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PRELIMINARY IDEAS FOR THE CONTROLS OF THE LHC MAGNETS SYSTEM

G.Benincasa

Geneva, Switzerland

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I) INTRODUCTION

Two preliminary remarks are necessary to better understand the present work:

- The first remark concerns the application domain of the proposition.
  We are not designing the LHC control system: we limit our concern to the superconducting magnets system. This means that the proposed solutions are "ad hoc" solutions and do not extend, in general, to the other parts of the control system.
  Neverthless, in the SC accelerators, the magnets protection system is of a fundamental importance and it turns out that the control system (see the experience with the Tevatron, SSC design etc..) should be in a certain sense, tailored around it. For this reason the presented layout has also been thought keeping in mind a future integration into the LHC controls.
- The second remark concerns the detailed hardware design.
  Experience in all laboratories shows that the evolution of new technologies in control field is so fast that systems just running get quickly obsolete. It is then useless, at the present stage of the LHC project, to get into very details of the control system.
  We prefer, for the time being, to discuss the main activities and functions needed for the magnets protection and, in general, for the magnets operation, using only an approximate description of the involved hardware.
  However, SC magnets require the implementation of several new ideas in controls whose feasibility must be investigated very early in the project: it is then strongly recommanded to start with some controls prototype as soon as possible.

II) SUPERCONDUCTING (SC) MAGNETS CONTROLS

SC accelerators as the LHC cannot be considered as usual accelerators from the controls point of view.
Traditional machines as PS, SPS, AGS, KEK etc... have powerful and sophisticated control systems, but the integrity of the accelerator itself and of its sub-systems does not depend, in general, on the control system: if this last fails, usually operation stops and accelerator can be restarted afterwards without other consequences, excepted the usual re-tuning operations.
In most of the cases, the control system acts as an intelligent and powerful extension of the operator hands and in this sense one could better speak of an operation assisted by computer.
In few cases (AA, SLAC and others) closed loops and model driven controls are used but, once again, without major risks for the hardware components.
The SC machines, together with another class of newly designed high intensity hadron facilities, require a new generation of control systems that are much more involved in the accelerator running: not only the quality of the operation, but also the integrity of the various systems depend on the reliability of the controls.
As a consequence the reliability and the avalaibility of the control system must be drastically improved as never has been requested in previous accelerators designs.
The most critical subject in SC magnets controls design is the quench treatment.
It is clear that the control system must be involved in this treatment: how deeply it should be involved is argument of debate and will be discussed in chapter 4.

For the moment it is useful to describe briefly the quench phenomenon and first of all those aspects that more concern the control system.

III) QUENCH TREATMENT

It is outside the goals of this paper to describe the quench and the behaviour of SC magnets under critical conditions. This subject is widely covered elsewhere; see for ex. Ref. [1] and [2].
Most of the causes producing quench are now well understood and a series of actions and devices to prevent its catastrophic consequences on SC magnets have been proposed and implemented since several years (see [6] to [17]). A large consensus exists on the actions required for quench protection in particle and storage rings.
Due to the very short time intervals involved during a quench, all these actions are based on the use of electric or eletronic devices.
Most of the concern of the chapter is the description of these devices. Existing experiences on already running or planned SC accelerators is very useful in this context, but it presents some inconvenient:

- only three examples exist of machines comparable in size to LHC: the Tevatron, already in operation, the Hera machine, not yet operational and the SSC that is only planned.
  Mereover, certain characteristics of LHC are unique: e.g. the exciting current of 17000 A requires solutions that cannot be directly extrapolated from the three mentionned machines whose currents range from 4500 A to 6500 A.
- there is no comparative operational experience that can guide us in the choice of such device instead of another one.

Neverthless, the studies already done for these machines have been of invaluable help for us and the proposed layout has been largely inspired by the concerned references.

III-1) THE QUENCH TRATMENT STEPS

In spite of all the cares used in the design of the SC magnets, quench cannot be completely avoided and only an adequate treatment can prevent from serious damages to the magnet system and to the cryogenic apparatus.
The quench itself can hardly be prevented (see III-2), but the consequences can be minimized by a series of devices and actions that must be triggered and sheduled appropriately. The main features of this quench protection system (QPS) are clearly determined by the characteristics of the phenomenon to be controled.
For this reason in the following pages, we describe in some details the different phases of a quench treatment in the chronological order. These phases are:

- The quench prevention
- The quench detection
- The quench protection
- The quench "post morten" analysis.

III-2) THE QUENCH PREVENTION

As already mentionned, a quench can hardly be prevented.
The causes of quench are various and a complete, continuous surveillance of all involved parameters is in practice impossible. Neverthless, prevention is possible in case of particle losses produced by orbit distortions.
Proton losses in vaccuum chamber produce a localized energy deposition that, in case of the LHC at the top energy of 8 Tev, has been estimated to

be in the order of 10^{-7} J/m^3 per proton [3].
Comparison between calculated limiting energy deposition density and experience at the Tevatron [16] have shown good agreement: an adequate distributed beam loss monitor (BLM) system can be used as a valid tool to prevent quench.
Adequate BLM should be provided for both instantaneous and integrated losses.

The quench prevention system is composed of two component subsystems:
- a closed orbit measurement system with at least 4 horizontal and vertical pick-up per betatron λ.
- a beam loss monitor system with a large number of detectors spread regularly around the machine (at Tevatron 1 detector at each dipole location), plus other detectors in critical points.

The two systems together provide a two-steps prevention system: the first one gives an early indication of orbit distributions that, if not corrected, could produce losses. The second one gives a semi-quantitative information of the losses and the corresponding energy deposition.
The two systems must be monitored in real time using a large, distributed microprocessor system, as proposed in the following.
We propose to use a graceful degradation prevention system based on three levels of actions:

1) LEVEL 1 - WARNING:
An abnormal orbit distortion or beam loss has been detected and an human action is required.
No immediate danger of quench exists.
2) LEVEL 2 - ALARM:
A very dangerous situation has been detected: immediate action is requested or the level 3 is entered in the next seconds.
This action could be an human action or an automatic correction by a more sophisticated surveillance system.
3) LEVEL 3 - BEAM ABORT:
The quench is imminent and inevitable; the beam is then dumped (see below).

It should be noted that a magnet system equipped with quench prevention <u>and</u> quench protection has two main advantages in comparison with a system having only the quench protection:
- the quench, also if carefully treated, has allways an inherent risk of damaging some components.
- the recovery procedure after a quench is much longer and more delicate than a recovery after a beam dump.

