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Accelerator Technology division, CERN, Geneva, Switzerland

Abstract

Key information for determination of fundamental design features of magnet powering and protection circuits can be retrieved from the results of transmission line calculations of the superconducting magnet chains in a particle accelerator. Modelling and simulation of the behaviour of long magnet strings provide important data for the expected electrical behaviour and performances under all operating conditions. The presented results of a transmission line study concerns the sixteen superconducting main quadrupole chains QF/QD of CERN's future LHC collider. The paper details the elaboration of the synthesized electrical model of the individual quadrupoles and the associated lumped transmission line. It presents results on the current ripple for a given converter voltage output characteristics, the magnet excitation, leakage and earth currents during the ramping procedure, the impedance resonance spectrum and the need for individual magnet damping and the propagation, reflection, superposition and damping of the voltage waves generated during activation of the energy extraction switches.

I. Introduction

The interest and potential of considering a chain of electrically series-connected magnets as a lumped transmission line and applying the method of passive impedance synthesis as a tool for analyzing the behaviour of the chain, originally applied at FNAL about 12 years ago, has significantly increased with the introduction of superconducting magnet technology for the bending, focusing and correction of the beams in particle accelerators. For conventional ('warm') magnet chains such transmission line considerations provide important input for

- determination of the complete impedance variation and its resonances, which are important for the operation of the machine,
- evaluation of the low-frequency tune modulation, originating from the ripple of the current source and contributing to a reduction in the dynamic aperture of the machine in presence of non-linear fields,
- quantitative estimation of the leakage currents during current ramping in the machine, affecting the tracking of the ideal current throughout the string.

In case of a superconducting magnet chain, due to the absence of longitudinal damping, a complement of other features of fundamental interest can be retrieved.

This concerns

- determination of the propagation / reflection / superposition / damping of the voltage waves originating from the opening of the energy extraction switches, which are needed for a safe and rapid de-excitation of the string, and

- evaluation of the need for additional, individual damping of each magnet.

For both the 'warm' and the cryo magnet chains the transmission line approach further enables an evaluation of various power circuit topologies and operational procedures.

The developed method can be applied as soon as the first of the identical magnets of the chain is available and has been subjected to a transfer function analysis.

II. The synthesis methodology

The approach is based on measurements of the amplitude and phase response of one magnet in the appropriate frequency range. In order to obtain a valid, synthesized, equivalent electrical model, containing only the passive elements R, L and C, it is necessary to merge the results of two transfer function measurements (TFA): one of the coil circuit (floating measurement) and one of the coil to ground. When the object is a superconducting magnet and if the model shall be valid for very low frequencies, it is necessary to compensate for the lack of information in the sub-Hertz region, where TFA measurements cannot be performed with the usual programmable frequency generators. Due to the presence of eddy currents in the superconducting strands the pure DC inductance of the coil is only valid up to some mHz. The DC inductance is obtained from energy measurements made during slow ramping of the magnet. With these input data the developed model is valid in the band 10 mHz-50 kHz. However, for most phenomena, related to the circuits of a particle collider, this sub-Hertz region is of little interest and was not considered for the quadrupole circuits described here.

The methodology, developed and used by the authors to evaluate the properties of the LHC Main Dipole chains, is described in details in an earlier PPC conference paper [1], including earlier references to this topic. The originally used trial and error method was replaced by a systematic tracking for poles and zeros of Laplace expressions, which match the measured amplitude and phase relations. After each step in this iteration process, the result is probed with the TFA measurements by a MatlabTM routine, written for the purpose. The process is stopped when a satisfactory fit is achieved, with errors not exceeding 0.3 dB in amplitude and 2 degrees in angle, typically obtained with 5-6 zeros and poles. Further refinement is useless for the present application.

The Laplace expression is then decomposed into continued impedance fractions from which the values and

interconnection of the R/L/C type of components can be directly deducted. If requested, negative component values can be eliminated by applying another developed Matlab™ algorithm, which provides a further decomposition in residues of the impedance fraction and searches the combinations, which can be synthesized without giving negative component values.

