is referred to as ‘reactive power’ i.e., it represents a flow of energy which alternates between positive and negative values. The challenge of the cyclic power converter is to control this flow of energy and provide the necessary storage system as significant quantities of energy circulate between the magnet and the power supply.

3.2 Categories of cycling systems

Before examining the various circuits and techniques which are used for power cycling accelerators, it is beneficial to consider the different regimes required for different accelerator applications.

Cycling systems can be categorized according to their repetition rates.

- Slow cycling: the term is usually applied to power systems with repetition rates in the range 0.1 to 1 Hz ; a typical figure would be 0.3 Hz, ie a cycle time of the order of 3 seconds. The supply systems for largest proton accelerators generally fall into this category, for the energy stored in the long chain of electro-magnets produces a large reactive power rating even at the low repetition rates.
- Fast cycling: corresponding to repetition rates of 10 to 50 Hz, these systems were used in the combined function electron accelerators in the 1950s and 1960s where rapid acceleration times were needed to limit beam blow-up at high energy. They now, currently, have applications in high-current medium-energy proton accelerators where the rapid cycling time provides intense fluxes of high-energy particles.
- Medium cycling: with repetition rates of 1 to 5 Hz; such systems have come to prominence more recently due to developments in power electronics which make this frequency range possible with full-waveform controlled circuits (as discussed below). They are typically used in separated-function electron accelerators where the lattice configuration eliminates the problem of beam anti-damping at high energy.

Three examples of these different types of accelerator requirements, with corresponding excitation and reactive power ratings are now presented.

3.2.1 A slow-cycling system: the CERN Super Proton Synchrotron (SPS)

This 450 GeV, slow cycling accelerator, used for high-energy particle physics, has undergone many modification during its long life and currently has a number of different operating modes. The presented data correspond to the ‘fixed-target’ mode, which demands the highest operational parameters. Details of the power system ratings are

– peak proton energy	450 GeV;
– cycle time (fixed target)	8.94 s;
– 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.

The waveforms corresponding to this mode of operation are shown in Figs. 8, 9 and 10.

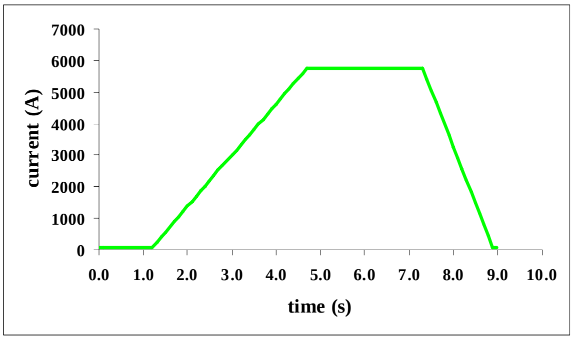

Fig. 8: Current waveform of the CERN SPS when operating in ‘fixed-target’ mode

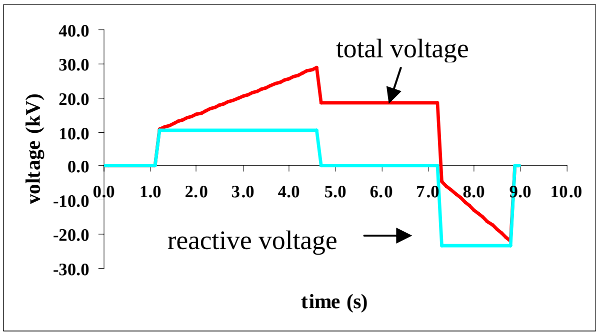

Fig. 9: Voltage waveforms of the CERN SPS corresponding to the current waveform of Fig. 8

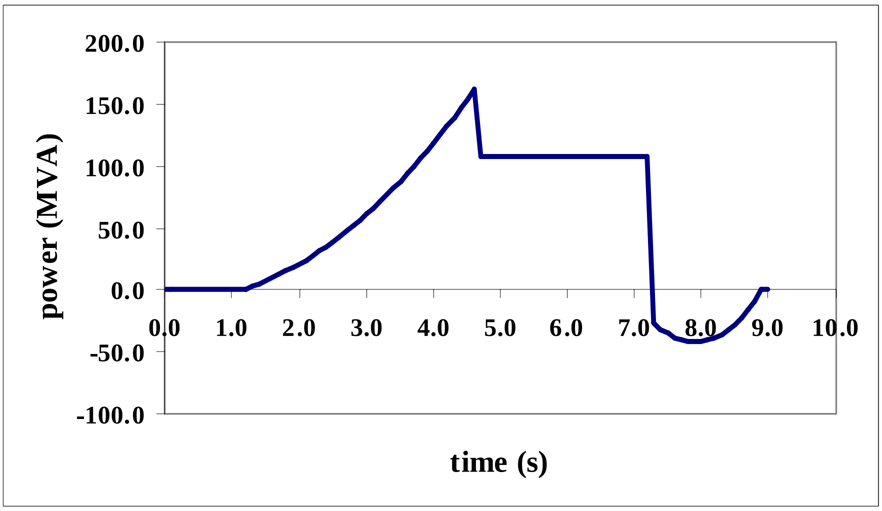

Fig. 10: Power waveform of the CERN SPS corresponding to the excitation levels shown in Figs. 8 and 9

It can be seen that the oscillation of energy between supply and load calls for forward voltages of 30 kV and reverse voltages of 20 kV. However, Fig. 9 demonstrates that the resistive voltage dominates during the acceleration and flat peak field part of the cycle; reactive power is small compared to the resistive loss. Thus, the reverse power shown in Fig. 10 is small compared to the forward power in the earlier part of the cycle; however, the reverse power is still of the order of 50 MVA.

3.2.2 A medium-cycling system: the European Synchrotron Radiation Facility (ESRF) Booster

The ESRF is a medium-sized electron storage ring which generates synchrotron radiation for a wide range of research applications; it has a fully energy (6 GeV), 10 Hz (medium cycling) booster synchrotron which accelerates electrons for injection into the main ring. The parameters of the booster’s power system are given below:

– peak electron energy	3.0 GeV;
– cycle time	100 ms;
– cycle frequency	10 Hz;

– peak dipole current	1588 A;
– magnet resistance	565 mΩ;
– magnet inductance	166 mH;
– magnet stored energy	209 kJ.

The power systems waveforms are shown in Figs. 11, 12 and 13.