III-3) <u>QUENCH DETECTION</u>

Detection is always based on voltage measurements across the SC coils.
When the quench initiates, a small region of the SC coil becomes normal with a certain resistance: the flowing current produces then a voltage that can be detected by adequate taps.
Detection is usually done in a differential way by measuring voltage differences between two points in the coil, e.g. an end and a central point, but never the two end points.
In effect, the inductive (L dI/dt) and the resistive (RI) voltages are opposed and roughly cancel each other.
The expression for the internal voltage has the form [1]:

$$V(t) = I(t) \cdot R(t) \, (1 - M/L)$$

where M is the mutual inductance between the normal zone and the rest of the coil and L is the self inductance of the whole magnet.
Qualitatively we can say that R and M increase as the normal zone expands, but I decays. As a result V will rise to a peak value and then will fall.
The crucial problem in a detection system is to assign a minimum threshold value to this peak: i.e which is the minimum value of V that could be considered unambigously as a quench indication.
The answer to this question strictly depends on the characteristics of each machine [5] [9] [10] [12] and on the design criteria followed by the different expert teams. We only recall that the threshold value has been fixed at 500 mV at Tevatron and a 100 mV at Hera.
Without entering in a discussion about these specific figures, we remember some general considerations.
First, the threshold value should be different during Flat-tops and ramping times: in this last case a constant voltage V=LdI/dt must be applied across each dipole. For LHC (L= ~35 mH and about 17000 A to be reached in 600 seconds) this voltage is of about 1 V, the same order of magnitude as the thredhold voltage.
The detection system must be clever and subtract adequately this value during the ramping time. In particular, the changes of slope (start and end of Flat-Tops) must be carefully treated to avoid false quench.
A second consideration concerns the noise level in the voltage detection. The detection signal can be distorted by several causes (noises) due to environment, to the lenght of cables between detectors and the electronics, and others: in several circumstances (Tevatron) it has been recognized that certain noises have the same amplitude as the quench detection signal.
When the causes of the noise are well understood, an adequate intelligent treatment [9] can prevent from false quench. In other cases, the detection threshold must be raised.
One could cure certain noises by putting the electronics as nearest as possible to the detectors: unfortunately most of moderns electronics is highly sensitive to radiations and this solution can only partially be implemented. In tackling this problem, the Tevatron and the Hera machine have followed different philosophies.
At the Tevatron, the detectors and the associated electronics are separated by about 200 m, so no problems of radiation exist.
The noise problems have been solved in one side by raising the detection threshold to a value that avoids most of the errors, and in the other side by adequately rejecting the restant noise errors using an intelligent treatment in microprocessors (this is a very crude shematization) [9] [10].
At the Hera machine the signal amplification is done in proximity of the detection by using a device non sensitive to the radiations, the magnetic amplifier [6].
This solution seems very interesting and we spend some lines to describe it in ANNEX 1.

III-4) QUENCH PROTECTION

When a quench occurs in one or more magnets of the accelerator, four basic actions are usually performed to protect the concerned magnet and its cryostat from damages, and to prevent consequences to the other parts of the whole ring.
These actions are:
A) the proton beams must be dumped into external beam dumps.
B) the energy stored in non-quenching magnets must be dissipated in resistors.
C) the energy stored in quenching magnet must be dissipated uniformely.

D) the quenching magnet must be bypassed.

The possibility to use an intelligent (i.e. computer controlled) quench protection greatly depends on the times scale involved in the quench process.

III-4.1) TIMES SCALE INVOLVED IN QUENCH

Quench usually initiates in a point inside the SC coils and propagates longitudinally and transversally along the coil with different velocities.
Longitudinal velocity is much higher than transversal velocity, mainly due to the insulation layers between coils.
Using appropriate computer simulations [1] and with LHC approximate parameters [2], longituninal velocities of 10 ÷ 20 m/s and transversal velocities of 30 ÷ 40 cm/s have been calculated: this order of magnitude has been confirmed [10] by Tevatron experiments.
With these figures, a total longitudinal and transversal quench propagation takes a time between 500 ms and 1 sec.
Another important parameters to be considered is the current decay rate in the quenching magnet.
Using the same method [1] [3] with a law of the form,

$$I = I_0\, e^{-\left[\frac{t}{\tau}\right]^4} \qquad (\tau \text{ between 0.7 and 1.1 sec})$$

one obtains results confirmed by experiments [10] (at a first approximation).
These semiquantitative results show that velocities involved in quench phenomena are relatively high, but they are compatible with computer based actions.
In particular, during the first 50 ÷ 100 ms after the quench beginning, appropriate treatment are possible without risk for the accelerator components.

III-4.2) BEAM DUMPING

During the normal LHC operation, each one of the two proton beams contains $\sim 10^{14}$ protons.
At an energy of 8 Tev per proton, the total energy carried per beam amounts to 120 Mj.
The loss of also a small fraction of such energy could produce serious damages and could induces quenches in the SC magnets.
For this reason, LHC is equipped with adequate external beam dumping facilities that permits a safe beam evacuation in about 200 μs after the beam dump request [3]. One of the causes of a beam dump request is a quench.
The current decay in the quenching magnet produces a dipole effect on the beam with consequent losses if not adequately end promptly treated.
As mentionned in the previous paragraph, the current decay ($\Delta I/I$) during the first 100 ms after the quench beginning (as an example) is of the order of 4.10^{-4}. This will produce, at a first approximation, a variation of the magnetic induction ($\Delta B/B$) of the same order of magnitude. The corresponding ΔB (of about 10^{-3} tesla) integrated over the magnet lenght (~ 10m) will generate a kick with a deflection angle of,

$$\theta = 0.3 \frac{\Delta B . L}{P} \text{ (Tm/Gev/c)} = \sim 10^{-6} \text{ RAD}$$

This deflection has in practice no effect, and it is still negligible in case of several magnets quenching at the same time.
There is, then, enough time for an intelligent (computer controlled) action.

III-4.3) MAGNETIC ENERGY DISSIPATION

A magnet powered with a current I and having an inductance L has accumulated a magnetic energy $1/2(L I^2)$.

With the LHC parameters this energy amounts at 6.8 Mj per magnet (both channels).
At the moment of the quench detection, the magnet power supplies are switched to bypass: the energy stored in non quenching and quenching (see III-4.4) magnets must then be dissipated in some way.
The used technique is to install dump resistors in series with the magnets. During the normal operation these resistors are by-passed by adequate thyristors that are turned on.
In case of quench the dump thyristors are turned off which introduces the dumps resistors into the magnetic circuit.
The current decay time depends on the ratio L/R between the magnet inductance and the dump resistor. The number and values of the dumps resistors depend on project considerations.
In any case the decay time is long compared with other phenomena involved in quenches.
As examples, at Hera this values is of about 18 s and at the Tevatron it is of about 12 s.
There are then no problems in implementing an intelligent control of the magnetic energy dissipation.

III-4.4) QUENCHING MAGNET BYPASS

The technique described in III-4.3 is not valid for the quenching magnet. In this case, the propagation of the normal zone produces an increasing quench resistance R_a that rapidly dominates the current decay time. For this reason, the quenching magnet is usually by-passed at the start of the quench.

Different techniques have been implemented for this by-pass action: at Hera passive cold diodes [6] are used; thryristors controled by microprocessor are used at Fermilab [10] and are proposed at SSC [18].
The time scale involved in this phenomenon (III-4.1) is of about one order of magnitude shorter than the previous one (III-4.3). To prevent the superconductor from overheating, the time dependent time constant,

$$t_a = \frac{L}{R_a + R}$$

(where R is the internal and cabling resistance) must be much smaller than the time constant of the dump resistors (12 ÷ 18 sec).
As already mentionned in III-4.1, the experimental results carried out at Fermilab [10] show a safety zone of 50 ÷ 100 ms at the start of the quench for intelligent intervention.

