Analysis of Short-Circuit Transients in the LHC Main Dipole Circuit and Development of an Automated Analysis Algorithm

Bachelor Thesis

Akrivi Liakopoulou

Supervisors:
Prof. Dr. J. Schmitz, University of Twente
Dr. Ir. C. Salm, University of Twente
Dr. E. Ravaioli, CERN

Geneva, Switzerland
March 2019
CONTENTS

List Of Abbreviations

Abstract

1 Introduction 1
   1.1 Project Introduction and Motivation 1
   1.1.1 Research Questions 2
   1.1.2 Thesis Structure 3

2 LHC Main Dipole Circuit Modeling 4
   2.1 Introduction to the LHC Main Dipole Circuit 4
   2.2 Superconducting Magnets and Quench 5
   2.3 Modeling the LHC Main Dipole Circuit 7
      2.3.1 Modeling Background 7
      2.3.2 Equivalent Model of the LHC Main Dipole Circuit and Magnets 8
      2.3.3 Circuit Behaviour Following Fast Power Abort 9

3 Worst-Case Analysis Of Short-Circuit Transients 14
   3.1 Modelling Short Circuit to Ground 14
      3.1.1 Circuit Behaviour Following Single Short Circuit to Ground 16
   3.2 Modeling Circuit Fuse Blow-Up Behaviour 19
   3.3 Fuse Parametric Analysis and Identification of Worst-Cases 24

4 Short Circuit Algorithm 32
# LIST OF ABBREVIATIONS

<table>
<thead>
<tr>
<th>Notation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALICE</td>
<td>A Large Ion Collider Experiment.</td>
</tr>
<tr>
<td>ATLAS</td>
<td>A Toroidal LHC ApparatuS.</td>
</tr>
<tr>
<td>CERN</td>
<td>Conseil Européen pour la Recherche Nucléaire.</td>
</tr>
<tr>
<td>CMS</td>
<td>Compact Muon Solenoid.</td>
</tr>
<tr>
<td>EE</td>
<td>Energy Extraction.</td>
</tr>
<tr>
<td>EE1</td>
<td>Energy Extraction 1.</td>
</tr>
<tr>
<td>EE2</td>
<td>Energy Extraction 2.</td>
</tr>
<tr>
<td>FPA</td>
<td>Fast Power Abort.</td>
</tr>
<tr>
<td>LHC</td>
<td>Large Hadron Collider.</td>
</tr>
<tr>
<td>LHCb</td>
<td>Large Hadron Collider-beauty.</td>
</tr>
<tr>
<td>STEAM</td>
<td>Simulation of Transient Effects in Accelerator Magnets.</td>
</tr>
<tr>
<td>TE-MPE-PE</td>
<td>Technology-Machine Protection and Electrical Integrity-Performance Evaluation.</td>
</tr>
</tbody>
</table>
Abstract

The Large Hadron Collider (LHC) spreads over a total distance of 26.7 km and comprises 8 sectors. In each sector there is one main dipole circuit, where 154 superconducting dipole magnets are connected in series. Since 2007, there have been 19 occurrences of short-to-ground faults in the superconducting LHC main dipole circuits, making their analysis and understanding necessary for the efficient operation of the accelerator.

In the case a short to ground event occurs, the short current that flows through the resistor to ground also flows through a fuse that is present in the grounding subcircuit. After the occurrence and detection of a short to ground, a fast power abort is triggered and the current in the circuit starts decaying semi-exponentially from a maximum value of 11.85 kA to zero, with a time constant of about 103 s. In the case a short to ground occurs, the current flows through the fuse that is present in the grounding subcircuit. Depending on the value of its thermal load, the fuse first enters a pre-arcing region where it starts intermittently blowing up, until the blow-up threshold is reached, after which the fuse stays definitively blown. A simulation scheme utilising a common interface between PSpice and MATLAB is proposed in order to simulate the blow-up behaviour of the fuse and hence to increase the accuracy of the circuit model. A parametric analysis of the short to ground parameters is performed and a better understanding of the circuit’s behaviour under different conditions is obtained. The worst-case values of the voltage to ground in the LHC main dipole circuit are identified for the case where the intermittent behaviour of the fuse is included in the model and a comparison is given with the values obtained when the behaviour of the fuse is not modelled.

The appearance of a fault in the circuit requires the immediate switch-off of the machine, so that experts can visit the site and resolve it. Due to the large circumference of the LHC, searching for the fault’s position without any prior knowledge requires a large amount of time, increasing the need of a more automated solution able to provide information on the short circuit.

With a better understanding of the circuit behaviour after the occurrence of a short to ground event stemming from the first part of the thesis, an equivalent circuit of the LHC main dipole circuit for short transients, that can be solved analytically, is derived. An algorithm is proposed to take advantage of the reduced time needed to solve the system analytically, when compared to a numerical approach. The algorithm is able to provide information regarding the short location, as well as identify the range of values in which the short resistance belongs. This greatly reduces the time needed by an expert to analyse a short-circuit event in the LHC main dipole circuit. The algorithm is tested using measured data from a real short-circuit event. Due to the fact that the simplified circuit model consists only of inductive and resistive elements, the algorithm is flexible and can also be applied to different accelerator magnet circuits.
CHAPTER 1

INTRODUCTION

1.1 Project Introduction and Motivation

CERN, the European Organization for Nuclear Research, operates since 1954 in Geneva. Alongside a plethora of contributions to science, the organization is also responsible for building and operating multiple accelerators, with the LHC reserving the title of the world’s largest machine and particle collider [1].

As is the case in all electrical systems, abnormal conditions commonly characterized as faults disturb the normal operation of the system and can cause damage to its electrical sub-parts. In the case of the LHC circuits, which include highly expensive superconducting magnets and store energy in the range of GJ [2], electrical faults can put equipment at risk or cause a temporary shutdown of the accelerator, until all problems have been resolved. Hence, it goes without saying that it is of utmost importance to ensure the protection of a machine operating under such high ratings as the LHC.

Despite a large amount of research preceding the initial startup of the accelerator in 2008, there have been in total 19 occurrences of earth failures in the LHC main dipole circuit. Mentioning the incident of 2008 at this point, can help clearly outline the effects of the appearance of a fault in the circuit. The specified fault occurred during the ramp-up of the main dipole circuit of the LHC in Sector 34 with the cause identified as the appearance of a resistive region in the electrical bus between a dipole and quadrupole magnet [3], that was not detected in time. The electrical arc that appeared, punctured the helium enclosure, which then started spreading to the insulation vacuum of the cryostat. This finally resulted in a pressure rise which in turn caused significant displacements of the magnet interconnections, as shown in figure 1.1. After a thorough investigation, the substitution of 29 superconducting magnets from the tunnel was deemed necessary [4].

With the installation of various sensors and specialized equipment in certain areas of the circuit, constant monitoring can be achieved during the LHC active operation periods. Hence, in case a fault occurs in the circuit, it will be identified quickly and the
1.1. PROJECT INTRODUCTION AND MOTIVATION

Figure 1.1: Visible damage on an LHC magnet interconnection after the occurrence of the 2008 incident [4].

protection systems will be triggered so that its effect can be confined. Following the event, if necessary, a team will visit the tunnel in order to perform potential equipment replacements, which implies that certain information about the fault, such as its position along the magnet chain, needs to be known. The process of obtaining information about the fault currently requires accessing the measured data of the time window that includes the time the fault occurred from a database, followed by thorough analysis so that conclusions can be drawn regarding the incident. Therefore, it becomes obvious that experts with knowledge of the LHC circuit and its behaviour need to perform the required analysis of the measured signals in order to provide more information about the event. It is hence clear that with a fault in the circuit, several working hours can be dedicated before useful conclusions can be drawn.

1.1.1 Research Questions

The main objectives of this thesis is to analyse the transients following the occurrence of a single short circuit to ground in the LHC main dipole circuit, assess worst cases and develop an algorithm that can be used to automate the process of providing fault information. The goal of the algorithm will be to draw conclusions regarding the fault significantly faster, compared to the time that an expert would require when using existing circuit models and numerical simulations. While working towards a solution, it is essential to obtain a better understanding of the circuit behaviour after the occurrence of the short to ground and hence a method to model more accurately the blow-up behaviour of the fuse in the circuit is investigated and presented. The research questions to be addressed are summarized below.