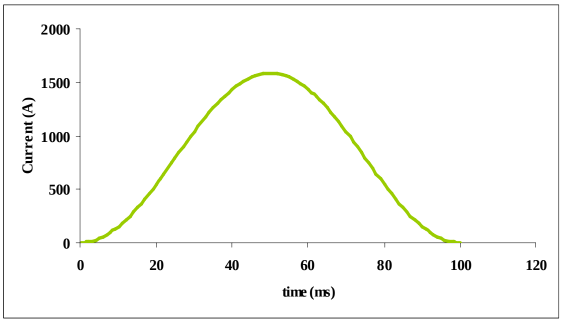

Fig. 11: Current waveform of the ESRF booster

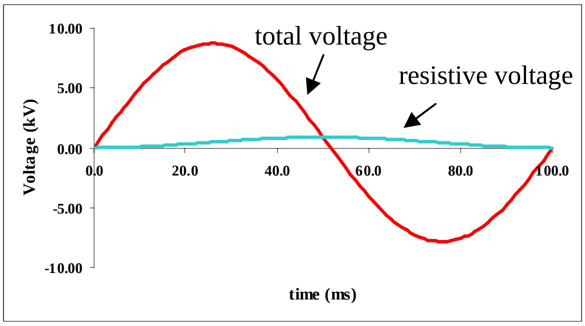

Fig. 12: Resistive and total voltage waveforms of the ESRF booster synchrotron

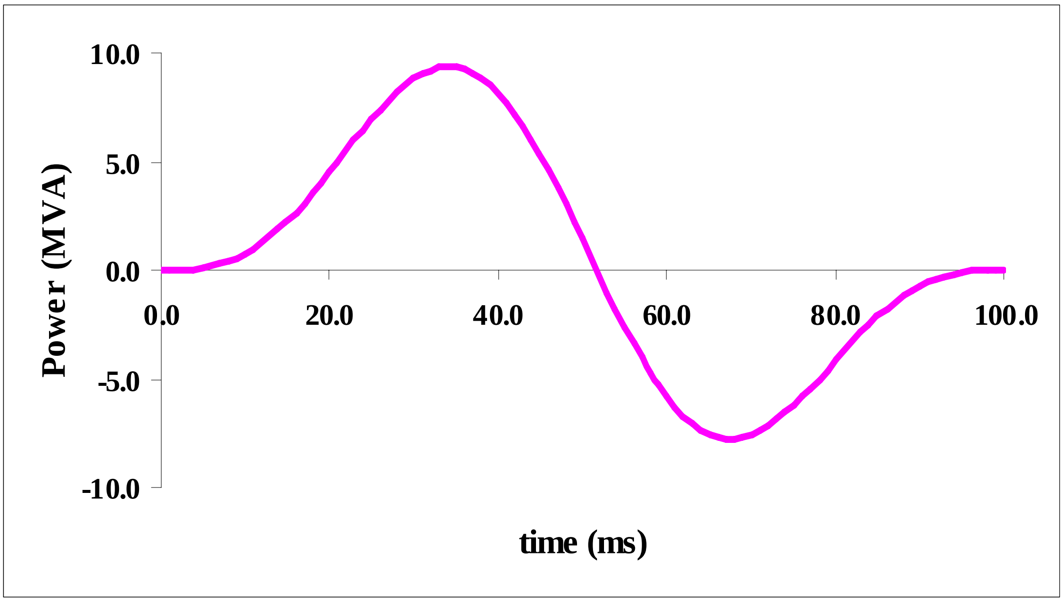

Fig. 13: Power waveform of the ESRF Booster corresponding to the excitation levels shown in Figs. 11 and 12

It can be seen that the reactive voltage greatly exceeds the resistive voltage; the energy stored is more than an order of magnitude greater than the loss per cycle. Consequently, the power waveform is far more symmetrical about the time axis, compared to the SPS data, and energy storage is a vital feature of this power system's performance.

3.2.3 A fast-cycling system: NINA

NINA was a 5 GeV fast cycling (50 Hz) electron accelerator providing beam for fixed-target particle physics; it was built at the Daresbury Laboratory in the early 1960s. Parameters of the power system are presented below:

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

Current, voltage and power waveforms are given below in Figs. 14, 15 and 16.

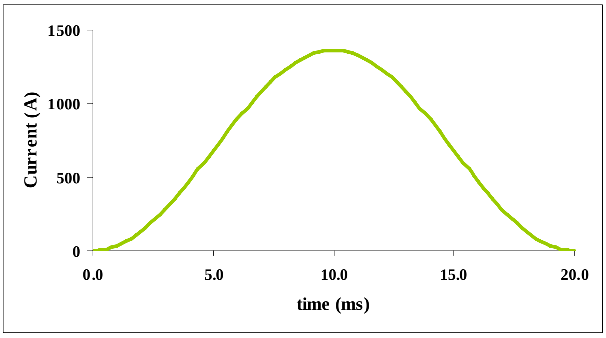

Fig 14: Current waveform of the NINA fast cycling magnet system

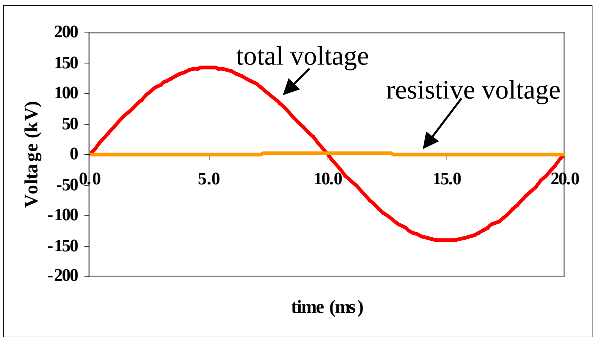

Fig 15: Resistive and total voltage waveforms of the NINA synchrotron

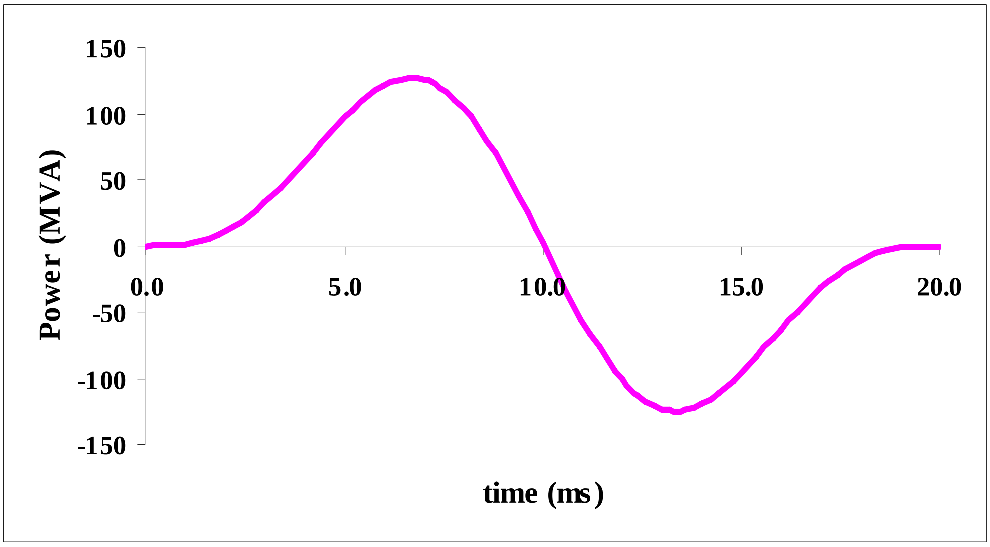

Fig. 16: Power waveform of the NINA synchrotron corresponding to the excitation levels shown in Figs. 14 and 15

Perhaps the most interesting feature of these data is that, in spite of NINA being a relatively small accelerator, the voltage and power ratings are very similar to those given for the SPS, above. Note also that the resistive voltage is negligible compared to the reactive voltage and that the reverse power almost equals the forward power demand during the acceleration cycle.

4 Cycling converter systems

Having examined the ratings of various cycling accelerators, it is now possible to move on to discussing the nature of the power systems used to excite the magnet circuits. As the energy storage system is fundamental to the design, the various circuits can be categorized according to the elements used for this purpose. They fall into three categories:

- mechanical energy storage;
- inductive energy storage;
- capacitative energy storage.

When considering the circuits that need to be assembled around the central storage device, it is worth while emphasizing the basic requirements. The 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’.

4.1 Slow-cycling mechanical energy storage

These circuits were used to power and control the slow-cycling synchrotrons of the second half of the twentieth century. A diagram of a typical mechanical energy storage system is shown in Fig. 17.