III-4.5) HEATERS

In III-4.1 we have given the order of magnitude of the normal zone propagation velocity. In certain cases, e.g. quench starting at low field, this velocity could prove insufficient to prevent from overheating at a specific point.
To avoid this inconvenient heater bands are incorporated in the dipole, connected to capacitors charged with an adequate energy.
At the quench detection, capacitors are discharged into the heaters and the produced heat brings quickly all the superconducting coil into the normal state. The stored magnetic energy is then dissipated uniformely in the overall coil.
As order of magnitude, the time interval elapsed between the firing trigger and the maximum of temperature on the heaters, ranges from 5 to 15 ms.
Heaters must be fired as soon as possible after the quench detection. The real time constraints are then similar to those mentionned in III-4.4.

III-5) THE QUENCH "POST MORTEM" ANALYSIS

Despite the care used to prevent them, quench will arrive.
In most of the cases the protection system works and the causes of the quench are well understood, as it has been demonstrated in the first test periods at Tevatron [9].
In other cases, the quench protection could not work satisfactorily or (and) the causes of the quench could remain mysterious.
For these reasons, it is necessary to have a continuous recording of a large number of machine parameters and measurements to be used for post morten analysis.
In case of quench (or, in general, of malfunctioning) it should then be possible to follow the evolution of important parameters (e.g. losses, orbits, working points etc..) that could greatly help in trouble shooting.
A similar system has been already implemented successfully at the Tevatron [9] [10] [17].
The scan period, the list of parameters to be monitored and the size of the memory buffer can be only decided at the moment of the final design and during the running-in periods.

IV) CHARACTERISTICS OF A CONTROL SYSTEM

IV-1) MAIN TASKS

Independently of the quench treatment (that will be discussed in the following paragraph), the control system has to execute a certain number of tasks that are not usual in traditional accelerators.
One of these task is the accelerator filling.
About twice per period of 24 hours, the LHC old beams must be dumped and new protons are injected from the SPS.

The filling operation includes:

- the old beams are dumped,
- magnetic field must be lowered for injection energy (450 Gev). This operation can be done at the same time for both channels (~ 10 min),
- check of the main systems (~ 10 min),
- tuning of transfer and capture process with pilot beams (~ 20 ÷ 30 min),
- injection of 8 batches of protons from 8 SPS cycles into the two LHC rings (~ 4 min),

- rising the magnetic field from 450 Gev to 8 Tev (~ 20 min).

The entire filling operation then lasts for 1.5 ÷ 2 hours and must be carefully driven and monitored by the control system. The most delicate part of the operation is the acceleration.
Each channel of the LHC has 8 independent power supplies feeding 8 sectors of the machine. Each power supply applies a constant voltage of about 200 V to the 196 dipoles and 49 quadrupoles of a sector (~ 1 V per dipole): the resulting current ramp (V = L dI/dt) must be rigorously identical for the 8 sectors of the machine.
The control system must warrant the perfect synchronization of the various function generators involved and must also provide the three levels of prevention-protection (see III) by continuously monitoring the relevant parameters.
Initial cooling-down and recooling after quench are also unusual operations that must be performed by the control system, but they do not seem to be very different from setting operations already existing in other accelerators. More traditional activities as logs, settings, adjusting parameters should be treated in an usual way.

IV-2) INTELLIGENT VERSUS DIRECT QUENCH TREATMENT

A direct protection system is based on the use of electric or electronic devices, activated by the quench detection signals, and producing directly the requested protection actions.
In an intelligent protection system, an intelligent device (microprocessor) analyses the various parameters and decides on the appropriate actions.
Considerable debate and design effort has been centered, in the different machine study teams, on the question of using an intelligent or direct protection system.

As a results, both philosophies have been implemented in different laboratories:

- a basically direct protection system has been selected at Hera, where microprocessors are used only as a second barrier.

- a completely intelligent system is used at Tevatron and is proposed for the SSC.

In general, keeping identical all other parameters, an intelligent system is less reliable than a direct one, just because in the protection chain more devices are added that can fail.
On the other hand, the complexity of the quench detection and the necessity to avoid false quench play in favour of an intelligent system. Let's examinate these two problems.
Exaustive tests carried out at the Tevatron [9] [10] have shown that the quench detection is not a mere question of measuring a voltage.
Measurements are done on resistive voltages during flat-tops, and by using the differences between applied voltages and inductive voltages during ramping, the signal of each voltage tap is compared with the neighbouring magnets of the same cell.
The signals are often affected by noise: to reduce the consequences of this phonemenon several sampling of measurement signal are collected before to decide if a quench occurred.
Moreover, the quench detection threshold and the used algorithm have to be modified several times experimentally before to fix these parameters.
All these activities can hardly be implemented in direct systems.

Another important argument to be considered is the prevention of false

quench. False quench arrives when a noise or other spurious signal indicates a quench where this one does not exist.
As already mentionned in IV-1, the procedure of filling the LHC is fairly long.
In case of quench (or false quench) most of this procedure must be executed with more time added for other operations as cryostat verifications, post mortem analysis, modifications etc..
This means that false quench are very time consuming.

Prevention of false quench requires often [9] [10] more complicated algorithm and in certain cases, comparisons with experimental data.
Once again these operations cannot be executed using direct systems.
Last, but not least, a powerful distributed control system is anyway necessary for the continuous monitoring of the quench parameters (quench prevention III-2), for orbit and loss observation and for post mortem analysis, that are essential activities in SC accelerators: there is then no question of saving much money by using direct systems.
For all these reasons, we suggest for LHC, an intelligent quench protection system.

As already mentionned, the increase in fault rate due to an intelligent system, must be compensated by a design permitting to improve the reliability.

IV-3) RELIABILITY AND REDUNDANCY

IV-3.1) RELIABILITY DEFINITIONS

The reliability R(t) of a system is the probability that it could perform its function without failure for a time t. The number of failures per time unit, $\lambda(t)$ is called the failure rate [20].
The inverse of the failure rate, $1/\lambda(t)$ is called the Mean Time Between Failures or MTBF.
For most of the electronic devices, the failure rate can be considered as constant with the time: as a consequence the reliability takes the very simple expression:

$$R(t) = e^{-\lambda t}$$

The constant failure rate assumption is valid in general for most of the life time of a system. During the first periods λ is usually much higher, due principally to the occurrence of fabrication and installation faults. After a long time of operation λ becomes also high due, this time, to the ageing of the system.
The result is a bath-shape failure rate curve that is well known by specialists.
The first phenomenon is particularly sharp in microprocessor, where to the mentionned problems the software debugging must be added.
In traditional accelerators controls, this is not a very critical problem, and adequate periods of time are foreseen for debugging during the commissionning.
In SC accelerators, the critical parts of the control system (e.g. the quench protection) must work without failures since the beginning: quench phenomenon does not accept debugging periods !
Only redundant systems can grant such reliability, as we shall see later.