III. The LHC Main Quadrupole Chains

The lattice quadrupoles in the LHC arc are twin-aperture magnets for two separate beams. The magnets operate at 1.9 K and are the principle element of the so-called ‘Short-Straight-Sections’ (SSS), present in every magnetic cell of the machine. The coils of the one aperture belongs to one power circuit (QF), the coils of the other aperture belongs to a second circuit (QD). In the LHC will be installed 16 such circuits, with a total of 392 arc quadrupoles. Half of the circuits will have 47 series-connected quadrupole apertures, the other half will have 51 series-connected apertures. The magnetic and geometric data of the quadrupole magnet are shown in table 1.

Parameter	Value / Unit
Peak field in coil	6.86 T
Integrated gradient	690 T
Rated current (7 TeV)	11870 A
Current at beam injection into the LHC (450 GeV)	763 A
Max current rating	13000 A
DC Inductance per magnet	11.2 mH
Stored energy per aperture at rated current	395 kJ
Mass of cold mass	6.5 tons
Overall length of cold mass	6480 mm

Table 1. LHC Main Quadrupole parameters

Figure 1 shows the prototype quadrupole, mounted in the experimental test string (LHC String II), constituting two complete half-cells of the machine arc and used for a validation program for a large variety of machine components. It is also this magnet, which was used for the transfer function analysis.

IV. Transfer Function Measurements and Modelling

With the coils of one quadrupole magnet disconnected from the power supply, the two apertures series-connected. The modelling of an equivalent R/L/C circuit followed the method of tracking and continued fraction decomposition, described in § II. Refinement of the Bode-fit algorithm

Fig. 1. One of the two main Quadrupole magnets (mid-picture) of the LHC/String II experiment, interconnected between LHC main dipoles (front and rear).

and floating with respect to ground and the complete cold mass cooled to 1.9 K, the open- and closed circuit impedances were measured with a TFA analyser, capable of covering the range 1Hz – 50 kHz, using the recently automated measuring and data acquisition system (program Promit). A subset of results is shown in table 2.

Freq. Hz	Coil Impedance		Impedance to ground	
	Amplitude dB	Phase Degrees	Amplitude dB	Phase Degrees
1	-25.8	89	104.7	-42.2
10	-6.2	86.3	88.6	-76.8
100	12.64	82.5	71.3	-77.8
1'000	30.67	79.1	53.6	-80.9
10'000	51.35	-19.6	40.5	-44.0
50'000	34.31	-68.1	27.7	-73.9

Table 2. Subset of values from impedance measurements, two apertures in series.

could be stopped at a 5-pole, 4-zero approximation. The resulting model for a single quadrupole aperture is shown in fig. 2. The herewith-calculated complex impedance relations of two, series-connected aperture models are shown in figure 3. The excellent correlation between measurements and model-based calculations can be seen by comparison with table 2 for the selected frequencies.

Fig. 2. Synthesized electrical model for one aperture.

Fig. 3. Closed and open circuit impedance of two apertures.

The capacitance to ground of each aperture is 307 nF. There is full agreement between measured and calculated values.

V. Properties of the LHC Quadrupole Chains

A. The Impedance Spectrum

The power circuit, consisting of 51 series-connected apertures, was prepared for input to the SABER[®] simulator, which has been the basic simulating tool for circuit calculations. The modelled power circuit contains approximately 1'000 components.

The resulting amplitude and phase diagrams of the load impedance of the 51 apertures are shown in fig. 4.

Fig. 4. Complete load impedance of quadrupole chain.

Shown is also the effect of 20 Ω additional damping (see § V).

Considered as a lumped transmission line, the basic data of the quadrupole string are:

- The characteristic impedance

$$Z_C = (L / C)^{1/2} = 115.3 \Omega$$

- The propagation delay in the chain

$$t_{prop} = 51 (L * C)^{1/2} = 1.80 \text{ ms} \text{ (35.4 } \mu\text{s per aperture)}$$

-The fundamental mode of oscillation in the chain is

$$f_{Fund} = (4 * 1.80 \text{ ms})^{-1} = 139 \text{ Hz and multiples.}$$

It can be concluded that the chain approximately behaves like an inductance of $51 * 4.082 \text{ mH} = 208 \text{ mH}$ from 1 Hz to 100 Hz, like a resistor of 115Ω from 100 Hz to approximately 5 kHz and as a capacitor above 5 kHz.

