OPTIMISATION OF THE CURRENT RAMP FOR THE LHC

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Abstract

The field quality of the main magnets in the LHC will be, in part, dependent upon the shape of the magnetic field as a function of time. A theoretical optimisation of this function has been carried-out with the aim of minimising the dynamic errors [3]. This work resulted in the definition of a current ramp function composed of mathematically defined, smoothly joining segments.
A prototype digital controller based on a DSP has been developed and built [4]. In this equipment the current ramp is computed from the segment equations in real time. The user need only supply the characteristic parameters for the segments in order to define the ramp. In this paper, the effect of the ramp function on the error terms is discussed and the corresponding segment equations are given. The prototype implementation is described and actual results are shown.

1 BACKGROUND

For the LHC, the shape of the dipole current acceleration ramp as a function of time will have a profound effect on the performance of the accelerator. In particular, the start of the ramp, just above injection energy will be critical due to the phenomenon known as "snap back".

Field errors in the LHC superconducting magnets have been studied extensively over the last few years [1] [2]. Non-linear field imperfections due to the ramping rate can be reduced to an acceptable level only by employing a smooth and gradually increasing transition to the linear ramp. The choice of this curve must also try to minimise the overall ramp time.

2 DYNAMIC ERROR SOURCES (AND POSSIBLE REMEDIES)

2.1 Magnetisation decay and "Snap-back"

The LHC superconducting magnets are characterised by a significant drift in the magnetic field when the current is constant (e.g. on the injection plateau). At the restart of the ramp (for beam acceleration) the field bounces back abruptly, reaching the original value at the start of the injection plateau after an increase in current of about 30 A.

This effect, called "snap-back", has a magnitude approximately independent of the ramp-rate. However, it occurs over a very small current increment and it can be shown [1] that the time duration of this effect is inversely proportional to the ramp rate (Fig 1).

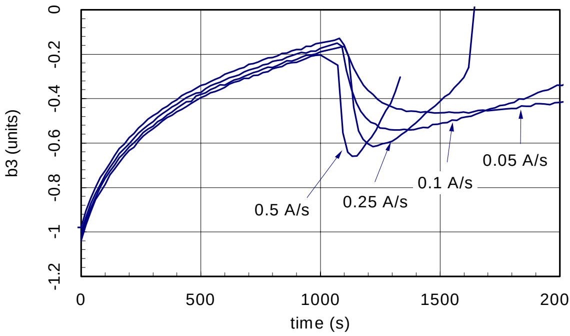

Figure 1: Snap-back observed in a dipole prototype at different ramp-rates after the injection plateau. Units are 10^{-4} of the main field, at 10 mm. reference radius.

The magnitudes of the field harmonics can be reduced by ramping very slowly, which would also give time for a feedback correction scheme to work. Of course, remaining at a very slow rate would result in excessive overall ramp times. The obvious remedy is to employ a gradually increasing ramp rate, such that "snap-back" occurs at a low rate, but the nominal maximum linear ramp rate is attained as early as possible.

Small, independently controlled corrector magnets will be needed to maintain the beam variables within the pre-specified tolerances, especially during the "snap back" phase. Control signals for the corrector circuits will be derived by real-time feedback algorithms

2.2 Inter-strand eddy currents

In a superconducting magnet, eddy currents develop in the loops formed by the twisted strands inside the superconducting cable. These currents, induced during ramping, produce field distortions having a magnitude proportional to the ramp-rate and inversely proportional to the inter-strand resistance. The relative value of ramp induced field harmonics *for a constant ramp rate:*

$$b_n = C_n \cdot \frac{\dot{B}}{B}$$

which is greatest at low field near injection. The effect of these imperfections is to distort the linear optics and cause a reduction of the dynamic aperture. The design of LHC sets limits on these harmonics and therefore directly determines the allowable ramp rate as a function of current. Any choice of ramp function must respect these limits while minimising the overall ramp time.

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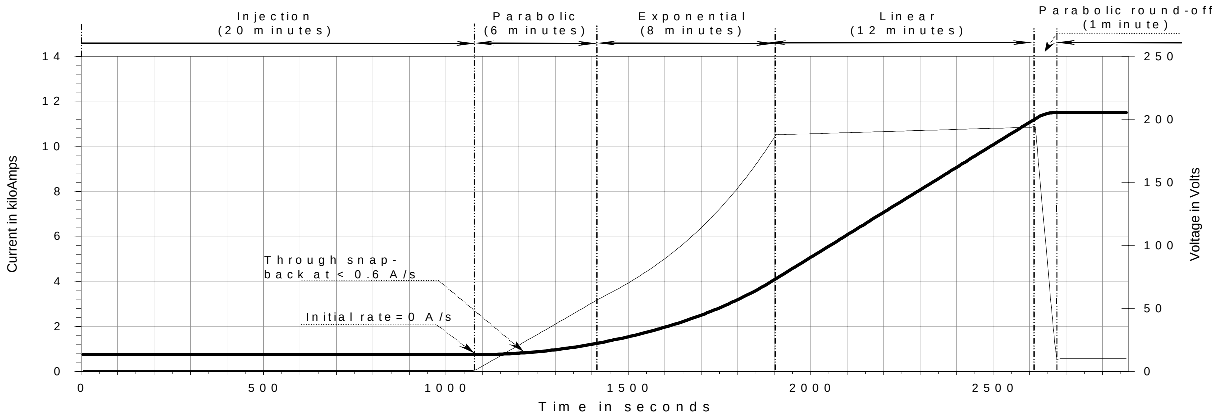

Figure 2:Current and voltage functions for the “Beam-in” part of the LHC cycle

3 POWER CONVERTER SYSTEM DESIGN CONSIDERATIONS

Each of the LHC power converters, along with its inductive magnet load, is a closed-loop device that has a limited bandwidth and a limited output voltage. Due to these considerations, the rates of change of current are limited, as well as the dynamic accuracy of the output current with respect to the value demanded. Step changes of both voltage and current cannot be produced by such a system and economic limits must also be imposed on the maximum output voltage required. This implies that an optimum choice of ramp rate must include these considerations and also that no discontinuities in ramp rate can be allowed. Furthermore, the desire to incorporate on-line magnetic and beam feedback at a suitable rate adds a further set of limits.