IV-3.2) HOW TO INCREASE RELIABILITY

In specialized handbooks (e.g MIL-HDBK-217 C) [18] one can find algorithms for component failure rate, that permit predictions within 1% to 10% of

observed rates.
At this stage of the LHC project, we prefer to give only a list of the factors that influence the reliability, leaving a more detailed treatment for futures notes.

These factors are:

- using Military-specification (MIL-SPEC) components.
  MIL-SPEC does not indicates, in general, that the components have been built for military use, but only that they have been selected in normal production after a certain number of tests ans screens.
  The failure rate between a commercial component and a very high MIL-SPEC can range from 1 to 70: in average a MIL-Spec has a ten times smaller failure rate. On the counterpart their cost is ten times higher.

- lowering the operating temperature.
  For example a factor two can be gained by lowering the temperature of 10°C.

- controling the environnment.
  A factor two can also be gained by operating in air conditionned rooms: humidity has a drastic effect on component reliability.

- packing the components.
  Replacing M components by a simple integrated circuit can improve the failure rate by $\sqrt{M}$.

IV-3.3) <u>RELIABILITY OF COMPOSITE SYSTEMS</u>

Electronic subsystems are in general used in connection with other subsystems to accomplish a certain function.

If the components are connected in series, the failure of any component determines the failure of the whole system.
If the components are connected in parallel, the definitions are more complicated and we will treat this case in IV-3.4.
In series connections the resulting failure rate and MTBF have the very simple form:

$$\Lambda = \sum_{\iota=1}^{n} \lambda_\iota \quad ; \quad MTBF = \frac{1}{\Lambda}$$

where λ_ι is the failure rate of the ι-th component.

As can be easily seen, in systems with several elements in series, the MTBF decreases quickly with the number of components: for example, for ten components, and assuming the same failure rate λ for all of them, the MTBF will be ten times shorter than the value for a simple component.

The quench protection system can be considered as a series connection system in which the total function of protection is executed only if all the component subsystems work without failures.
For a first analysis, the different activities involved in quench protection can be represented in a block reliability diagram, as in fig.1:

- the quench detection block, included the pick-up itself (electrical taps) and the associated hardware (magnetic amplifier or other).

- a microprocessor for the various treatments.

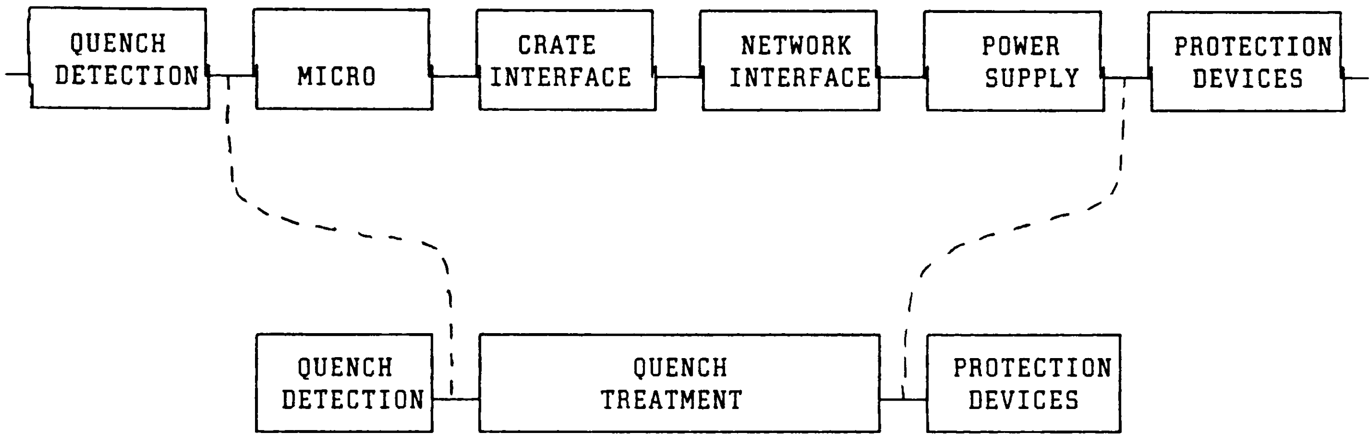


Fig. 1 RELIABILITY BLOCK DIAGRAM FOR THE QUENCH PROTECTION SYSTEM AND ITS SIMPLIFIED VERSION.

- the microprocessor is housed in a crate (e.g. a VME crate) with other control modules.

- information for necessary actions must be sent via a network (e.g. ETHERNET) to other parts of accelerators: beam dumping, heaters and dump resistors firing in other magnets of the same sector etc..

- the microprocessor with its crate and interfaces are energized by a local power supply.

- protection devices.
  A certain number of devices must work correctly to grant the complete success of the protection:

  - thyristors or cold diodes for the quenching magnet,
  - thyristors and capacitors for heaters,
  - thyristors for resistor dump etc...

To obtain quantitative information on the overall reliability of the quench protection chain, several steps are necessary:

1) Each box of fig.1 should be detailed in the component subsystems and the various serial and parallel connections should be identified.

2) For each subsystem the adequate electronic components should be selected on the market.

3) Using the appropriate literature (e.g. MIL-HDBK-217C) the intrinsic reliability of each component should be noted.

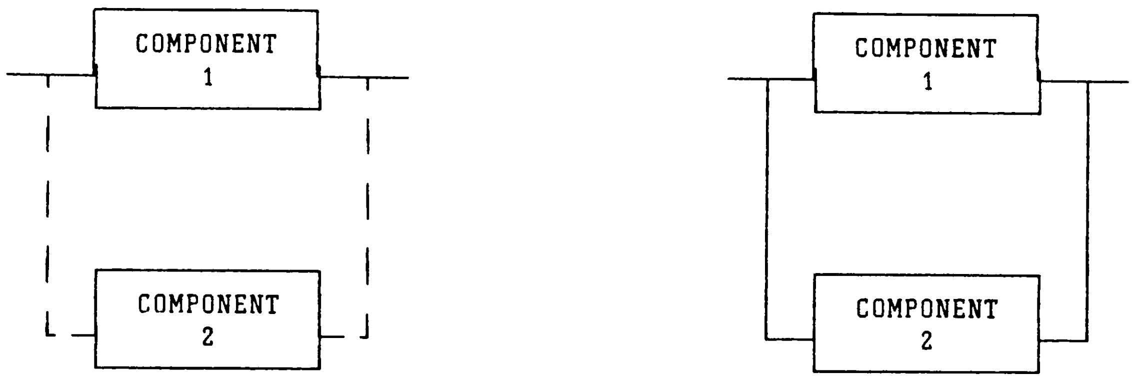
4) At last, the overall reliability could be determined using the theory for the different serial and parallel connections.

This work has been done by the Tevatron specialists: good agreement is claimed between calculated and observed failure rates on the overall protection system.

In the SSC design report [18] a similar work has been done: due mainly to the size of the machine, the resulting failure rate for the overall quench protection chain results at least one order of magnitude superior to the design goals.
They are now investigating in the field of redundancy.