B. Ripple behaviour

From the above considerations, the current ripple behaviour of the complete chain can be calculated as follows:

1. In the frequency range [1 Hz; 100 Hz]:

$$I_{p-p} = V_{p-p} / (0.208 * \omega)$$

2. For higher frequencies:

$$I_{p-p} = V_{p-p} / 115 \text{ (= 9 mA/V)}$$

C. Current Ramping in the LHC

In the LHC machine the quadrupole chain will be energized at 763 A DC for the injection of 450 GeV protons into its two rings. The acceleration to higher beam momenta (max 7 TeV per beam) requires ramping of the magnet excitation current. The corresponding voltage application is tailored to provide a smooth start and end of the ramp (a parabolic/exponential/linear/parabolic shape is applied across the string of quads, with the linear part at 10 A/s, giving a total ramping time of typically 1200 s). This will lead to capacitive and resistive leakage currents, which will return to the circuit through the 100 Ω grounding resistor. The chain model and SABER[®] were used to calculate the total leakage current to ground and the current deviation as function of frequency and location in the chain. Simulation circuit and results are displayed in figs. 5 and 6.

Fig. 5. Worst case current error at the end of the quadrupole chain. Error defined as difference between the measured current (DCCT) and the actual excitation current of the considered magnet.

Fig. 6. Total leakage current through the 100 Ω earthing resistor as function of frequency.

During LHC ramping the typical leakage current is 1 $\mu\text{A/A}$ of current in the string.

D. Damping of the individual Quadrupole Apertures

Additional damping of the individual, superconducting elements in a magnet string is applied for at least three reasons: A suitable damping will strongly attenuate the voltage oscillations after opening of the switches of the energy extraction systems for rapid and safe de-excitation of the chain, it will smoothen the impedance spectrum and herewith increase the attenuation of low-voltage perturbations and, finally, it will protect the cold by-pass diode against damage from transient voltages during electrical tests. Damping can be achieved with either a RC snubber circuit or with an Ohmic resistance alone. A capacitor will eliminate the DC leakage component during ramping, but as a low capacitance will cause additional oscillations, reducing the effect of the damping resistor, the necessary capacitor becomes difficult to install because of its physical size. As the ramping voltage for the complete quadrupole chain is only a few Volts, the leakage current without snubber capacitor will amount to a few ppm at injection current. Consequently, damping is provided with a resistor alone.

Quantitative evaluation of the impact of damping on the above three phenomena were conducted with both SABER[®] and PSPICE[®]. A satisfactory solution was found with the resistor ratings of table 3.

Parameter	Value / Unit
Resistance value	20 Ω $\pm$ 2.5 %
Residual self inductance	< 50 nH
Continuous power rating	< 10 mW
Peak power, 1 ms	2000 W
Max. short-term energy deposition	0.5 J, 1 ms
Long-term energy deposition	40 J, 200 s
Max. voltage across terminals	200 V

Table 3. Damping resistor requirements for one aperture of the LHC main quadrupole magnet.

The smoothing effect of the 20 Ω damping resistor on the total chain impedance is shown on fig. 4.

E. Transient oscillations

Upon opening of the energy extraction switches, the quadrupole chain will be subjected to their worst-case dielectric stresses. With an extraction resistance of 7.7 m Ω the steady-state peak voltage to ground is 100 V (earthing of one converter terminal), occurring at the beginning of the current decay ($\tau \approx 40$ s). The voltage may locally exceed the steady-state value and without additional damping the voltage oscillations will first be eliminated after 5-6 passages of the reflected waves. Fig. 8 shows the significant damping achieved with 20 Ω , for magnets no. 10 and 26 (mid) in the chain.

Fig. 7. Damped and un-damped oscillations due to opening of the extraction switches.

VI. CONCLUSION

The complete set of software tools, developed by the AT/MEL group at CERN for all phases of data taking, modelling and simulations of magnet chains was successfully used for the LHC quadrupole strings. The results are conclusive and have been used for component rating and selection of topologies.

VII. ACKNOWLEDGEMENTS

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VIII. REFERENCES

- [1] F. Bourgeois and K. Dahlerup-Petersen, Methods and Results of Modelling and Transmission-line Calculations of the Superconducting Dipole Chains of CERN's LHC Collider, PPC- June 2001.