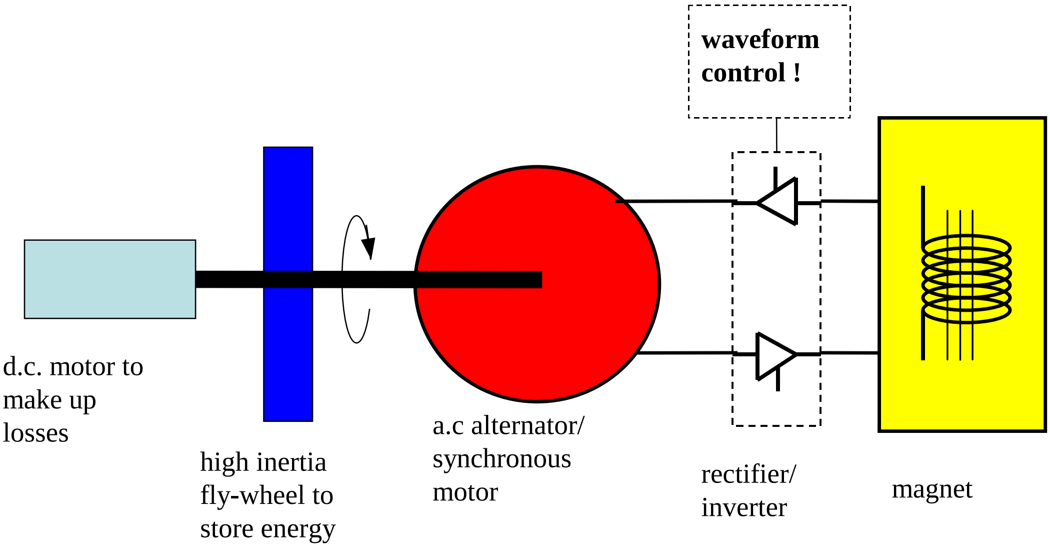

Fig. 17: Diagram of a typical mechanical energy storage system

The magnet circuit is powered from an alternator, with controlled rectifiers (in the 1950s and 60s these were mercury arc rectifiers; more recently, thyristors) in the output producing the unidirectional current that is required. The alternator is driven from a large fly-wheel which, necessarily, stores considerably more energy than is required in a single magnet excursion from low to high energy. At the start of the acceleration cycle, the rectifiers are phased forward and energy is fed from the fly-wheel to the magnet; control of the rectifiers provides waveform control.

At the end of the acceleration cycle, the rectifiers are phased back into inversion, the magnet voltage becomes negative, the current decreases and energy is returned to the fly-wheel. This continues until the injection level is again reached; the cycle then recommences.

Throughout the cycle, the d.c. motor at the front-end of the rotating system is driven by controlled rectifiers connected to the public a.c. supply, this making up the circuit losses so that cycling can continue at the correct amplitude.

It can be seen that whilst this system, with it mechanical components, may appear rather old-fashioned to electrical engineers now accustomed to modern silicon power devices with microsecond switching, the circuit provides all the features listed above for the satisfactory operation of a cyclic accelerator. However, it is limited in the cycle frequency that can be supported, these being typically well below 1 Hz. There were also, in some installations, problems with reliability, with the alternators failing due to the repeated pulse duty, speed and load variation.

4.1.1 The 'NIMROD' mechanical storage system

As an example, data is given for the mechanical storage system design for the 7 GeV, slow-cycling, weak-focusing proton synchrotron, NIMROD, built at the Rutherford High Energy Laboratory in the early 1960s. A photograph of the rotating machinery, comprising two fly-wheels, alternators and motors is shown in Fig. 18 below. The parameters of the system are given in Table 2.

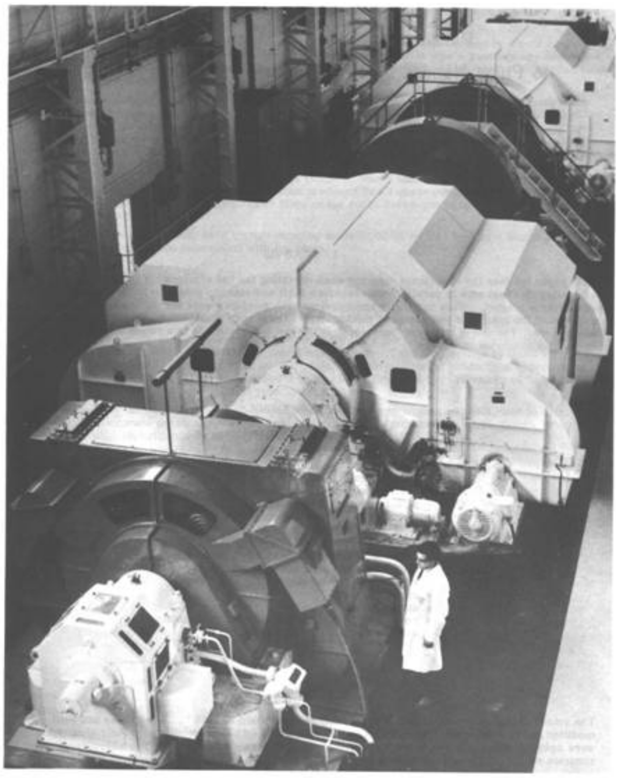

Fig. 18: Photograph of the double mechanical energy storage system used to power the magnet of the 7 GeV proton synchrotron, NIMROD

Table 2: Parameters of the mechanical energy storage system used on the 7 GeV weak-focusing proton synchrotron NIMROD

Parameter	Number	
Alternator ratings	2	60 MVA
Fly-wheel inertia	2	23 650 lb ft/s^2
Total inertia (per shaft)	2	36 105 lb ft/s^2
d.c. motor rating	2	5100 hp

A diagram of the circuits between the alternators and the NIMROD magnets, using phased control mercury arc rectifiers, is shown in Fig. 19.This is taken from a 1964 conference proceedings and is a little indistinct in places.