IV-3.4) REDUNDANCY

Redundancy is obtained with a particular kind of parallel connections where the components are identical and execute the same function. In this case, the overall system fails only if all components fail.
For simplicity, we will consider the case of only two redundant components (Fig. 2).



a) cold Redundancy

b) hot Redundancy

Fig. 2 REDUNDANCY CONNECTIONS

There are two cases of redundant coupling:

- cold redundancy, where the second component is not working at the same time, but it is in stand-by and can be put in operation when the first component fails.
- hot redundancy, where the two components are in operation at the same time.

We treat only of the hot redundancy in the following; cold redundancy does not offer enough reliability for our purposes.
Intuitively, the redundancy must improve the reliability of a system. To obtain some quantitative indication we must distinguish between unrepairable and repairable systems [2].

- A system is called unrepairable if it cannot be repaired to perform its task after a failure (it could be repaired too late for the performed function).
  The reliability parameters for such systems are the same already mentionned in IV-3.3, excepted the definition of MTBF that is now called MTTF or mean time to fail.

  If we have n subsystems with identical failure rate λ in hot redundancy, the resulting reliability is:

$$R(t) = 1 - \left[1 - e^{-\lambda t} \right]^n$$

  and the resulting MTTF is:

$$MTTF = \left[\sum_{k=1}^{n} \frac{1}{k} \right] MTTF_{comp.}$$

  using only two components we improve the MTTF by 50%.

- A system is said repairable if, after failure, it can be restored by repairing components.
  The reliability parameters are the same as in IV-3.3, but we add the definition of a mean time to repair, or MTTR, having an intuitive

meaning.
Redundant repairable systems are much more complicated to treat.
To find the reliability parameters of such systems usually involves the solution of a set of differential equations: in more complicated cases only Montecarlo simulations can help.
The case of two identical repairable systems in hot redundancy has been recently treated [21] and we report here some results.
A fundamental parameter in these calculations is the ratio between the mean time between failures and the mean time to repair:

$$\eta = \frac{MTBF}{MTTR}$$

The most important result is that the overall reliability is extremely high at any moment.
After a short transient period (where the reliability is even higher) one obtain the simple expression:

$$R = e^{-\lambda t} \qquad \text{where } \lambda = \frac{1}{1 + \eta + \frac{1}{2}\eta^2}$$

$$\text{and MTBF} = 1 + \eta + \frac{1}{2}\eta^2$$

An example will better explain this.
From the PS control system experience, we know that a microprocessor housed in a CAMAC crate has a MTBF = ~ 10000 h. and a MTTR = ~ 1 h. The value of η is then 10000.
For a redundant hot connection of two such systems, we obtain:

$$MTBF = \sim 5.10^7 \text{ hours.}$$

that means roughly a fault each five thousands years !!

V) POSSIBLE LAYOUT OF CONTROL SYSTEM

V-1) MAIN CHARACTERISTICS

V-1.1) EXTENDED USE OF REDUNDANCY

If we refer to Fig.1 (simplified chain), we see that the protection chain is composed of the serial connection of three blocks.
Let's consider first the quench treatment block.
We have assumed for this block a failure rate of $\lambda = 10^{-4}\ h^{-1}$.
This figure (PS experience) is confirmed by Tevatron and SSC studies. In a machine as LHC the number of these blocks should be of about 200 (see V-2).
The resulting failure rate will be $\lambda = 2.10^{-2}\ h^{-1}$ and a MTBF = ~ 50 h.
As already mentionned, this figure can become one order of magnitude worst during the first periods of running. Using the hot redundancy for each treatment block, one obtain $\lambda = 4.10^{-6}\ h^{-1}$ and MTBF = 25.10^4 h.
The reliability of the treatment block (microprocessor and associated hardware) is then very high also during running-in periods.

In the following paragraphs, we discuss also the reliability of the other part of the quench protection system.

V-1.2) USE OF MIL-STANDARD COMPONENTS

In certain cases, as for example the quench detection and the protection devices blocks, it is not easy (or too expensive) to introduce hot redundancy.
In these cases, the use of MIL-Standard components could be the solution.
As already mentionned the use of these components can improve the failure rate of one order of magnitude.
The SSC design study reports a failure rate of 10^{-4} h^{-1} for the quench detection system.
Much more difficult is to give reliability figures for the third block, the protection devices.
This block is composed of etherogeneous equipments and we do not have figures for reliability.
Considerations on the complexity of these equipments compared, for example, with the quench detection system bring us to the feeling that the reliability should not be worst than for these last.
We then guess a $\lambda = 10^{-4}\ h^{-1}$.

We can now compare the reliability of the simplified quench protection diagram (Fig.3) without and with the proposed improvements.

- A) Without improvements, we have:
  - quench detection block $\lambda = 10^{-4}\ h^{-1}$; MTBF = 10^4 h
  - quench treatment block $\lambda = 10^{-4}\ h^{-1}$; MTBF = 10^4 h
  - protection devices block $\lambda = 10^{-4}\ h^{-1}$; MTBF = 10^4 h

The three blocks are connected in series, then we have for a complete chain:

$$\Lambda = \Sigma\ \lambda_i = 3.10^{-4}\ h^{-1}\ ;\ \mathrm{MTBF} = \frac{1}{\Lambda} = 3,3.10^{3}\ h$$

and for the complete LHC quench protection system (~ 200 chains):

$$\Lambda = 6.10^{-2}\ h^{-1} \quad ; \quad \mathrm{MTBF} = \sim 17\ h$$

This figure for the overall MTBF is clearly unacceptable. In effect, if we consider that the MTTR is of about 3 h (see V-1-4), we obtain an avalaibility of the system [A = MTBF/(MTBF + MTTR)] of only the 85%.

- B) With the proposed improvements, we obtain:
  - quench detection (MIL-STAND) $\lambda = 10^{-5}\ h^{-1}$ MTBF = 10^5 h
  - quench treatment (HOT-Redund.) $\lambda = 2.10^{-8}\ h^{-1}$ MTBF = 5.10^7 h
  - protection devices (MIL-STAND) $\lambda = 10^{-5}\ h^{-1}$ MTBF = 10^5 h

For one complete chain, we have:

$$\Lambda = \sim 2.10^{-5}\ h^{-1} \qquad \mathrm{MTBF} = \sim 5.10^{4}\ h$$

And for the overall LHC quench protection system:

$$\Lambda = 4.10^{-3}\ h^{-1} \quad ; \quad MTBF = 250\ h \quad ; \quad A = \sim 99\%$$

The last figure for MTBF has the same order of magnitude as target figures given for Tevatron and SSC.

An usual requirement found in reports [15] [19], is that the MTBF of the quench protection system should have the same order of magnitude of one period of run of the accelerator.
If the run period of LHC will be longer than 250 hours, then other improvements are necessary.
In this case, we suggest to introduce the hot redundancy in the detection system (resulting MTBF = ~ 500 h).

V-1.3) CONTINUOUS SURVEILLANCE

All the electronic components of the quench protection system should be checked continuously (this means as frequently as possible) to detect malfunctionning.
This is an essential task of the front-end microprocessors that, at their turn, should be monitored by central computer.
The checking procedure for each component must be established separately by specialists.