1. What worst cases can be identified when a single short appears in the circuit? Can the model of the LHC be improved by including the blow up behaviour of the fuse present in the circuit’s earthing point?
2. How much can the electrical equivalent circuit model of the LHC main dipole circuit be simplified, while still providing useful information about the circuit behaviour during a fault?

3. Is it possible to construct an algorithm to provide information concerning a fault that occurred in the LHC main dipole circuit faster than a mediating expert working with numerical simulations? What level of confidence does such an algorithm have?

1.1.2 Thesis Structure

Although this work aims to answer more than one research questions, the fact that they are closely related allows for results drawn in the first part of the thesis to be used in later sections. The structure implemented in the thesis is outlined next. The first part focuses on how the circuit behaves under the occurrence of a fault, while in the second part the steps taken towards automating the procedure of providing information on a potential fault, as well as the proposed algorithm, are presented. More specifically:

In chapter 2, a general introduction to the LHC main dipole circuit is given and the design choices for the main dipole equivalent model are briefly discussed. This aims to get readers without previous knowledge of the LHC main dipole circuit familiar with the various models and circuit components analyzed in the thesis, making hence the results accessible to a wider audience.

In chapter 3, the chosen method for modeling a short to ground, as well as a simulation scheme that models the blow-up behaviour of the circuit fuse are outlined. The simulation results for different parameters of the short are also presented and discussed. From the simulation data, the worst cases in terms of the peak voltage to ground achieved in the LHC main dipole circuit, are identified and the conditions under which they occur are outlined.

In chapter 4, the schematic of the LHC main dipole circuit is reduced to an equivalent, that models the behaviour of the circuit when a short to ground has occurred. An algorithm is proposed which is based on the analytical solution of the circuit. It can provide information on a single short to ground that occurred, starting from the measured data of the event. The accuracy of the algorithm is tested using measured signals from the event of December 8th 2016, when a single short to ground occurred in the circuit. Results and further applications are also discussed.


2.1 Introduction to the LHC Main Dipole Circuit

The LHC accelerator located at CERN has a perimeter of about 27 km and is the largest particle accelerator in the world crossing the border of two countries, namely France and Switzerland. Experiments are being carried out in the institute with the goal of gaining a better understanding of particle physics and the universe. A visual representation of the accelerator is shown in figure 2.1, where special attention can be drawn to its eight sectors, with names ranging from Sector 12 to Sector 81.

![Figure 2.1: Graphical representation of the LHC layout [5].](image)

One of the main purposes of the accelerator is to allow particle beams to circulate in a stable orbit, by keeping the particles’ trajectory well defined and aligned with high
levels of precision. It is also responsible for colliding the two particle beams and detecting secondary particles after the collisions. Since the beam is charged, it is essential to have control over it, so that damage to the magnets is avoided and the points where the collisions are allowed to happen remain well defined. A total of about 6000 magnets are necessary for the operation of the accelerator. Among them 1232 are main dipole or main bending magnets (MB), which take up more than 2/3 of the accelerator’s tunnel, 392 are main quadropole magnets, with the rest being other magnet types such as insertion quadropole magnets and corrector magnets.

Each proton beam circulating in the accelerator reaches a maximum energy of $3.5 \text{ TeV}$ and collisions take place at twice this energy level for approximately 10 hours. Figure 2.1 also includes the four largest experiments located along the circumference of the accelerator, namely ATLAS, ALICE, CMS and LHCb. These are the locations of the caverns containing either general purpose or specialised detectors, which aim to collect information from the particle collisions that occur at those points [6].

2.2 Superconducting Magnets and Quench

Following the laws of electromagnetism for the trajectory of the beam, the boundaries of the circumference where a beam can circulate under the existence of a constant magnetic field are defined by its energy as well as the strength of the magnetic field. The two variables are proportional and their relationship can be written as $E \propto Br$, where $E$ is the collision energy, $B$ the dipole magnetic field and $r$, the radius of the accelerator. Under the existence of a constant magnetic field, this means that in order for the beam energy to reach higher values, the circumference of the accelerator would also have to be increased. Since this is not possible due to the fixed size of the tunnel where the accelerator is located at, it follows that the desired energy value can only be reached by increasing the strength of the magnetic field. A way to achieve this is to increase the value of the current through the magnets. In order to ensure magnet compactness, while keeping at the same time operating costs to a minimum, the phenomenon of superconductivity can be exploited. Materials that are superconductive at cryogenic temperatures, allow current to flow through them without any resistance and hence dissipate no energy [7].

This is therefore the reason why some of the LHC ordinary electromagnets have been replaced by superconducting ones of different types, depending on their role and position in the accelerator. A large amount of studies exist on the development of the superconducting magnets and an extensive analysis of all the design choices is presented in the LHC Design Report [8]. For this reason, only a short reference to the main bending superconducting dipole magnets, that will be included in the simulations and models discussed in the thesis, is provided in this chapter.

The magnets consist of two apertures powered in series, which confine the space where the beams are allowed to circulate during operation. The nominal current specified during the design of the magnets is equal to $11.85 \text{ kA}$, while the nominal field at the bore reaches a value of $8.3 \text{ T}$. The two apertures are surrounded by a non-magnetic collar
made of stainless steel, capable of handling the stress and forces acting on the coil during operation, while maintaining the desired coil geometry. The iron yoke surrounds the two apertures as well as the collar and aims to achieve magnetic shielding by reducing the value of the magnetic field beyond a certain distance from the magnet’s aperture. A six block geometry is chosen for the construction of the dipole coils, consisting of layers further split into blocks of conductors [9]. From a construction perspective, each of the 1232 main dipole magnets of the LHC main dipole circuit has a curvature of $\approx 9$ mm so that when placed in series, the circular shape of the accelerator can be achieved. These superconducting magnets are made of $NbTi$ strands arranged in a Rutherford cable [10]. $NbTi$, a type II superconductor, has a critical temperature of 9.2 K, meaning that it loses all its electrical resistance when cooled down to temperatures below this value. Through the cryogenic system installed in the circuit, liquid helium can be cooled down to temperatures of 1.9 K, where its superfluid properties occur and hence sufficient margin is achieved with respect to the normal state [11]. The main magnet parameters are presented in table 2.1 and a complete analysis of the design is outlined in [8].

A quench is defined as the abrupt loss of the superconducting state in a region of the coil. With a specific part of the coil switching to the normal state, and current in the order of kA flowing through it, the stored energy converted into heat can cause damage if the quench is not detected in time. For this reason, a large amount of research has been dedicated to the design of quench protection systems [12, 13], with the quench heaters and cold by-pass diodes being the two choices currently installed in the main dipole circuit. Additionally, a quench detection system $QDS$ consisting of two subsystems, namely $iQPS$ and $nQPS$, is in place in order to detect the occurrence of a quench in the main dipole circuit. These systems are triggered when the values of the signals they monitor exceed a certain threshold, with the former monitoring the differential aperture voltage of the magnets and the latter the voltage over each magnet [14]. The collection and storing of the signals from the two systems is organised by the Post-Mortem system [15], from where signals with specified timestamps can be queried. These systems do not save the signal values in the database continuously, but only after they have been triggered and only for the magnets that quenched.