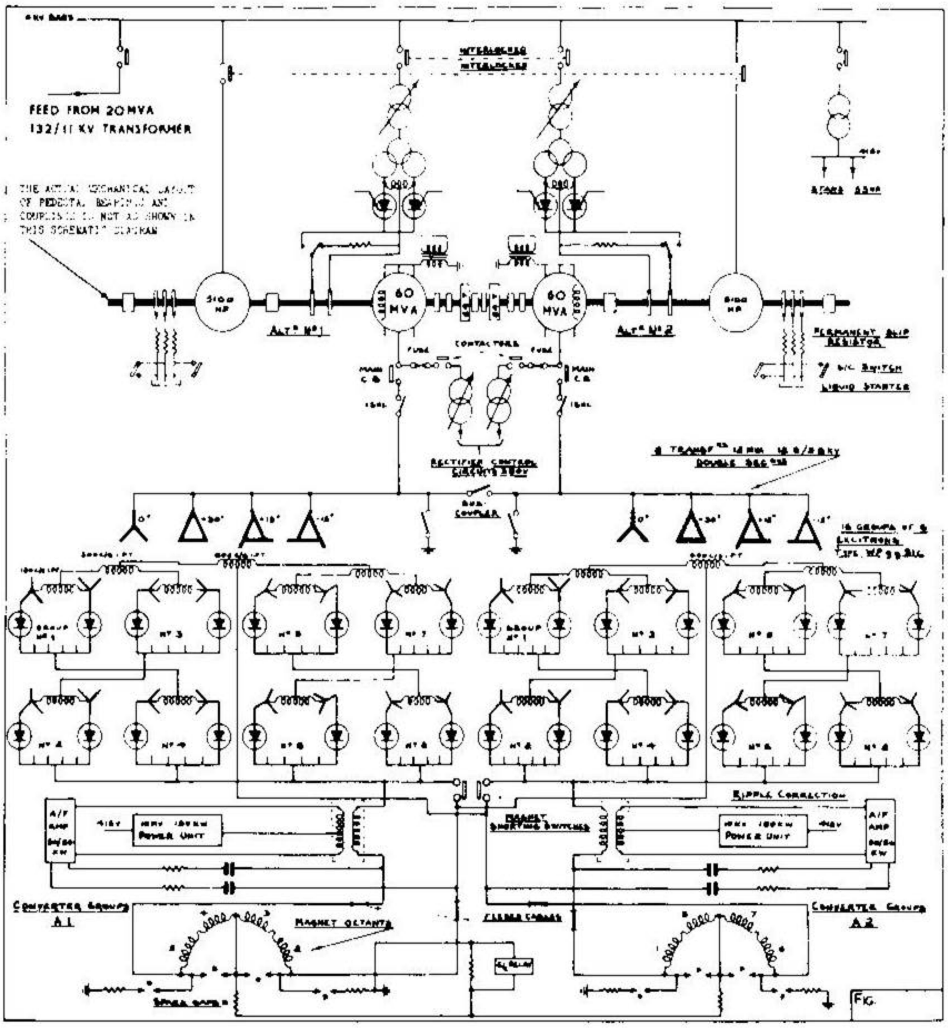

Fig. 19: Electrical circuit used to power the magnets of the 7 GeV proton synchrotron NIMROD. The two alternators, which are driven from the energy storage fly-wheels, are connected to the magnet load by a network of 32 mercury arc rectifiers. When these are in rectification, energy is transferred from the fly-wheels to the magnets, whilst inversion stores the magnet energy in the fly-wheels. Energy lost is made up from the two d.c. motors mounted on the same shafts as the fly-wheels and alternators.

The use of mechanical energy storage is only suitable for slow-cycling accelerators. Furthermore, the use of rotating machinery resulted in high capital and maintenance costs and, in some cases, the pulse duty caused faults in the alternators. In the later part of the twentieth century, the concept of mechanical storage was replaced by the use of direct connection to large very rigid national and international electrical supply grid systems.

4.2 Slow-cycling direct connection

National supply networks have large, inductive stored energy. Given the correct interface, this can be utilized to provide and receive back the reactive power of a large accelerator.

Compliance with supply authority regulations must minimize:

- voltage ripple at the feeder;
- phase disturbances at the accelerator and neighbouring sites;
- frequency fluctuations over the entire network.

A very 'rigid' (i.e., high short-circuit capacity) high-voltage line into the accelerator equipment is necessary.

4.2.1 The magnet power supply system for the SPS (CERN)

A simplified diagram of this system is given in Fig. 20.

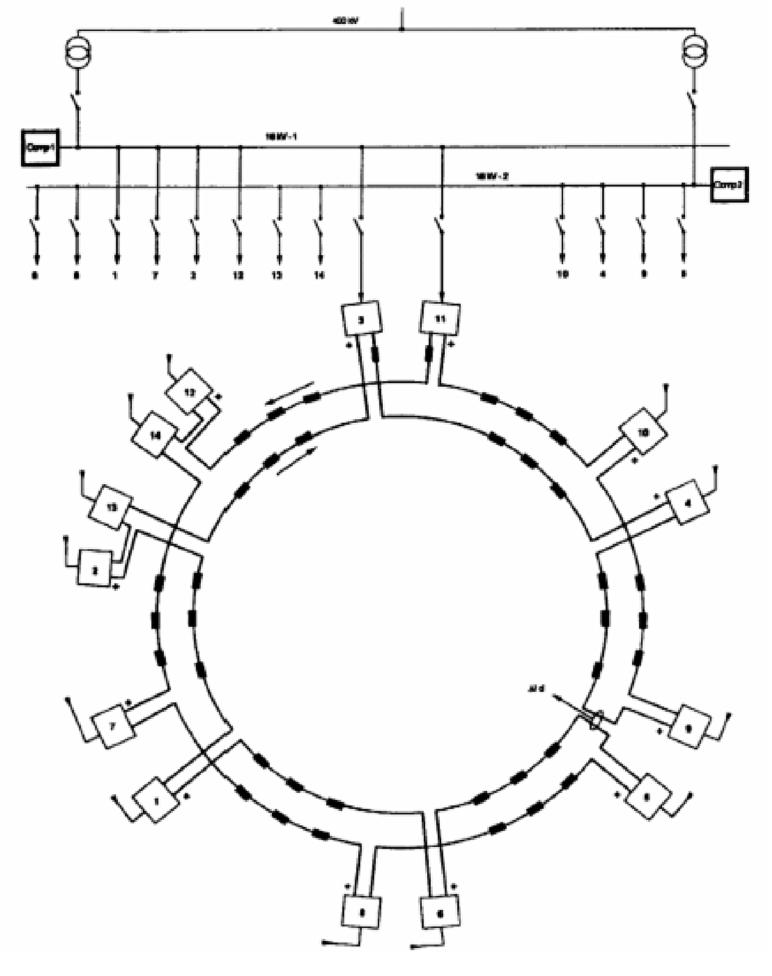

Fig. 20: The directly connected power supply system of the CERN SPS magnets

The diagram shows fourteen converter modules, each two sets of twelve pulse phase controlled thyristor rectifiers. These are connected to the ring dipoles in series, with segments of the load located between successive power units; this prevents the required circuit voltage being applied in a single step. Each module is connected to its own 18 kV feeder, which is directly fed from the 400 kV French network.

As with the mechanical energy storage systems, the magnet current is controlled through phase controlled rectifiers — solid-state thyristors in this case. Hence control of the magnet waveform, within the limitations of the converter's output voltage, is available.

Whilst the direct connection to the extensive and very rigid French grid provides an adequate source and sink of energy, compensation is necessary to prevent excessive phase swings at the CERN site. This is provided by a number of filters using saturable reactors, which are connected to the 18 kV line, as shown in Fig. 21.