V-1.4) USE A POWERFUL DIAGNOSTIC SYSTEM

When an element fails in the protection chain, the reparation time (MTTR) can be decomposed chronologically in four steps:

1) the failed element must be identified,
2) the specialist has to go to the failure point,
3) the failed element must be replaced,
4) the specialist has to come back.

In a large complex as the LHC, the last three steps should last for about two hours.
The first step largely depends on the skillness of the diagnostic system.
For this reason, we suggest to implement, from the very beginning, a powerful diagnostic system using the more modern techniques (e.g. Expert Systems).

V-1.5) OTHER IMPROVEMENTS

In the design report of the SSC, the front-end crates are housed in holes drilled in the ceiling of the main ring.
This looks a bad environment for electronics and increases the repair time (trips can be very long).

By using magnetic amplifiers in the detection chain, it could be possible to fulfill three goals:
- most of the electronics can be put very far from dangerous environment (radiation, temperature, dust etc..),
- electronics can be grouped in air-conditionned rooms (high reliability),
- MTTR are reduced (shorter trips).

There are other auguments in favour of this device (M.A.) that should be studied in more details.

V-2) LAYOUT

Each ring of the LHC contains 1568 dipoles and 392 quadrupoles: to be more precise a certain number of other magnetic elements should be added to this numbers.
For simplicity, we assume that 2000 elements per ring (total 4000) must be protected.
Each ring is divided into 8 sectors, having each an independent power supply. The basic repetitive element of the magnetic system is the cell, composed of 8 dipoles and 2 quadrupoles. Each sector includes 25 cells.
As results there are 200 cells per ring.
Due to the "two in one" [3] design of the LHC magnets, each dipole and quadrupole assembly contains the two magnets for the two rings.
We propose to use an independent quench protection system (QPS) per each cell (a cell = 20 magnets, 10 per each ring).
Each QPS is composed of a crate containing all the necessary intelligence, the interface for the various detection and action systems, and the network interface (Fig.3 and 4).
An identical system runs at the same time with identical functions and hardware: this provides the second level of the hot redundancy.
Each level of crates in a sector has its own uninterruptable power supply.
Each crate is connected to the ten magnets composing a cell with a cell detection and action system (CDA).

The detection system is composed of electrical taps (at least two per magnet and per ring) with the associated hardware (possibly the magnetic amplifier).

The action system includes those actions that must be performed by a single intelligent crate on the magnets depending on it (10 magnets); these actions are essentially:
- firing the thyristors to by-pass the quenching magnet (both channels), if no diodes are used.
- firing the heaters thyristors (capacity discharge) for the quenching magnet.
- firing the dump resistors thyristors for all the others cell magnets.

As already mentionned, the complete quench protection requires a certain number of actions involving systems far from the quenching magnet.
For this reason, each crate is connected to three independent communication systems (this improves reliability):

1) A sector Local Area Network (ETHERNET ??) connecting all the crates of the same sector. Its main tasks are:
   A) to communicate to the other crates of the sector the quench informations to initiate protection and recovery procedures for other systems as cryogenics, vacuum, main power supplies etc...
   B) to initiate in all crates of the sector the data taking for the "post mortem analysis"
   C) the LAN communicates with a sector computer and, from it, with the overall LHC control system.

2) A sector action communication system.
This independent communication channel sends to all crates of the same sector the command to start the resistor dump procedure.

3) A dedicated ring beam dump communication system covers all the LHC ring and starts the corresponding beam dump procedure. The beam dump procedure will be probably executed in a dedicated processor.

All these operations will be executed within the first tens of ms after the

quench detection.
Identical actions are executed by the second level of protection (redundant system).

V-3 MICROPROCESSOR'S TASKS

The quench protection treatment is the most important and critical task of the control system and the proposed solution using hot redundancy should give the required reliability figures.
Neverthless, other essential tasks exist that require also high reliability to prevent damages: first of all are the beam losses and orbit monitoring.
In the SSC design report, these tasks are executed by independent processors housed in the same crate as the quench protection system.
It is our opinion that, given the exceptionnal reliability figures provided by the hot redundancy, we could afford to introduce the mentionned tasks in the same microprocessor as the quench treatment.
In this optic, each micro should execute essentially four tasks:

1) continuous beam losses measurement and treatment with several levels of alarms and actions (see III-2).
2) same action for orbit measurement.
3) continuous scanning of the essential parameters of the quench protection system and other critical systems.
   For this activity, a special investigation is necessary to identify the needed status informations for each system and subsystem.
4) the quench protection task already described.

The first three tasks should be executed as a continuous scanning with a repetition rate as short as possible.

It is question of debate if the protection task should also be included into the continuous scan loop, or if it should be executed on interrupt.
For optimum protection, this task should start actions no later than 10 ms after the quench detection: if the scan loop in the microprocessor can grant this time interval, it could be also used for quench treatment; on the contrary high priority interrupts could be used.
If a solution using the scan loop also for quench treatment is implemented, we could take advantage from the existence of the redundant system: in effect, by adequately delaying the starts of the two identical tasks in the two systems, it is possible to divide by two the response time to a quench.

VI) CONCLUSIONS

We have sketched the generalities of a layout for a LHC magnets control system that is powerful and reliable.
For this, we have suggested the use of hot redundancy in the intelligent part of the system and the use of MIL-Standard components for other parts.
At this stage of the project, it is neither possible nor useful to enter in detailed implementation study.
The proposed layout represents also the front end part of the overall LHC control system: matter of discussion is how this last should be integrated with the LEP control system. This problem will be investigated later on.
For the time being, we remember that the hot redundancy and the continuous surveillance of the beam are fairly new concepts in accelerators control field: their implementation requires deep investigations that should be started as soon as possible.