To better understand the behaviour of a magnet during a quench, the measured voltage

### Table 2.1: Parameters of LHC Main Dipole Magnet [8].

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal field (7 TeV beam energy)</td>
<td>8.33</td>
<td>T</td>
</tr>
<tr>
<td>Current at nominal field</td>
<td>11850</td>
<td>A</td>
</tr>
<tr>
<td>Inductance at nominal field</td>
<td>$98.7 \times 10^{-3}$</td>
<td>H</td>
</tr>
<tr>
<td>Stored energy at nominal field (both apertures)</td>
<td>6.93</td>
<td>MJ</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>1.9</td>
<td>K</td>
</tr>
<tr>
<td>Cold mass length</td>
<td>15.18</td>
<td>m</td>
</tr>
<tr>
<td>Total mass</td>
<td>27.5</td>
<td>t</td>
</tr>
</tbody>
</table>
CHAPTER 2. LHC MAIN DIPOLE CIRCUIT MODELING

Figure 2.2: Measured voltage over magnet B13L4 showing the superconducting magnet’s quenching behaviour. First a short to ground occurs around 1.54 s with the quench following at the time of about 1.58 s. The voltage first reaches a value of 6 V which then decays to 1.2 V in about 40 ms, due to the diode’s thermal behaviour [16].

over a selected magnet \textit{B13L4} during the quenching state is queried from Post-Mortem and presented in figure 2.2. For the specific signal, first a short to ground occurs at a time of about 1.54 s, which causes an abrupt change of the magnet’s voltage from its previous value of about \(-11 \text{ V}\), which was obtained during the ramp up of the circuit current. In the circuit, a diode is connected in parallel to every magnet, which in the case of a quench allows for the magnet to be bypassed as current flows through the diode instead. This behaviour can be seen in the measured signal around 1.6 s where the voltage peaks at a value of approximately 6 V, which is equal to the voltage drop of the diode. Attention should be drawn to the fact that the voltage will then drop and obtain a steady value at approximately 1.2 V, an effect that is caused by the thermal effect of the diode, whose temperature increases as current flows through it. Although a quench follows the appearance of a short in this case, this is not a necessary condition, as one can happen at any time. In case such an event occurs, the circulation of the beam is immediately interrupted and the accelerator shuts down for a couple of hours. Despite all that, as long as a quench is detected in time and the protection systems are activated, it should not be considered dangerous, but rather a part of a magnet’s lifecycle.

2.3 Modeling the LHC Main Dipole Circuit

2.3.1 Modeling Background

The work presented in this thesis has been performed during a period of 10 weeks as part of the STEAM [17] collaboration of the TE-MPE-PE group [18] at CERN. Due to the complexity and the size of the LHC main dipole circuit, the modeling configurations regarding the main dipole magnets of the circuit have been drawn from previous work mentioned in [19] and [20]. The choices regarding the short to ground and fuse modeling presented in the next sections, build on top of the netlist models of the main dipole circuit
2.3. MODELING THE LHC MAIN DIPOLE CIRCUIT

![Electrical schematic of the LHC main dipole circuit](image)

Figure 2.3: Electrical schematic of the LHC main dipole circuit [19]. Added in red: 1) a single short to ground appearing in magnet 77 2) the fuse resistor in the grounding lines.

developed by the STEAM team. In terms of tools, the STEAM PSpice Manager tool package is used to solve the netlist models and parse the resulting simulated signals from the PSpice output .csd file to the MATLAB workspace for post-processing. The package also contains the STEAM Stimulus Generator, which allows the creation of stimuli starting from CSV files, that can be used as PWL inputs of various components in the netlist models.

2.3.2 Equivalent Model of the LHC Main Dipole Circuit and Magnets

Each of the eight LHC main dipole circuits contain 154 superconducting magnets connected in series to the power converter. The equivalent model of the circuit, developed with PSpice, is presented in figure 2.3 and the modeling choices are thoroughly explained in [19]. In the figure, a single short to ground, as well as the fuse connected in the ground lines, are included in red. These are the two additions to the model that will be discussed in more detail in the next chapter of the thesis.

In the schematic, the superconducting dipole magnets are represented by inductors connected in parallel to a bypass diode. However, in order to accurately model their nonlinear behaviour during transients, the more detailed model of figure 2.4 is introduced [19]. In the model, the subcircuits of the two apertures $A_p^1$ and $A_p^2$ are connected in series, with a resistor $R_p$ and the bypass diode connected in parallel. The inductance of the apertures is represented by $L$, while the capacitors $C$ model the coil to ground parasitic capacitance. The inclusion of the factor $k$ in the inductance values, as well as resistances $R_1, R_2$, achieve modeling of the induced eddy current effects. Table 2.2 provides a quick reference to the values of the above mentioned parameters, that have been calibrated in order to achieve the best match with the measured behaviour of the magnets [19].

When a short to ground occurs in the circuit, a low resistance path appears between the dipole magnet and ground. In figure 2.3, this is represented by resistor $R_{short}$. The main dipole circuit is connected to ground through the grounding system, where the fuse is also found. In its simplified form, the resistor $R_{fuse}$ can be seen connected between the middle point of the energy extraction resistor $R_{EE2}$ and ground. For both the short
Figure 2.4: Circuit equivalent model of a LHC main dipole magnet [19].

Table 2.2: Parameters of Main Dipole Magnet Model.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>L</td>
<td>$49 \times 10^{-3}$</td>
<td>H</td>
</tr>
<tr>
<td>$R_p$</td>
<td>100</td>
<td>Ω</td>
</tr>
<tr>
<td>C</td>
<td>$150 \times 10^{-9}$</td>
<td>F</td>
</tr>
<tr>
<td>k</td>
<td>0.75</td>
<td>-</td>
</tr>
<tr>
<td>$R_1, R_2$</td>
<td>∈ {7,10}</td>
<td>Ω</td>
</tr>
</tbody>
</table>

...to ground, as well as the fuse resistor, only a brief introduction is given at this point, since both concepts are analysed in detail in sections 3.1 and 3.2, respectively.

The power converter is connected in series to the sector and its main function is to increase the circuit current initially with a certain ramp rate $\frac{dI}{dt}$ up to the specified nominal current value. The existence of the crowbar in parallel to the power converter allows the current to continue circulating in the circuit after the switch-off of the former, as is the case when a Fast Power Abort is triggered. The high frequency noise of the power converter is reduced by the inclusion of a low-pass LC filter with a cutoff frequency of 31.8 Hz [19]. A second crowbar is connected in parallel to the filter, an addition that reduces the voltage waves propagating through the circuit following a power converter switch-off. After an initial period of current ramp-up, a steady state is reached for the voltage over the magnets, which is maintained under normal operation conditions.

2.3.3 Circuit Behaviour Following Fast Power Abort

In the case of extreme events occurring in the circuit, the non-linear behaviour of the various circuit elements leads to the appearance of transient effects that require thorough analysis and understanding. Common examples where these effects have been observed include Fast Power Aborts (FPA) as well as faults appearing in the circuit. During an FPA, most of the energy stored in the circuit is extracted, meaning that the current also decreases to a zero value. Although it is triggered in the case of unexpected events occurring in the circuit, including problems such as quenching magnets or related to the...
2.3. MODELING THE LHC MAIN DIPOLE CIRCUIT

![Plot of simulated power converter and circuit current. The abrupt switch-off of the power converter can be seen occurring at time $t_{FPA}$. The current in the circuit follows a semi-exponential decay to zero with a time constant of 103 s.](image)

Figure 2.5: Plot of simulated power converter and circuit current. The abrupt switch-off of the power converter can be seen occurring at time $t_{FPA}$. The current in the circuit follows a semi-exponential decay to zero with a time constant of 103 s.

Power aborts have also been triggered in past years in order to carry out special tests [21]. These tests have resulted in the acquisition of measured signal data from various sensors in the circuit, at six different current levels, namely 760 A, 2 kA, 4 kA, 6 kA, 8 kA and 10 kA, which provide a better understanding of the circuit behaviour.

To gain a better idea of the current behaviour during the initial ramp-up, the plot of figure 2.5 is provided, where the increase of the current from zero up to its nominal value, at which point the FPA is triggered, is shown. In the figure, two regions can be identified, namely one where the current increases quadratically and one where it increases linearly. In the quadratic region the nominal ramp rate is equal to $\frac{d^2I}{dt^2} = 0.05 \frac{A}{s^2}$, while in the linear region the current increases with a nominal rate of $\frac{dI}{dt} = 10 \frac{A}{s}$ [8]. It therefore becomes evident that the value of the current in the circuit at the time when the FPA occurs is a function of $t_{FPA}$, as well as the nominal ramp rates of both regions.