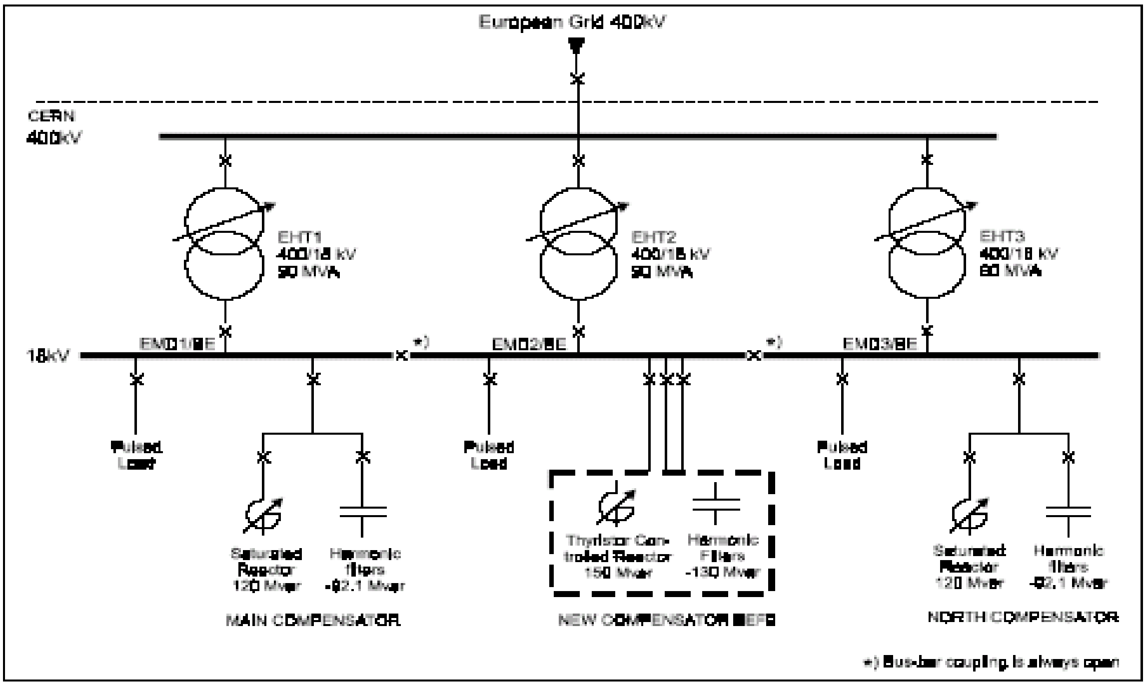

Fig. 21: Connection of filters using saturable reactors to the 18 kV feeder for the SPS magnet power supply system; the filters compensate for the inductive nature of the supply system and minimize phase swings that would otherwise occur, resulting from the power fluctuation during the acceleration and deceleration cycles

This system represents significant capital savings compared to the earlier fly-wheel/alternator system. The maintenance cost and necessary downtime associated with rotating machines are reduced. This therefore is now the preferred converter for large, slow cycling accelerators; the CERN equipment has work reliably and successfully since the commissioning of the SPS and other particle physics laboratories have adopted this solution. However, it is strongly dependant on the energy storage characteristics of the local electrical network, on the availability of a very rigid high-voltage supply line and on the agreement and co-operation of the electrical utility company.

4.3 Medium- and fast-cycling inductive storage systems

Neither mechanical storage nor direct connection is suitable for systems with cycling frequencies much above 1 Hz. Hence the fast- and medium-cycling accelerators (mainly electron synchrotrons) developed in 1960/70s used inductive energy storage. At that time inductive storage was roughly half the cost per kJ of capacitative energy storage, though this situation changed towards the end of the 20th century (see below). The ‘standard circuit’ was developed originally at the Princeton-Pen accelerator and was named the ‘White Circuit’ after that laboratories director Professor Milton White.

4.3.1 The single cell White circuit

In its simplest form the White circuit comprises a complete series string of the accelerator magnets, connected into a parallel network of resonating capacitors and an energy storage inductor. A diagram of such a circuit is given in Fig. 22.

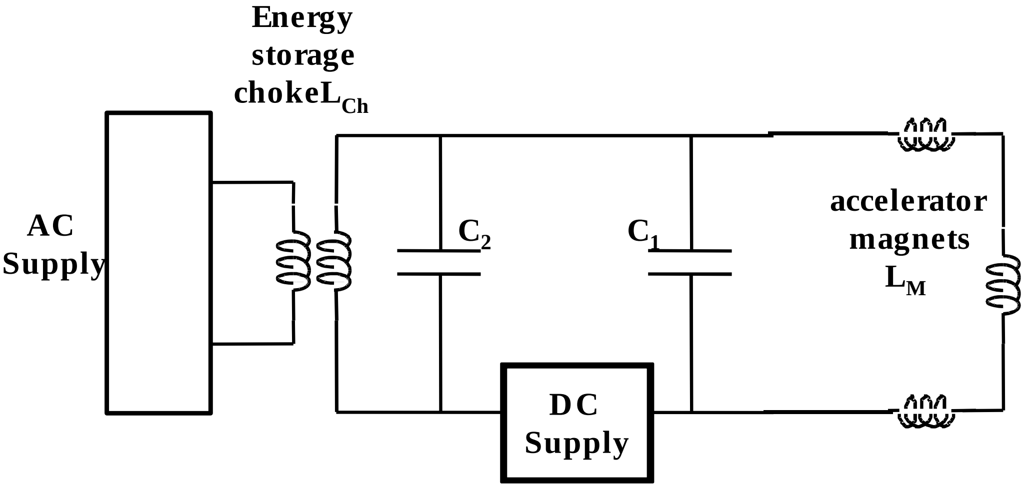

Fig. 22: Schematic diagram of a single cell ‘White circuit’

The series connected accelerator magnets are resonated at the cycling frequency by capacitance C_1. In parallel with this circuit is another resonant system comprising an inductor, referred to as the ‘energy storage choke’ and the resonating capacitor C_2. The d.c converter which generates the direct current required to bias the alternating sine-wave is located between these two parallel circuits; providing the two circuits are correctly resonated, there will only be a small alternating current flowing through this rectifier set. The a.c excitation is provided by an inverter supply powering the parallel circuits by means of a further winding on the inductor, which is closely coupled to the main inductive winding. Again, providing the resonant tunes are correct, the a.c. supply sees a resistive load and, of course, sees no direct current. Consequently, the basic feature of the system is to connect the magnets to two separate supplies, one d.c., one a.c. which do not interfere with each other, which are orthogonal in their control functions and which, together, generate a fully biased sine-wave in the accelerator magnets.

These features of the circuit are summarized below:

- magnets are all in series — ensures field uniformity around the accelerator;
- circuit oscillation frequency ω;
- C_1 resonates magnet in parallel: $C_1 = \omega^2/L_M$;
- C_2 resonates energy storage choke: $C_2 = \omega^2/L_{Ch}$;
- the energy storage choke has a primary winding which is closely coupled to the main winding;
- only small a.c. present in d.c. source;

- no d.c. present in a.c source;
- there is no waveform control.

A diagram of the current waveform is given in Fig. 23; this defines the parameters used in the following section.

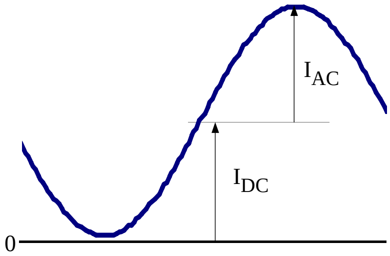

Fig. 23: Diagram of the current waveform generated in the accelerator magnets by the 'White circuit'

The equations corresponding to this circuit are given below:

- magnet current: $I_M = I_{DC} + I_{AC} \cdot \sin(\omega t)$;
- magnet voltage: $V_M = R_M I_M + \omega I_{AC} L_M \cdot \cos(\omega t)$
- choke inductance: $L_{Ch} = \alpha L_M$ (α is determined by inductor/capacitor economics)
- choke current: $I_{Ch} = I_{DC} – (1/\alpha) I_{AC} \cdot \sin(\omega t)$;
- peak magnet energy: $E_M = 1/2 L_M \cdot (I_{DC} + I_{AC})^2$;
- peak choke energy: $E_{Ch} = 1/2 \alpha L_M \cdot (I_{DC} + I_{AC}/\alpha)^2$;
- typical values: $I_{DC} \sim I_{AC}$; $\alpha \sim 2$;
- then $E_M \sim 2 L_M (I_{DC})^2$;

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

4.3.2 The single-cell, single-power-source alternative

A modified version of the single-cell White circuit was pioneered at the Fermi laboratory; a simplified circuit diagram is shown in Fig. 24.