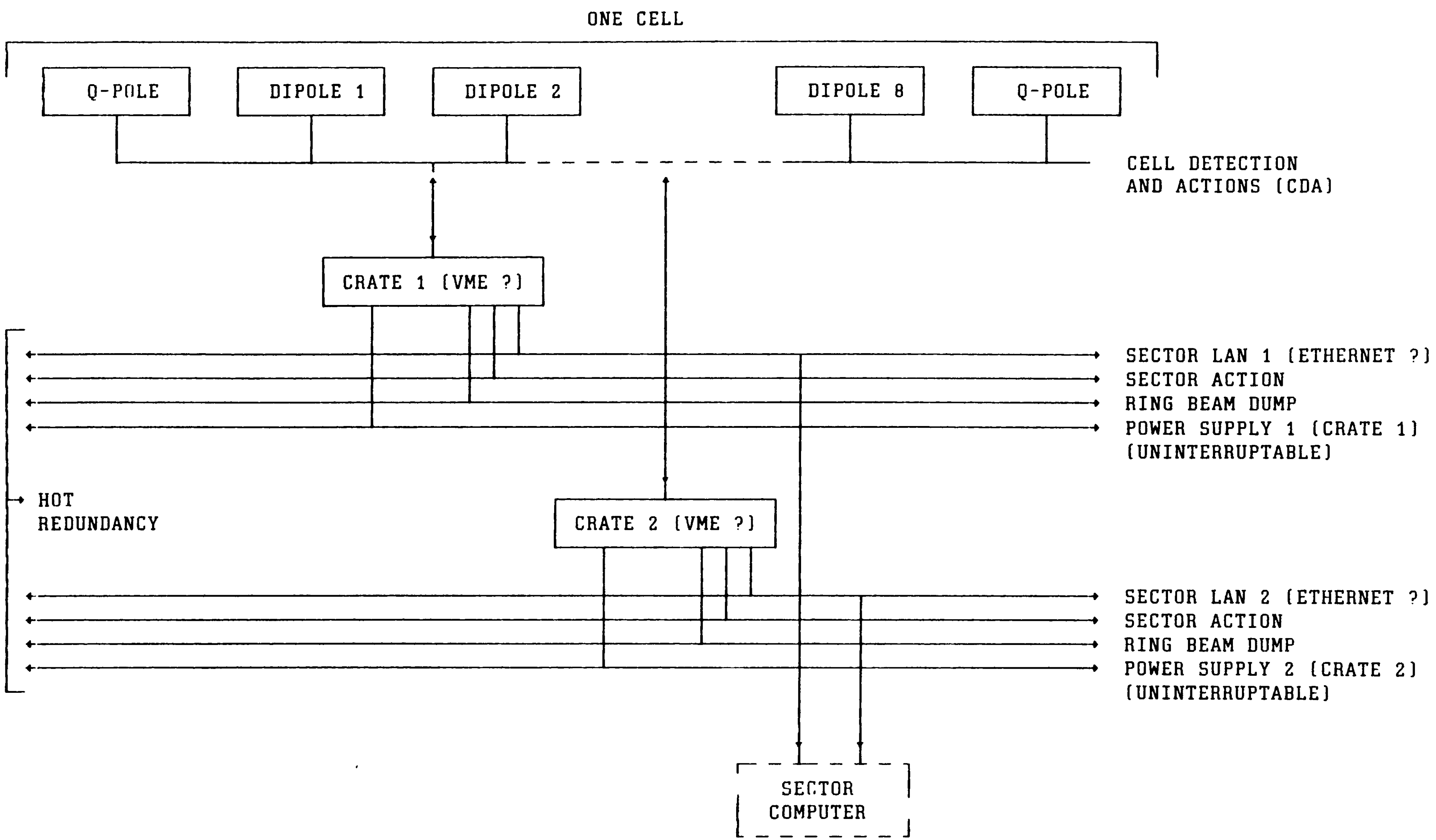


Fig. 3 CELL QUENCH PROTECTION SYSTEM

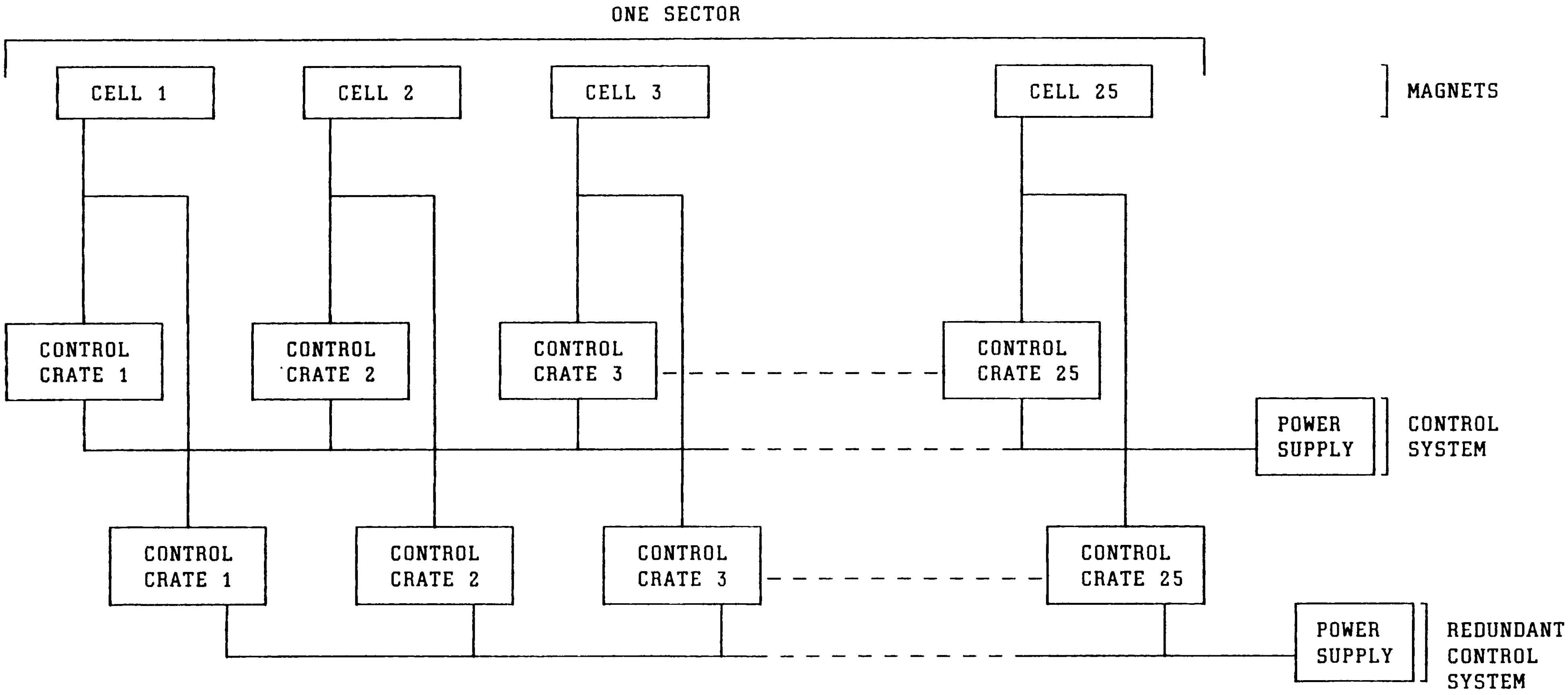


Fig.4 BASIC LAYOUT FOR THE REDUNDANT QUENCH PROTECTION SYTEM OF A SECTOR

ANNEX 1

THE MAGNETIC AMPLIFIER

The magnetic amplifier (MA) [19] is a low impedance device in which the amplification is achieved by using non linear properties of ferromagnetic materials.
The simple transductor of fig.5 represents the basic features of a MA.
Two circuits, called the a.c. circuit and the control circuit, are magnetically coupled with identical mutual inductances M_a and M_b.

The particular winding arrangement used (fluxes magnetically opposed) avoids a.c. components to be transduced from a.c. circuit to the control circuit when $E_c = 0$.