In view of the above, the design of the reference generation and regulation system in each power converter must also be optimised to ensure that no additional sources of discontinuities, overshoots or following errors are significant. In order to address these issues, a digital approach has been adopted [4]. These methods can generate smooth ramping functions as opposed to the traditional straight line segment method, and can ensure that resolution, overshoot and following errors will be less than one part per million of the maximum current.

4 DEFINITION OF THE RAMP SEGMENTS

The optimised LHC acceleration ramp that is proposed has been divided into four segments which are joined to the constant, injection and flat-top regions. This ramp is shown in Fig. 2. At the end of the flat-top another region comprised of six segments brings the field down to injection value. These latter segments along with 'degaussing' and pre-injection porches are not the subject of this paper and will not be mentioned further. Each of the segments has been chosen such that the criteria outlined above are met and in addition are joined together such that no discontinuity occurs. This optimisation process is essentially iterative and the rates chosen are determined largely from field harmonic results obtained during testing of prototype LHC dipoles. However, care has been taken to ensure that all power converter specifications of maximum output voltage and slew rate etc. are adequate to allow the needed corrections to take place well within the performance limits of each converter.

The first segment has a ***parabolic function:*** $I = I_{inj} \cdot (1 + \alpha \cdot t^2)$ from injection current to the end of the segment. The rate of acceleration for this segment is presently constant at $9 \cdot 10^{-3}$ A/s^2 (that is ~ 0.75 ppm/s^2) which gives a total time to traverse the “snap back” region of approximately 67 seconds, thus allowing corrections to be applied.

The second segment follows an ***exponential function***: $I = I_0 \cdot e^{\beta \cdot t}$. The reason to change to an exponential is that the magnitude of sextupole (b_3) and other terms is bound to a constant value as long as such a function is applied. This would also reduce the ramp time by one minute.

The third segment is ***linear*** and corresponds to the design rate of 10A/s. This segment continues to just before the flat top is reached.

The fourth segment is also a ***parabolic*** function, but which now decelerates to zero. The deceleration rate is chosen here to ensure that no power converter limit is exceeded, and in particular that absolutely no overshoot of the current can occur. All segments join together at the same acceleration rate to ensure no discontinuities.

The entire acceleration curve can therefore be defined by the mathematical expressions for each segment and by the desired and permitted rates of change. From a given injection current, just four numbers need to be input to the digital function generator to produce the entire LHC acceleration current ramp. The ramp is started with a synchronising pulse and every millisecond the function generator evaluates the ramp equations to determine the precise current required. The ramp algorithm determines precisely the points of transfer from one function to the next, such that no abrupt change of rate occurs. The digital regulation system employed in the prototype power converter control equipment then ensures that the actual current is accurate to approximately 1ppm of full-scale current.

5 PRELIMINARY RESULTS

The prototype digital controller was programmed in C to generate an LHC ramp based on the segment equations described above. The controller period is 1ms. Figure 3 shows the measurement of the current in a 10m superconducting dipole during a short LHC ramp.

The current was limited to 5kA, however, all the segments are included.

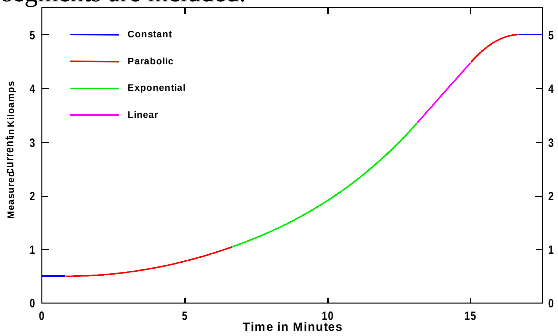

Figure 3: Measured current ramp to 5kA on 10m dipole.

Figure 4 shows an expanded view of the beginning of the ramp where it can be seen that the resolution and errors are less than 1ppm.

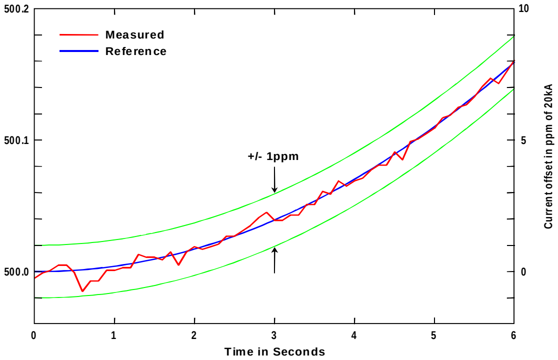

Figure 4: Detail of the start of ramp from figure 3.

6 CONCLUSIONS

An optimised shape for the LHC acceleration ramp has been developed, based on the constraints of field quality, time minimisation and practical power converter limits as well as on-line feedback considerations. This complex curve has been implemented in a prototype power converter system and has shown that the expected result can be obtained. The fact that this curve is mathematically defined considerably simplifies implementation and subsequent magnetic testing methods. Magnetic measurements will now proceed in order to further prove and refine the ramp function.

REFERENCES

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