This system has the benefit of a single power converter, which leads to some reduction in capital cost. The rectifier is programmed to generate a voltage waveform with a small direct component, which determines the d.c. bias that is applied to the magnets, and an alternating component, to control the oscillating field amplitude.

Whilst the voltage output of the rectifier can be bi-directional, with the system in inversion for part of the waveform, the rectifier is a two-quadrant power converter, so the output current must be unidirectional; the alternating current amplitude in the power source must be less than the d.c output. As the magnet will be approximately fully biased, the choke inductance must be significantly greater than magnet inductance to prevent such current reversal in the rectifier.

A major problem with this system is a consequence of the full choke alternating component passing through the rectifier. There is therefore a large fluctuating power demand on the mains supply which, depending on the capacity of the network, may not be acceptable.

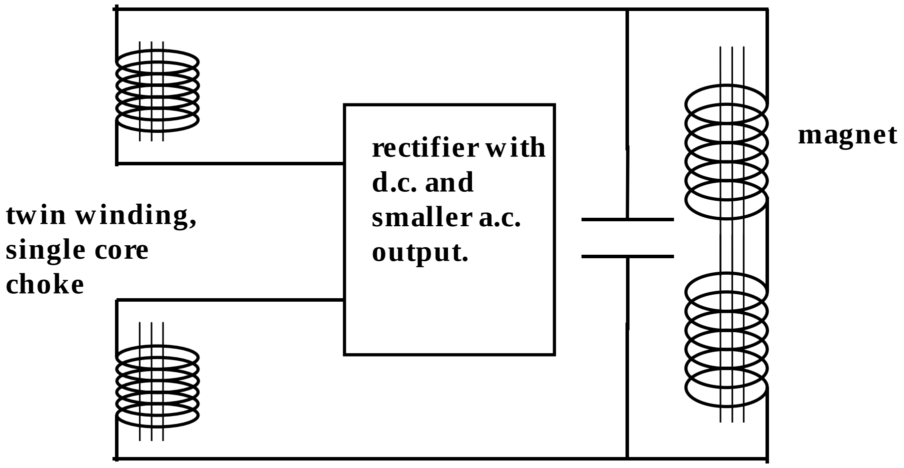

Fig. 24: Modified version of the single-cell White circuit which utilizes a single power source to generate both alternating and direct current in the magnet

4.3.3 The multi-cell distributed White circuit

The single-cell White circuit has all magnets series connected and resonated by a capacitor bank, the complete magnet voltage appearing across this single parallel circuit. For large fast cycling accelerators, where the magnet alternating voltage significantly exceeds 10 kV, it is necessary to divide the White circuit into a number of separate cells, which are series connected, with a capacitor/choke parallel circuit separating each cell. Such an arrangement is shown in Fig. 25.

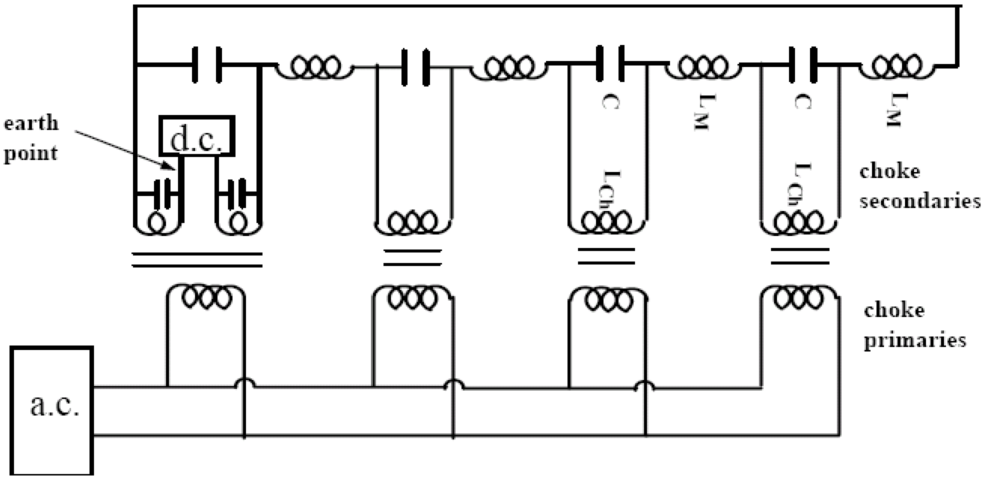

Fig. 25: The distributed White circuit arrangement, as required when the magnet series alternating voltage would be excessively high across a single cell; the example shown is a four-cell circuit

The nomenclature used in Fig. 25 is as defined in Section 4.3.1, with the magnets identified as L_M. It can be seen that these are still series connected, to ensure current continuity. The diagram is for a four-cell system but, in principle, the circuit can be assembled with any number of cells as required to limit the voltages to earth (see below).

The energy storage choke is now divided into a number of separate secondary windings, each closely coupled to a corresponding primary. One secondary winding is further divided into two, with the source of the d.c. bias located at this point, which is also made the single firm earth point in the network. The capacitance in the circuit is also segmented, with a bank connected in parallel with each secondary; each bank combines the magnet and choke capacitances (C_1 and C_2 of Fig. 22). At the split secondary, the capacitances that resonate the choke in parallel and the magnets in series are separated. With these provisos, the equations of Section 4.3.1 for the single-cell circuit are equally valid for this circuit.

The primary windings are all connected in parallel; this prevents unwanted ‘spurious modes of resonance’ which can occur when multiple resonant systems are coupled. With primary windings absent, a four-cell secondary network has spurious resonances which are the four eigen values ω_n predicted by the following equation:

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

where:

- K_nm are coupling coefficients between choke 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 but can represent a serious energy loss mechanism in the circuit; hence, the use of closely coupled parallel connected choke primaries is strongly advisable.

The paralleled primaries also ensures that the voltages across each section are equalized — an arrangement that prevents the alternating currents *at the fundamental frequency of oscillation* that pass through stray capacitances to earth resulting in dissimilarity of magnet current around the network. Given this equalization of voltage across each section, the voltage distribution to earth along the magnet and choke secondary circuit is as shown in Fig. 26 (for clarity, the primary windings are not shown). It can be seen that the multi-cell arrangement prevents the magnet voltages accumulating to a level that would provide difficulty with coil and bus-bar insulation.

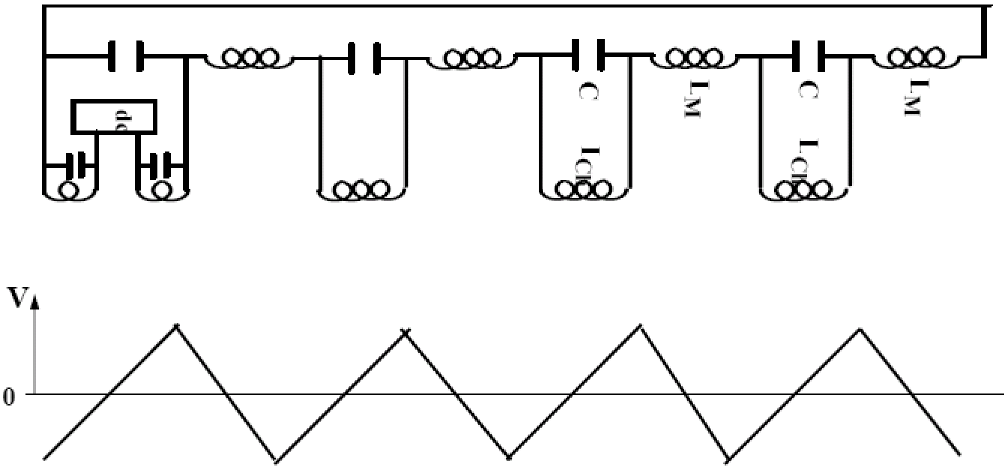

Fig. 26: Voltage distribution to earth in the secondary circuit of the multi-cell White circuit

The principle features of an ‘*n*’ cell White circuit are summarized below:

- magnets are still in series for current continuity;
- voltage across each section is only 1/*n* of total magnet voltage;
- maximum voltage to earth is only 1/2*n* of total;
- choke has to be split into *n* separate windings;
- d.c. supply is at centre of one split secondary winding — this is the circuit’s firm 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;
- there is still NO waveform control.