Two energy extraction (EE) systems, namely EE1 and EE2 can be seen in the circuit. Each of them is composed of a switch in parallel to a resistor of approximately 73 mΩ. When the switches open, the energy extraction resistors become part of the circuit. This happens approximately 350 ms and 600 ms after the power supply switch-off [19] for the first and second switch respectively. The circuit current is hence forced to flow through the resistors and starts decreasing roughly exponentially, as shown in the plot of figure 2.5. The time constant of the decay can be calculated as shown in equation 2.1, where $N_{mag}$ is the total number of magnets, $L_{mag}$ the inductance of a single magnet and $R_{EE}$ the value of the EE resistance [19].
A first simulation can be performed in order to better understand the behaviour of the circuit in the case that no faults have occurred. In the simulations throughout this work, \( I(t_{FPA}) \), the current value when the FPA occurs, is ramped-up to 11.5 kA. Although a slightly higher value was provided for the current at nominal field shown in table 2.1, the current loses its linear behaviour slightly before it reaches its peak value, making the value of 11.5 kA the last value where its ramp rate \( \frac{dI}{dt} \) is still equal to \( 10 \text{ A/s} \). With the chosen ramp rate, this current value is reached after 1200 s in the simulation. Choosing this current value, will therefore provide consistency with the simulations investigating the worst cases that can occur in the circuit, presented in the following chapters.

Due to the large number of magnets, simulation results need to be plotted in such a way that useful conclusions can be drawn from the figures. For this reason, color coding using the jet colormap array [22] is used for the signals in the figures of this report, so that they can be easily read even with the legend omitted. The analysis is also performed with the simulated voltages to ground plotted against two different axes both presented in figure 2.6 for the case where no failures occur in the circuit.

Starting with figure 2.6a, the voltages to ground are plotted against time. In this plot, the time when the power converter switches-off \( t_{FPA} \), as well as the moments that the EE switches open \( t_{EE1} \) and \( t_{EE2} \), become easily distinguishable, since a time window including all three of them is chosen. As can be seen in the figure, these events occur at times 1200 s, 1200.36 s and 1200.57 s, respectively. They are the main reason for the appearance of transients in the circuit, which can be observed right after the specified times and are followed by changes in the voltage to ground values and polarities of the magnets. After time \( t_{EE2} \), when both EE resistors are in series with the magnets, the current in the circuit starts its semi-exponential decay until it reaches a zero value, with the voltages to ground of all magnets also showing this decay.

In the plot of figure 2.6b, the voltage to ground values at specific times are plotted against the electrical position of the magnets in the chain. This allows to better observe the voltage distribution in the circuit and how it varies over time.

The first time chosen is at 1200 s, which allows for the voltage distribution exactly at the time when the FPA occurs to be plotted. The initial voltage to ground at magnet 1 in this case has a value of about 150 V, calculated as a function of the total circuit inductance \( N_{mag}L_{mag} \) and the initial ramp rate of the current \( \frac{dI}{dt} \). The resistance of the warm copper cables \( R_{warm} \), which precede the first magnet of the chain, also need to be taken into consideration and hence the expression from which the voltage value is found, is presented in equation 2.2. The fact that all magnets have the same inductance value, causes the voltage to be linearly distributed across the chain. A linear voltage decrease of about 1 V is observed when moving from one magnet to the next until an almost zero value is reached for the last magnet of the chain, which is connected to the grounding point of the circuit.
2.3. MODELING THE LHC MAIN DIPOLE CIRCUIT

\[ V_{PC} = R_{WARM}I + N_{mag}L_{mag} \frac{dI}{dt} \] (2.2)

The following two time points, namely 1200.40 s and 1200.78 s, are chosen after the transient effects that follow each EE switch opening have died-off, as can be seen from figure 2.6a. At the time of 1200.40 s, the first energy extraction resistor has become part of the main circuit loop. For a current value of 11.5 kA when the FPA occurs chosen for the simulation and an energy extraction resistor of about 73 mΩ, the voltage drop that occurs over the resistor is approximately equal to 800 V. Since the first energy extraction system is connected in between magnet 77 and 78, this voltage drop can be observed in the figure in the middle of the magnet chain.

Since the voltage is linearly distributed in the circuit, a voltage difference of approximately 5 V is observed between the voltage to ground values of neighbouring magnets in this case. The maximum values can be seen obtained by the magnets in electrical positions 77 and 78 and are equal to a value of \( \pm \frac{R_{EE}I}{2} \).

At the time instance of 1200.78 s, with the voltage drop occurring over both EE resistors, both magnets in positions 1 and 154, as well as 77 and 78 obtain the maximum voltage drop value previously only reached by magnets 77 and 78. The minimum values in this case are obtained by the magnets in the middle of each half chain, namely 39 and 116, since the voltage is once again distributed evenly over the magnets in the chain.

An expression for the value of the voltage drop over the EE resistors as a function of \( I(t_{FPA}) \) and the value of total EE resistance, is provided in equation 2.3 [19]. The value of the total voltage in the circuit is equally distributed over the 154 magnets making up the chain, which have the same inductance value. Thus, there is a linear increase in the value when moving from one magnet to the next, that can be calculated by dividing equation 2.3 by the total number of magnets. After both the switches have been triggered, the increase is equal to about \(-11 V\).

\[ V_{magnetChain} = -2R_{EE} \cdot I(t_{FPA}) \] (2.3)
(a) Simulated voltage to ground signals for all 154 magnets plotted as a function of time. The times when the FPA occurs and the EE switches open are also visible. All three events are followed by transients and occur within less than 1 s after the FPA. The signals are color-coded as a function of the magnet position in the chain starting with blue for the magnet in electrical position 1 and scaling up to red for the magnet in position 154.

(b) Simulated voltage to ground signals of subfigure 2.6a plotted for specific time instances as a function of the electrical position of the magnet in the main dipole chain where the voltage is measured.

Figure 2.6: Two graphical representations of simulated voltage to ground signals for all 154 magnets in the chain.
CHAPTER 3

WORST-CASE ANALYSIS OF SHORT-CIRCUIT TRANSIENTS

3.1 Modelling Short Circuit to Ground

Different types of short circuits to ground can occur in an accelerator circuit. As has been mentioned before, the LHC main dipole circuit consists of various electrical components and magnets, which implies that faults can appear in any part of the chain. However, this work will concentrate on single shorts to ground occurring in the LHC main dipole circuit during operation. Starting from the existing netlist circuit model, a method to include the short connection that can unexpectedly appear between a superconducting magnet and ground is first described.

The method chosen to achieve this is the inclusion of a voltage controlled switch in the model between the point where the short occurs and ground. More specifically with the closing of the switch, a connection between two nodes (node where the short occurs and ground) is created, which can easily change back to an open circuit when the switch opens. Due to the fact that the existence of a short circuit is from an electrical perspective equivalent to a finite value resistor establishing the connection, its resemblance to the behaviour of the voltage controlled switch becomes visible and its addition to the netlist model can hence be justified.

The component implementation is shown in figure 3.1, with the short occurring at magnet 77. The subcircuit consists of a voltage source connected to a node independent of the rest of the circuit, in this case called control, with the voltage of the source obtaining either the value of 1 or 0. Referring to the nodes of figure 2.4, the connection to ground occurs between node 1 and the ground of the magnet specified in the first line of figure 3.1. As the names of the parameters suggest, when the switch is open, it acts as an open circuit due to the resistor $R_{\text{off}}$ been set to $1\,\text{M}\Omega$, while when the switch is closed, resistor $R_{\text{on}}$ sets the fault resistance equal to $R_{\text{SHORT}}$. Another important detail
Figure 3.1: Netlist implementation of short circuit between one side of magnet 77 and ground as a voltage controlled switch.

To notice is the use of a stimulus for the voltage of the controlling voltage source, which specifies the time its voltage switches from 0 to 1. In terms of simulation, in the stimulus it is essential to specify the last time index the voltage has a value of 0 as a couple ms before the time when the switch occurs. This forces the solver to execute the switching during the in between time, avoiding hence a potential slow ramp up of the voltage that would cause the model to diverge from the circuit’s physical behaviour.

With the position and the resistance of the short to ground being the independent variables, it follows that the analysis of simulation results for different position and resistance values can provide a better understanding of the circuit behaviour. Although a finite number of possibilities exist for the position where the short can appear, its resistance can take any value in the set of real numbers. However, resistances above and below a certain value act either as an open or a short circuit, respectively and a change past those ranges has no significant effect. Hence, by choosing 5 resistance values from the in-between set, the effect of the resistance can also be understood for certain ranges instead of discrete values. The chosen resistance values are $[0.001, 1, 10, 100, 1000] \, \Omega$.