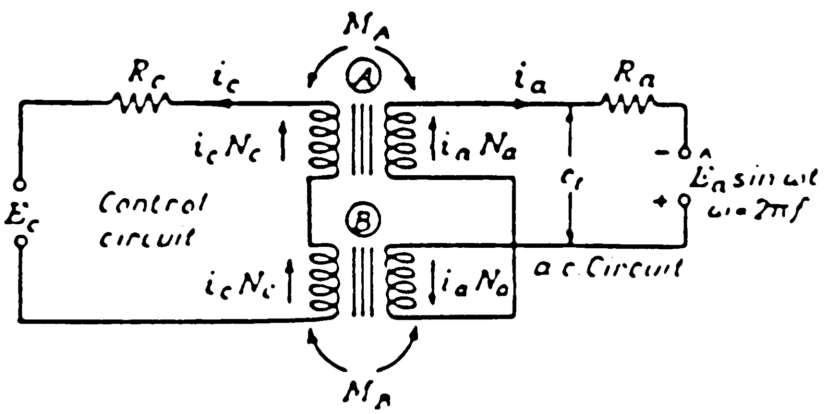
Core materials are selected to have a very small hysteresis loop ("magnetically soft") and a sharp "Knee" between the linear part and the saturation part of the magnetization curve.
Under these conditions ($E_c = 0$) the total voltage E_a applied to the a.c. circuit is shared between the resistive and the inductive charge:

$$E_a = R_a i_a + L \frac{di_a}{dt}$$

During the linear part of the magnetization curve, inductance L is high, the voltage drop across the resistance is then small and the same is then for the current i_a.
If the amplitude of the applied voltage E_a is such to bring the circuit in the saturation zone, then the inverse happens: inductance falls producing most of voltage to appear across the resistance with a consequent high value for i_a: the circuit behaviour is then non linear.
Let's assume now that the supply voltage E_a has been adjusted so that ($E_c = 0$) its peak value just fails to saturate the magnetic core.

If a voltage $E_c > 0$ is now applied to the control circuit, the corresponding current ($i_c = E_c / R_c$) will change the flux level into the common core (polarizing field): the magnetic curve of the a.c. circuit will be consequently displaced by an amount proportional to the control current i_c, and the circuit will enter more and more in the saturated zone (big values for i_a)

fig. 5 CIRCUIT FOR A SIMPLE TRANSDUCTOR



The amplification effect is:

$$i_a = \frac{N_c}{N_a} i_c$$

It can be easily demonstrated [19] that, despite the feeding power E_a is a sinusoïdal voltage, the average value for $\bar{e}_t$, $\bar{i}_a$ and $\bar{i}_c$ are different from zero. Using these three variables the family of curves in fig.6 are usually plotted to summarize the behaviour of an MA (amplification factor $N_c/N_a = 10$).

The line ABCD corresponds to the condition of no load on the a.c. circuit.
The line A'B'C'D' is the usual condition with a load R_a on the a.c. circuit.

Characteristics of a MA are:

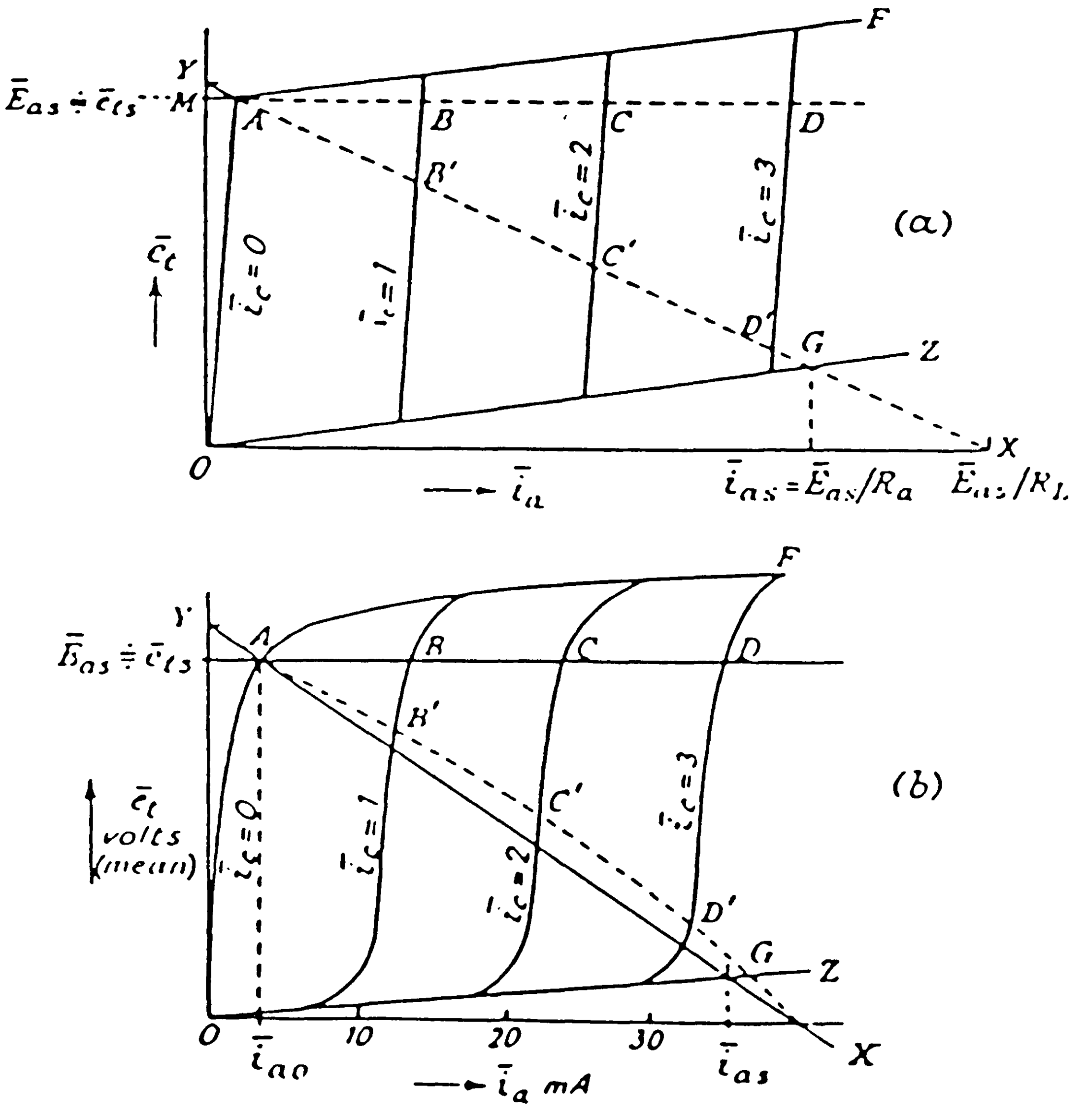
- Robustness,
- Reliability: in practice no maintenance is required,
- Low power dissipation,
- No fast response ($\tau \geq 1$ms): this value is sufficient for quench detection,
- Limited in frequency for losses in iron to $F \leq 1$ MHZ : no problem for our application.

The device is usually completed by ancillary equipment as, for example, a test winding.
At Hera machine [6] a quench signal of ~ 100 mV is applied to the control circuit: the resulting current in the a.c. circuit produces a 10 V signal (at a convenient distance from the detector), well above the usual ambiguous signal/noise ratios.

fig.6

a] idealized voltage-current characteristics
b] the same curves for practical transducer

$$\frac{N_c}{N_a} = 10$$



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