4.4 Modern capacitative energy storage systems with switch mode control

Technical and economic developments in electrolytic capacitors manufacture now result in capacitative energy storage being lower cost than inductive energy storage (providing voltage reversal is not needed). Additionally, semiconductor technology now allows the use of fully controlled devices (Insulated Gate Bi-polar Transistors — IGBTs) giving waveform control at medium current and voltages, using the ‘switch mode’ principle. 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, with waveform control available, within the limits of the current and voltage ratings.

This innovation was pioneered by Irminger, Horvat, Jenni and Boksberger at the Swiss Light Source (SLS); the circuit that they developed to power the 3 Hz booster synchrotron is shown in Fig. 27.

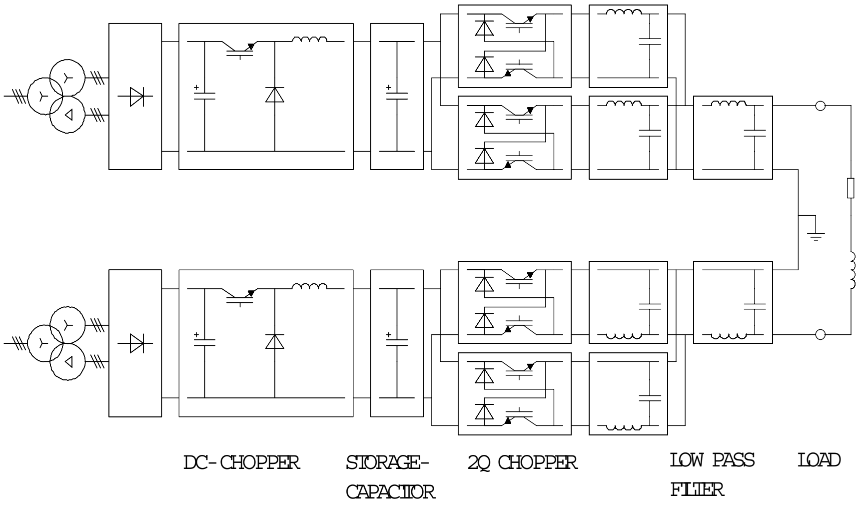

Fig. 27: Controlled capacitative energy storage system developed for the SLS

The accelerator magnets (identified as LOAD) are series connected and are fed by two power converter circuits, each comprising

- a d.c. power source;
- a d.c. chopper, which controls the flow of energy to make up the system losses;
- the main energy storage capacitor;

- a high-frequency ‘switch-mode’ chopper circuit which is capable of transferring energy into the magnet, allowing the load to ‘free-wheel’ in a passive state or inverting the energy flow and recharging the capacitor from the energy stored in the magnet;
- a number of low-pass filters, which smooth out the chopping ripple and deliver the low-frequency voltage waveform to the magnet.

The basic parameters of the SLS booster installation are given in Table 3 below.

Table 3: Parameters of the SLS booster synchrotron power supply system

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

The waveforms associated with this circuit are shown in Fig. 28 (magnet current and voltage), Fig. 29 (total power into the magnet) and Fig. 30 (capacitor voltage and input current).

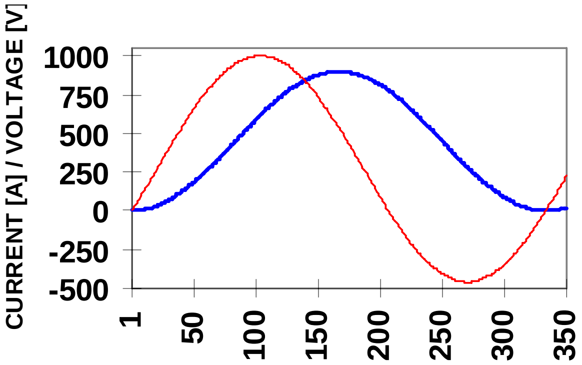

Fig. 28: Magnet current and voltage vs time (ms) in the SLS booster capacitative energy storage power supply system

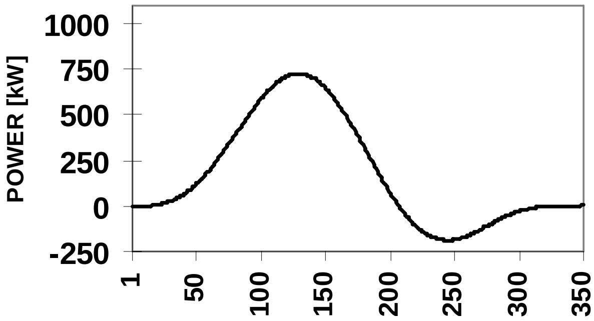

Fig. 29: Magnet power vs time (ms) in the SLS booster capacitative energy storage power supply system

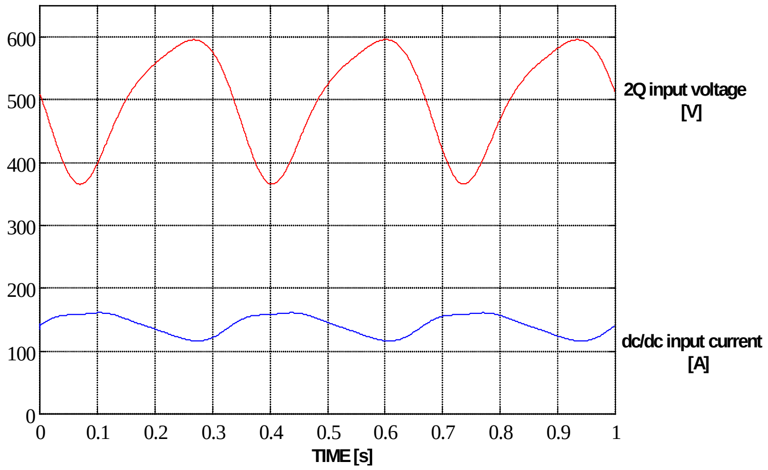

Fig. 30: Capacitor voltage and input current vs time in the SLS booster capacitative energy storage power supply system

It should be noted that it is the development of the power IGBT that allows this switch-mode circuit to control the magnet waveform. The switching of the high-frequency chopper controls both the direction and the rate of flow of energy between the capacitor and magnet and this is only possible in the frequency domain of a few hertz with the use of the power semi-conductors, which can switch on and off whilst conducting currents of the order of hundreds of amperes.