For values larger than 1000 $\Omega$, the current flowing through the short obtains a small value and hence those values can be considered an open circuit. For the main dipole circuit, it is important to mention that the short resistance is in series with the equivalent resistance of the earthing system, which is in the order of 10 $\Omega$. Hence, it is expected that resistance values lower than 1 $\Omega$ have little impact to the total equivalent resistance of the ground.

Making use of the Low-Level File I/O package in MATLAB, the value of the short position and resistance can be read and changed programmatically in the main netlist file or one of its subcircuits. This allows for an automated workflow to be developed, enabling a parametric sweep to be performed for the above mentioned input parameters. As a result, a large amount of data containing the simulation results for 154 different short positions and 5 different short resistance values, can be saved recursively in an organised way. A link to the code scripts implementing the above can be found in the repository provided in Appendix A.4.
3.1. MODELLING SHORT CIRCUIT TO GROUND

3.1.1 Circuit Behaviour Following Single Short Circuit to Ground

As an example, a simulation can be performed for a short between magnet 70 and ground, which appears at time \( t = 1202 \text{s} \). Due to the fast decay of the current in the circuit and the need to investigate the conditions leading to worst cases, the time at which the short occurs is chosen closely after the transient oscillations, caused by the opening of the EE2 switch, have died off. This hence ensures that the value of the current in the circuit has not decreased majorly from its peak value. The behaviour of the current around the time when the FPA occurs can be seen in figure 3.2. The exact value of the current at \( t = 1202 \text{s} \) when the short occurs can also be specified as being almost equal to 11.3 kA, meaning that the current has decayed by 2% of its maximum value. The results of this simulation for the voltages to ground of all the magnets in the circuit are plotted in figure 3.3a and 3.3b as a function of time and electrical magnet position, respectively.

With no change made to the simulation parameters, no variation is expected in the curves of figure 3.3b before the time that the short occurs which are plotted as dashed lines and match the ones plotted in figure 2.6b. For all time instances after \( t = 1202 \text{s} \), when the short occurred, a shift of the curve along the y axis, corresponding to a change in the voltage to ground distribution along the circuit can be observed in the curve, which brings the voltage to ground of the magnet where the short occurred close to zero. With a negligible short resistance value, the voltage to ground value is equal to zero, since a direct connection to ground is present. However, although it is true that the voltage to ground at the shorted magnet greatly decreases and obtains a minimum value when compared to the rest of the magnets, the zero value is never obtained due to the voltage drop being a function of the short resistance value, \( V_{\text{SHORT}} = R_{\text{SHORT}} I_{\text{SHORT}} \). Finally, the exponential decay of the voltages to zero can be visualised once again by plotting.
Simulated Voltage to Ground signals for all 154 magnets plotted as a function of time, with the FPA, EE1 and EE2 times specified. A short occurs in Magnet 70 at $t_{\text{SHORT}} = 1202$ s with a short resistance of $R = 1 \, \Omega$

(b) Simulated Voltage to Ground values of subfigure 3.3a plotted for specific time instances before (dashed line) and after the short, as a function of the electrical magnet position.

Figure 3.3: Two graphical representations of all 154 magnet voltage to ground signals for the case with a short appearing at Magnet 70 at $1202$ s with a resistance of $R = 1 \, \Omega$. 

17
3.1. MODELLING SHORT CIRCUIT TO GROUND

![Graph showing simulated voltages to ground for all magnets at time $t = 1208$ s with a short occurring at magnet 70 at $t = 1202$ s. The curves, short position and time the short occurs remain constant, while the value of the short resistance is varied.](image)

Figure 3.4: Simulated voltages to ground for all magnets at time $t = 1208$ s with a short occurring at magnet 70 at $t = 1202$ s. For the curves, short position and time the short occurs remain constant, while the value of the short resistance is varied.

the voltages of all magnets in the chain at a time instance of about 200 s after the short occurred, where all the magnet voltages have been reduced, following the total circuit current behaviour of figure 2.5.

From the above, the effect of varying the short resistance also becomes clear, which visually corresponds to a shift of the curve along the y axis, as seen in figure 3.4. For a short occurring at a specific magnet, the change of the short resistance relative to a previous value, determines the shift of the value of the voltage to ground at the specific magnet and consequently all of the other magnets in the chain. The effect of changes in the values of the two other independent variables, namely short position and time the short occurs, are presented in figures 3.5 and 3.6 and are discussed next.

The effect of the time when the short occurs is closely connected to the behaviour of the current in the circuit presented in figure 2.5 and its exponential decay. In figure 3.5, with the short occurring between magnet in electrical position 70 and ground with a resistance of $1 \, \Omega$, a change in the slope of the curves is caused by a variation of the time at which the short occurs. More specifically, the 3 different times that are chosen for the short to appear are 1202 s, 1247 s and 1300 s, with the voltage at the electrical magnet position plotted for $\approx 1$ s before (dotted line) and $\approx 2$ s after each time instance. As expected, for the time instances before the short, the minimum voltage to ground is achieved in the middle of each half chain, with the position shifting to magnet 70 after the short. Depending on the time instance, the point of minimum voltage to ground remains the same with the difference being a larger voltage drop that is equally distributed over the magnets for earlier times, when the current in the circuit has a higher value.

The shifting of the curve due to the voltage drop obtaining a minimum value at the magnet where the short occurs can also be used to define the worst cases that can
appear in the circuit. It can hence be said that when the short occurs between magnets in positions 1, 77, 78 or 154 and ground, the peak voltage to ground value is obtained in the circuit. It is easily seen that these magnets are at either side of the two EE resistors, while the maximum voltage to ground value is obtained by the magnet at the opposite end of the half chain, which becomes clear in the curves of figure 3.6. The equation to calculate the maximum value as a function of the current at the moment the FPA occurs $I_{FPA}$ and the value of the total EE resistance $R_{EE}$, is presented in equation 3.1.

$$V_{MAX} = I_{FPA}R_{EE}$$  \hspace{1cm} (3.1)

It is important to note that with a short occurring at the specified magnet positions, this value is twice higher than the peak voltage to ground in absence of shorts to ground presented in equation 2.3. In figure 3.6, the curves of the 4 previously mentioned short positions that obtain the maximum voltage values, are plotted. Evaluating the equation for the maximum current value of 11.85 kA in the LHC main dipole circuit and each EE resistor equal to 73.3 mΩ, it follows that the maximum voltage value that can be achieved is equal to about 870 V.

### 3.2 Modeling Circuit Fuse Blow-Up Behaviour

The series of magnets in each LHC main dipole circuit, is grounded to earth through the grounding lines connected to the middle point of resistor EE2. In its simplest form,
3.2. MODELING CIRCUIT FUSE BLOW-UP BEHAVIOUR

![Graph showing voltage to ground values for all magnets at the time instance of $t=1208$ s with a short occurring between 4 different magnet positions and ground at $t=1202$ s. The short position is varied in this case while the time the short appears and its resistance remain constant.](image)

Figure 3.6: Simulated voltage to ground values for all magnets at the time instance of $t=1208$ s with a short occurring between 4 different magnet positions and ground at $t=1202$ s. The short position is varied in this case while the time the short appears and its resistance remain constant.

the inclusion of the fuse in the model of the main dipole circuit has been shown in figure 2.3, where a resistor connected to the subcircuit model of $R_{EE2}$, was effectively in series to the path of the circuit current to ground. To be more precise, the energy extraction resistor consists of 4 resistors placed in a parallel branch configuration, where resistors $R_{EE21}$ and $R_{EE22}$ are in series and the fuse is connected between $R_{EE23}$ and $R_{EE24}$. Taking into account all the electrical components that compose the earthing point, as well as the exact connection point in resistor $R_{EE2}$, a more accurate schematic is provided in figure 3.7.

Placing a fuse in series with a specific branch of an electrical circuit ensures its protection from the circulation of currents through the branch with values above a certain threshold where the fuse has blown up. It follows hence, that depending on the state of the fuse, the grounding subcircuit of figure 3.7 obtains different resistance values. For the specific circuit, the fuse has a resistance of 1 $\Omega$, while it can be considered that it obtains an infinite value after a specified threshold is reached, where it blows up. In this case, the current can only flow through the 10 k$\Omega$ resistor to ground connected in parallel.

For the case when the fuse has not blown up, the total resistance of the grounding subcircuit is calculated from the parallel connection of the two branches having resistance values of 11 $\Omega$ and 10 k$\Omega$ respectively, which results in a total resistance of 10.99 $\Omega$. In figure 3.7, two back to back diodes can also be seen connected in parallel to the 10 $\Omega$ resistor, which start conducting after the voltage exceeds the value of 15 V. When this happens, a resistor of 33 $\Omega$ is also connected in parallel to the 10 $\Omega$ resistor, which makes the resistance of the left branch equal to 8.67 $\Omega$ and hence the total subcircuit resistance
obtains a value of 8.66 $\Omega$.

With the configuration shown in the figure, it also becomes clear that the fuse subcircuit can be considered effectively in series to the short to ground analyzed in the previous section. After the blow up of the fuse, a high resistance value is obtained by the grounding subcircuit and hence the current flowing through the short is also limited. The final expression for the equivalent resistance to ground depending on the state of the fuse is presented in (3.2).

$$R_{eq} = \begin{cases} R_{SHORT} + 10.99\Omega, & \text{if fuse not blown up \& } V_{DiodesGND} < 15V \\ R_{SHORT} + 8.66\Omega, & \text{if fuse not blown up \& } V_{DiodesGND} \geq 15V \\ R_{SHORT} + 10k\Omega, & \text{if fuse blown up} \end{cases} \tag{3.2}$$

In the datasheet of the fuse, the threshold values regarding its blow up behaviour are specified and together with its resistance value are presented in table 3.1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{FUSE}$ (If not blown up)</td>
<td>1</td>
<td>$\Omega$</td>
</tr>
<tr>
<td>Pre-arcing Threshold</td>
<td>0.23</td>
<td>A$^2$s</td>
</tr>
<tr>
<td>Blow up Threshold</td>
<td>1.2</td>
<td>A$^2$s</td>
</tr>
</tbody>
</table>

A further elaboration is needed for the threshold values and their units, since two different ones are provided. More precisely, the two values refer to the thermal thresholds of the fuse, meaning that a direct relation to the energy deposited in the fuse is drawn.
The value of the thermal load can be calculated as the time integral of the square of the fuse current over time $\int I_{FUSE}^2 dt$, measured in A$^2$s, with an initial value at $t_{SHORT}$ equal to 0. With the specified values, the fuse blows up shortly after time $t_{SHORT}$, when current starts flowing through it.

From experimental data, it has been observed that in the pre-arcing region, the fuse enters a state of uncertainty, where it intermittently blows up and recovers. After the blow up thermal limit is reached however, it can be said that the fuse acts as an open circuit, since it has blown up.

It becomes clear that in order to model the fuse blow up behaviour, the current flowing through it needs to be known so that the state of the fuse can be altered once the thermal thresholds are reached. There is currently however no component in the Spice language that can monitor the current in real time and force the fuse to change its state when a certain condition has been reached. For simulations included in past case studies, the time of the blow up was set up manually for each simulation. Therefore, in order to create a model that accurately matches the blow up behaviour of the fuse, a new method has to be developed.

Following the same logic as with the modeling of the single short to ground, the fuse resistor has to be replaced by a voltage controlled switch. The circuit parameters as well as those of the short to ground (position, resistance value) are required as user input for the simulation to begin. With these values, a first PSpice simulation for the case where the fuse never blows up is performed, from which only the signal of $I_{FUSE}$ is returned in the MATLAB workspace, so that the required computational power and time are reduced. Applying the trapezoidal rule on the signal data, the numerical integral of the square of the dataset is computed, hence obtaining the thermal load of the fuse. The point in time when the value of the blow up threshold is reached can then be found.

With the time when the lower threshold is reached known, pulses can be triggered starting from that point until the end of the simulation, occurring with a specific frequency. For the specified frequency value, the calculation of on and off times is performed by MATLAB, which also inserts them in the stimulus file of the fuse. A simulation is then run in PSpice with $I_{FUSE}$ returned to the MATLAB workspace after its end. The signal of the current through the fuse under the effect of switching pulses has now been captured and is numerically integrated in MATLAB to obtain the second threshold value. After the blow up limit of the fuse is found, the stimulus is again overwritten, with pulses starting at the pre-arcing threshold and ending when the second threshold is reached, after which the switch stays open. The final simulation is then run, with the data saved in a nested structure array indexed with the magnet position number where the fault occurred. When compared to a simulation scheme that does not include the blow-up behaviour of the fuse, the specific method increases the accuracy of the model. On the other hand, the additional simulations than need to be performed in order to obtain the current profile of the fuse, increase the overall simulation time. A flowchart summarising the steps followed in the proposed simulation scheme is presented in figure 3.8.
CHAPTER 3. WORST-CASE ANALYSIS OF SHORT-CIRCUIT TRANSIENTS

**Figure 3.8**: Block diagram of simulation scheme 3 that includes the blow-up behaviour of the fuse in the model.
3.3 Fuse Parametric Analysis and Identification of Worst-Cases

As has been mentioned previously, in order to begin the simulation including the blow-up behaviour of the fuse, the input parameters need to be set. A parametric sweep of these parameters can easily be performed by programmatically changing the values. Each simulation case is performed for all short positions in the range of [1:154] and for 5 different short resistance values with different orders of magnitude, namely [0.001, 1, 10, 100, 1000] Ω. By analysing the obtained data, several conclusions can be drawn, which will be discussed in this section.

The behaviour of the fuse current $I_{FUSE}$ over time for the simulation scheme including the fuse behaviour, is presented in figure 3.9. The current through the fuse in the case where no blow up occurs in the simulation is also included for reference in the same figure. For the case where the fuse does not blow up, the current through it will continue to increase as shown in the figure, eventually reaching a peak value of about 32 A, after which it decreases almost exponentially to zero. On the other hand, the pulses that are triggered after the pre-arcing threshold is reached, become clearly visible in the case where the fuse behaviour is included in the simulation and last for about 30 ms. It is interesting to note that the maximum amplitude of the current obtained during the intermittent blow-up behaviour of the fuse is less than the peak current value obtained in the case of no blow-up.

Proceeding with the voltage to ground plots for the case that the fuse blow up behaviour is modeled, the same two plot configuration for the visualisation of the voltages to ground at all magnet positions that has been presented previously in figures 2.6 and 3.3 for the cases when no short occurred and the fuse did not blow up is used, with the plots presented in figure 3.10. For the plots, the same parameter choices are made as in previous parts of the thesis, with the short occurring between magnet 77 and ground at time $t = 1202$ s and a short resistance of 1 Ω.

In the figure, it can be seen that the peak voltage to ground after the fuse blows up reaches an absolute magnitude of about 2000 V. As expected from previous analysis, with a short at magnet 77, the peak value is achieved by the voltage to ground signal of magnet 1. This value is obtained approximately 140 ms after the blow up threshold is reached. After the peak voltage value is reached, a slow decrease to a value of about 1950 V occurs in about 10 ms, after which the voltage starts rapidly decreasing. Drawing a comparison with figure 3.3b, this value is higher than the worst case scenario discussed previously when the fuse did not blow up and the maximum value calculated in equation 3.1.

In order to better understand the increase of the peak voltage to ground, it is helpful to look at figure 3.10b. An obvious difference is observed between the curves at time instances after 1202.07 s when compared to the ones before that time, with a change in the slope and hence the polarity of the voltages to ground observed for the magnet in positions higher than position 77. The voltage drop across each magnet corresponds
to the by-pass diode opening voltage of about 6 V, connected in parallel to each dipole magnet. In figure 3.11, it can be seen that the bypass diodes in parallel to the magnets of the second half of the chain are conducting conduct in the same time window.

For the time instance of 1202.10 s, the voltage to ground at magnet 154 reaches a value of about 1060 V. The second EE resistor is connected in series following magnet 154 and has a voltage drop of about 900 V at the chosen time. This results in the voltage to ground of magnet 1 reaching a value of about 2000 V.