It is instructive to contrast this relatively new solution to powering a cycling synchrotron with the older White circuit:

- the switch-mode circuit does not need a costly energy storage choke with increased power losses;
- within limits of rated current and voltage, the switch-mode circuit provides flexibility of output waveform;
- after switch on, the switch-mode circuit requires less than one second to stabilize (valuable in ‘top-up mode’).
- however, the current and voltages possible in switched circuits are currently restricted by component ratings.

The booster synchrotrons for the next generation of light-sources (Soleil, Diamond) are using this circuit, with component ratings now being adequate to power the 3 GeV, 5 Hz booster for Diamond. However, the use of such a circuit for a 50 Hz fast cycling accelerator is still some way off and capacitor and IGBT voltage ratings will need to rise by approximately an order of magnitude before this becomes realistic.

5 Delay-line mode of resonance

Before completing this overview on power converters for cycling accelerators, it is worth discussing this mode of resonance. The phenomenon can produce severe disruption in a cycling accelerator, causing beam-loss for a number of acceleration cycles and hence reduce the facility’s operational efficiency. In principle, it exists in slow-cycling as well as fast-cycling accelerators but, in practice, in the past it has proved most damaging in fast-cycling machines, where the time between peak-field, when extraction equipment may excite the resonance, and injection, when the beam is most sensitive to disturbance, is low.

The diagram in Fig. 7 shows leakage capacitance to earth as one of the features of an accelerator magnet. It is the resonance between this leakage capacitance and the magnet’s series inductance that is the source of the resonance. Considering the magnet string as an extended inductor, each section will have capacitance to earth; hence the circuit looks like a delay line, as in Fig. 31.

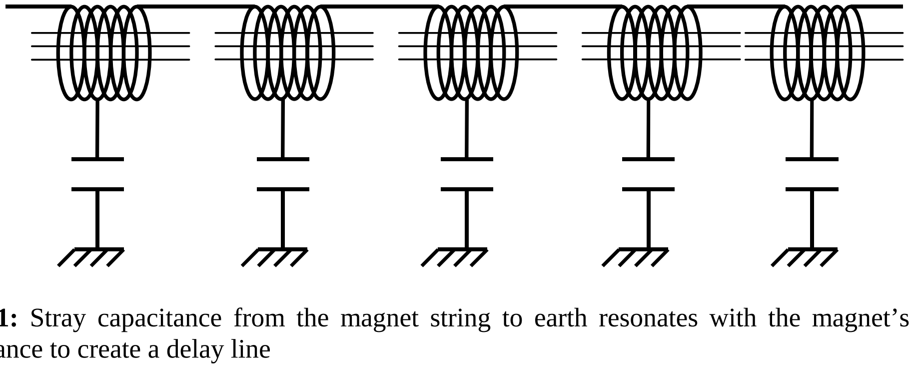

Fig. 31: Stray capacitance from the magnet string to earth resonates with the magnet’s series inductance to create a delay line

Travelling and standing waves (current and voltage) can therefore occur on the series magnet string, leading to different current in dipoles at different positions — a source of possible beam mis-steering and loss. Given a source of excitation which is not fully symmetrical along the magnet series connection, a travelling voltage disturbance will be generated and this will propagate along the line, being reflected at earth points or at any other change in the line's impedance. After a number of transits, this travelling wave damps, leaving a set of standing waves, as shown in Fig. 32.

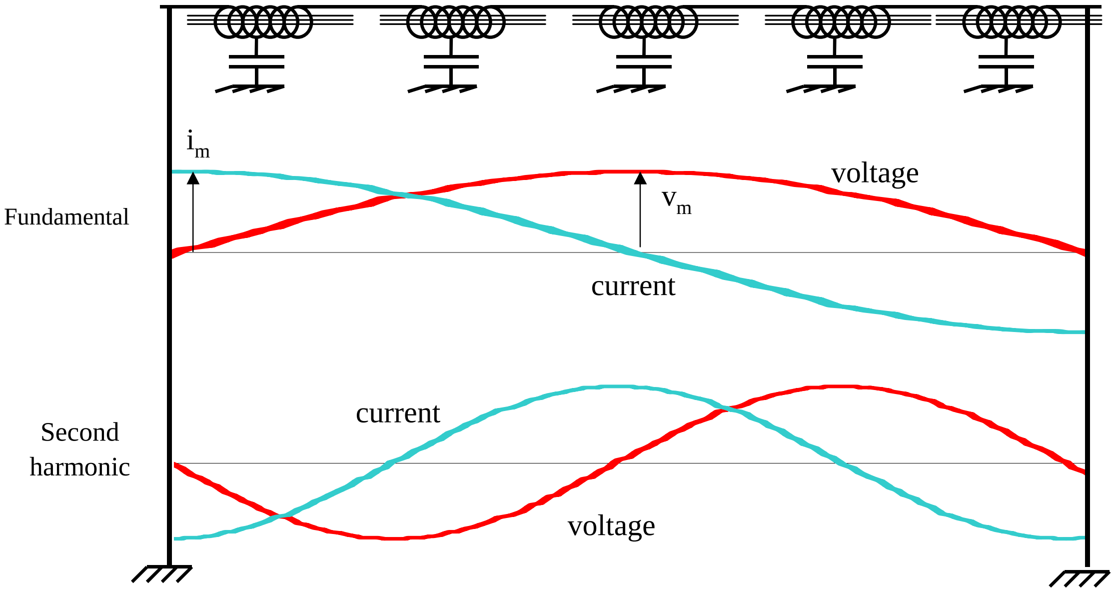

Fig. 32: The distribution of the voltage and current standing waves for the fundamental and second harmonic of the delay line mode of resonance

The diagram shows the distribution of the voltage to earth and the currents in the magnets for the fundamental and second harmonic of the delay-line mode. It can be seen that the fundamental has only a single half sine-wave with zero voltage points at the earth bond; the current is a half cosine-wave, with currents of opposite polarity flowing at each end of the magnet string. The second harmonic shows distribution corresponding to twice the fundamental frequency.

The equations for the critical parameters of the mode are given below; the nomenclature is as defined in Fig. 7, where:

- L_M is total magnet inductance;
- C is total stray capacitance in the magnet chain.

Then:

- surge impedance: $Z = V_M / I_M = \sqrt{(L_M/C)}$;
- transit time around the complete magnet chain: $\tau = \sqrt{(L_M/C)}$;
- fundamental frequency: $\omega_1 = 1/\left(2\sqrt{L_M C}\right)$.

This fundamental frequency will be in the region of 10s to 100s of hertz in medium-sized accelerators; the 5 GeV synchrotron NINA had a fundamental mode frequency of ~ 250 Hz whilst in the larger DESY machine, it was less than 200 Hz. As both accelerators cycled at 50 Hz, the mode was very disruptive in both accelerators.

Note that the mode will be present in all magnet chains but will only be excited if rapid voltage-to-earth excursions are induced locally at high energy (‘beam-bumps’); the next injection in a fast cycling machine is then compromised.

To minimize problems due to this mode:

– keep stray capacitance to earth as low as possible;

– avoid local voltage-to-earth disturbances in magnet ring.

If problems still occur, solutions involving damping loops coupling magnets from different parts of the ring in parallel are possible.

6 Conclusion

The power converters are a vital part of a cycling accelerator and the operational efficiency and susceptibility of the machine to parameter drift are dependent on the stability and accuracy of the converters and whether their waveform can be adjusted to match the beam requirements during acceleration. It is therefore important that the engineers designing and operating the converters be in close collaboration and communication with the magnet designers and those that be defining the lattice and predicting the beam behaviour. In this way the most suitable circuit will be chosen and the optimum performance obtained.