From this analysis, it becomes clear that a new formula for the calculation of a peak voltage to ground needs to be provided. This can be calculated from the expression in equation 3.3, where $N_{mag}$ is the total number of magnets in the circuit, $R_{EE}$ the EE resistance and $V_D$ the diode voltage drop.

$$V_{MAX} = 2I_{FPA}R_{EE} + \frac{N_{MAG}}{2}V_D$$  \hspace{1cm} (3.3)$$

Considering the current at nominal field for the LHC main dipole $I = 11.85$ kA and each EE extractor as having a value of about 73 mΩ, the maximum value for the voltage to ground that can be achieved in the circuit is equal to about 2.2 kV.

It is important to verify that the value is independent of the frequency of the pulses inserted between the two fuse thermal thresholds. Due to the fact that uncertainty characterises the region following the pre-arcing threshold, the choice of the frequency
3.3. FUSE PARAMETRIC ANALYSIS AND IDENTIFICATION OF WORST-CASES

(a) Simulated voltage to ground signals for all 154 magnets plotted as a function of time, with the FPA, EE1 and EE2 times specified. A short occurs at Magnet 77 at \( t_{\text{short}} = 1202 \) s with a short resistance of \( R = 1 \, \Omega \) and with the fuse blowing up.

(b) Simulated voltage to ground values of subfigure 3.10a plotted for specific times before (dotted line) and after the short, as a function of the magnet’s electrical position.

Figure 3.10: Two graphical representations of all 154 magnet voltage to ground signals for the case of a short appearing at Magnet 77 at 1202 s with a resistance of \( R = 1 \, \Omega \). The blow up behaviour of the fuse is included in these simulations.
with which the pulses are triggered is arbitrary and should not alter the results of the worst case. Since a voltage to ground close to the maximum possible value has been obtained by magnet 1 in the case where the short occurs at magnet 77, the same simulation can be performed with frequency values at different orders of magnitude.

In figure 3.12 it can be seen that pulses triggered with lower frequencies reach higher current values than the ones triggered with higher frequencies. However, in terms of voltage, as shown in figure 3.13, the value of the frequency has the opposite effect on the peak voltage to ground, with higher values of frequency causing higher peak amplitudes, which are all similar in value. From the figure it also becomes interesting to note that every time a pulse occurs, the slope with which the voltage starts decreasing remains the same, which means that the value of $\frac{dI}{dt}$ also stays the same. Hence, the similarity between the pulses for a single frequency can be seen, which also makes clear that was it not for the pulse switch off, the voltage would have the same oscillatory behaviour as seen when the fuse reaches the blow up threshold. As a conclusion of this analysis, it follows that although the frequency set for the pulses in the simulation has some effect on the peak value of the voltage drop, it is not a parameter that alters the worst case found for the peak voltage to ground in the circuit.

After performing a parametric sweep, it is also important to assess the effect of the independent variables set in the beginning of the simulation on the circuit behaviour. The results of the analysis are summarised in the color plots of figures 3.14 and 3.15 where the colors contain information about the peak voltage to ground values for different short positions, magnet electrical positions as well as short resistance values, allowing for points of interest to be easily identified.
3.3. FUSE PARAMETRIC ANALYSIS AND IDENTIFICATION OF WORST-CASES

Figure 3.12: Effect of frequency of pulse occurrence after pre-arcing threshold is reached on the behaviour of $I_{FUSE}$ for a short of 1Ω occurring at magnet 77.

Figure 3.13: Effect of frequency of pulse occurrence after pre-arcing threshold is reached on the behaviour of the voltage to ground at magnet 1 with a short of 1Ω occurring at magnet 77.

Starting with figure 3.14, a comparison is presented for the peak voltage to ground values obtained from simulations where the fuse did not blow up and the ones where
Figure 3.14: Comparison of peak voltage to ground values for a short resistance value of \( R_{\text{SHORT}} = 1 \Omega \) for the case when the fuse never blows up and the one when the blow up behaviour is included in the simulation.

The blow up behaviour of the fuse was implemented. In the case where the fuse blew up, the magnets in between electrical positions 1 and 30 obtain the peak values for shorts occurring between magnets in positions 57 and 77. Peak values can also be seen for the magnets in positions 124-154 when the short occurs between magnets 78 and 98. The same pattern for the peak values is maintained in the color plot of the no blow up case, since the peak voltage is obtained by the same combination of magnet and short position. However, the peak voltages in this case have values almost half the ones obtained in the case where the fuse blew up, an expected result since the high values appear during the transient behaviour of the voltage to ground signals after the fuse blows up, as was previously analysed.

A comparison of the peak voltage values obtained in the case that the blow up behaviour of the fuse is modeled for different short resistance values is presented in figure 3.15. The similarity of the plots for the short resistance values of \( R_{\text{SHORT}} = 1 \Omega \) and \( R_{\text{SHORT}} = 10 \Omega \) becomes immediately visible. As became clear in figure 3.10a, the voltage to ground obtains a peak value after the fuse has blown up. According to expression 3.2, the value that the equivalent resistance to ground obtains in that case is equal to 10 k\( \Omega \). Since the equivalent resistance can be up to 3 orders of magnitude larger than the value obtained by the short, when \( R_{\text{SHORT}} \) has a value of less than 10 \( \Omega \), different resistance values belonging in the aforementioned range don’t cause a significant change in the peak voltages and the color plot remains the same.

For resistances less than 10 \( \Omega \), with two values shown in figures 3.15a and 3.15b, high voltage to ground values are reached for magnets in positions 1 to 30 for shorts occurring between magnets 57 to 77 and magnets 124 to 154 for short in positions 78 to 98. For shorts occurring between positions 30 to 40 and 110 to 120, it can be seen that irrespectively of the magnet position where the voltage to ground is measured, only small values can be obtained for the peak. This is expected, since those magnets obtain the lowest voltage drop values even during the absence of a short in the circuit, as was seen in figure 2.6b. The middle range voltage values of about 1000 - 1200 V are obtained.
3.3. Fuse Parametric Analysis and Identification of Worst-Cases

Table 3.2: Cases of Peak Voltages To Ground For $R_{\text{short}} \leq 10 \Omega$

<table>
<thead>
<tr>
<th>Notable Case #</th>
<th>Short Position</th>
<th>Magnet Position</th>
<th>Voltage Range [kV]</th>
<th>Peak Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>57-77</td>
<td>1-30</td>
<td>1.7 - 1.9 kV</td>
<td>$2R_{EE}l + \frac{N_{\text{MAG}}}{2} V_D$</td>
</tr>
<tr>
<td>2</td>
<td>78-98</td>
<td>124-154</td>
<td>1.7 - 1.9 kV</td>
<td>$2R_{EE}l + \frac{N_{\text{MAG}}}{2} V_D$</td>
</tr>
<tr>
<td>3</td>
<td>78-98</td>
<td>1-77</td>
<td>0.8 - 1.3 kV</td>
<td>$R_{EE}l + \frac{N_{\text{MAG}}}{2} V_D$</td>
</tr>
<tr>
<td>4</td>
<td>57-77</td>
<td>78-154</td>
<td>0.8 - 1.3 kV</td>
<td>$R_{EE}l + \frac{N_{\text{MAG}}}{2} V_D$</td>
</tr>
<tr>
<td>5</td>
<td>150-154</td>
<td>1-5</td>
<td>0.1 - 0.8 kV</td>
<td>$R_{EE}l$</td>
</tr>
<tr>
<td>6</td>
<td>1-5</td>
<td>73-77</td>
<td>0.1 - 0.8 kV</td>
<td>$R_{EE}l$</td>
</tr>
<tr>
<td>7</td>
<td>150-154</td>
<td>78-98</td>
<td>0.1 - 0.8 kV</td>
<td>$R_{EE}l$</td>
</tr>
<tr>
<td>8</td>
<td>1-5</td>
<td>150-154</td>
<td>0.1 - 0.8 kV</td>
<td>$R_{EE}l$</td>
</tr>
</tbody>
</table>

by all magnets up to number 77 in the cases where a short occurs at magnet positions in the range of 78 to 98 and magnets from 78 to 154 when the short occurs at position in the range of 57 to 77.

For the case when the resistance of the short is equal to 100Ω, the color plot is presented in figure 3.15c. For easier reference, the colorbar limits have been kept the same as in the plots of the smaller resistance values, which reveals that for this value of resistance, the voltage to ground values in the circuit are significantly smaller when compared to the peak of 1.9 kV. The maximum value obtained in this plot has a value of about 1.3 kV for magnet 154 with a short occurring at position 78. For this resistance value, peak voltages can be seen when the short appears at magnets 57 to 77 for magnets with positions ranging from 1 to 30, while for magnets at electrical positions 124 to 154, the largest voltage values appear when the short occurs at magnets 78 to 98. Mid-range voltage values are obtained for this resistance at magnet positions 57-77 when a short occurs at magnets 1 to 22 and 78 to 90. This is also the case when a short appears at positions 57 to 77 and 140 to 154 for magnets at positions 78-98. Finally, voltages of the same range are observed for magnets in positions 1 to 22 for a short that occurs at magnets 140 to 154, as well as positions 140 to 154 for a short at positions 1 to 20.

The same analysis follows for the plot in figure 3.15d where $R_{\text{short}} = 1kΩ$, with the difference that the voltage to ground values obtain even smaller magnitudes, with peak voltages reaching values of about 900 V. For high resistance values, the current flowing through the short resistor is limited, which means that the lower voltage to ground values obtained, are expected.

The above analysis can be summarised in 8 notable cases presented in table 3.2. The table includes the peak values obtained for short resistance values $\leq 10 \Omega$, where the worst cases are achieved. The table also aims to act as a quick reference for the voltage value obtained for specific magnets, by providing the formula to calculate the peak voltage when the short and magnet positions are within specified ranges.
Figure 3.15: Colorplots of voltage to ground peak values as function of magnet electrical position and position where the short occurs for 4 different $R_{\text{SHORT}}$ values.
A thorough analysis of the circuit after a short occurs has been performed in the previous chapter of this thesis and a better understanding of its behaviour has been achieved. The main goal of this chapter is to investigate whether the relation that exists between the fault parameters and the behaviour of different circuit signals can be used in order for an automated scheme to be implemented, able to provide information regarding the short to ground.

A method that could be used to achieve this, is to perform a comparison between the measured signals obtained and the simulation results, since an accurate model of the LHC main dipole circuit exists [19]. However, in order to obtain the results of the numerical simulations, as already thoroughly discussed, the input parameters of the current in the circuit, as well as the position of the short and its resistance, need to be set in advance. This makes clear the fact that obtaining the simulation results for a large number of different parameter values is both computationally expensive and time consuming.

It has already been seen from plots of the voltages over time, like the one presented in figure 2.6a, that abrupt events in the circuit are followed by transients. However, after the transients have died off, the voltage values can be defined as a function of the current circulating in the circuit, with the total voltage distributed equally over the magnets of the chain. It can hence be suggested that obtaining an analytical solution for the current in the circuit and through the short can lead to the derivation of the voltages to ground.

With a large number of possible values for the initial current and short resistance parameters, the derivation of a system of analytical equations, would provide an efficient way to calculate the voltage to ground distribution in the magnet circuit. By taking into consideration certain assumptions and performing simplifications, the circuit of the LHC main dipole circuit presented in figure 2.3 can be reduced to an equivalent model, that can be solved analytically. It has to be mentioned that the equivalent circuit presented in this section can only be used for a circuit analysis after a short has occurred and is not a substitution of the dipole equivalent model presented in [19].
4.1 Simplifying The LHC Main Dipole Equivalent Electrical Circuit

During the analysis of the LHC main dipole circuit model, and more specifically table 2.2, it has been mentioned that distributed capacitances to ground are included in the circuit to model parasitic effects. In the case that these capacitances to ground are neglected, the model will show inaccuracies during fast transients, but should still be able to capture the behaviour of the circuit well during slower transients. Since the behaviour of the magnet in the frequency domain is of little interest to this thesis and transients occur occasionally only during abrupt events, the capacitors to ground are removed from the model. The resulting voltage to ground signal for a single magnet, specifically the one at electrical position 10, is presented in figure 4.1 so that a comparison can be drawn between the case where the capacitors to ground are included and the one they are omitted from the circuit. Although the signal of a single magnet is shown in the figure, the same effect is observed for the voltages of all the other magnets, which is expected since the equivalent model of figure 2.4 is used to model them. It becomes visible that the two signals for the case when the capacitors are included in the circuit and the one where they are not match well, except for the parts where the fast transients occur.

The magnets in the circuit are placed in cryogenic cells, with each cell including either two or three magnets. This is also the reason why a magnet’s electrical position does not necessarily correspond to its physical position along the circuit. A table relating the two, showing the magnets included in each cell, is presented in figure A.2 of Appendix A.2.

A common grounding point exists for the magnets belonging to the same cell, which depending on its position in the circuit, is connected further or closer to the grounding

![Figure 4.1](image-url)  
**Figure 4.1:** Comparison of voltage to ground at magnet 10 of the LHC main dipole circuit, showing the effect of the omission of the capacitances to ground in the equivalent model.
4.1. SIMPLIFYING THE LHC MAIN DIPOLE EQUIVALENT ELECTRICAL CIRCUIT

point of the EE resistor. The distance of the cell from the actual ground point determines the amount of added resistance and inductance to the grounding lines, due to the existence of parasitic resistance and inductance existing in the connections between the cells. The additional inductance and resistance due to the grounding lines can be calculated using expressions 4.1 and 4.2, with the equivalent resistance $R_{eq}$ depending on the state of the fuse and calculated using equation 3.2.

$$L_{groundTotal} = CellPositionNumber \cdot 1\mu H$$ (4.1)

$$R_{groundTotal} = R_{eq} + CellPositionNumber \cdot 3m\Omega$$ (4.2)

However, using the formula it can be seen that even for the case where the cell in position 54 is considered, which has the largest distance from the ground point, the added inductance of the grounding lines is equal to $54\mu H$ and the added resistance is equal to $0.16\Omega$. With the inductance of the magnets being in the order of mH and the resistance of the grounding lines in all cases of equation 3.2 at least two orders of magnitude higher, the additional values of the cell interconnections could be ignored, without significantly affecting the accuracy of the model.

Finally, the power supply and the crowbar can be simplified by having a current circulating in the circuit with an initial value at time $t_0$. The behaviour of the current greatly depends on the total inductance, as well as resistance of the circuit. For this reason, accurate values need to be provided for both.

Starting with the equivalent inductance, the magnets are considered the main inductive elements having an inductance $L_{mag} = 98mH$. Additional inductance exists at the busbars connecting the different elements in the circuit, however this value is 3 orders of magnitude lower than that of the magnet inductance and can hence be neglected without causing significant deviations of the signal values.

As far as the equivalent resistance is concerned, the EE switch and a snubber capacitor are connected in parallel to each energy extraction resistor. When the switch is closed, the subcircuit of the EE can be modeled as a resistor connected in series with the chain of the magnets. More accurate results are obtained for the equivalent circuit model when the resistances $R_{warm1}$, $R_{warm2}$, $R_{warm3}$ and $R_{warm4}$ of the warm copper cables are also included. Resistor $R_{warm1}$ is connected between the output of the power converter and magnet in position 1 and it has a value of $775.5\mu\Omega$. Resistors $R_{warm2}$ and $R_{warm3}$ both have a value of $69.5\mu\Omega$ and are connected in either side of the EE1 resistor. Resistor $R_{warm4}$ is connected between magnet 154 and the EE2 resistor and has a value of $428.5\mu\Omega$. Since the total value of the warm resistances is in the m\Omega range, the inclusion of the warm resistances increases the equivalent circuit resistance.

A reduced equivalent circuit has been developed in this section, with a behaviour that matches closely the one of the LHC main dipole circuit during slow transients. The schematic of the reduced circuit is shown in figure 4.2.

The model in the figure, assumes that a short circuit exists at node 3, representing
the point of the connection between a specific magnet and ground. The resistances and
inductances before and after the short position are lumped together and represented
by $L_{\text{total}1}$, $L_{\text{total}2}$ for the inductances and $R_{\text{total}1}$ and $R_{\text{total}2}$ for the resistances. The
equivalent ground resistance $R_g$ connects to the middle point of EE2 and is effectively
in series to the ground resistor $R_g$.

4.2 Analytical Solution Of Simplified Model

The circuit has now been simplified to a network of resistors and inductors and 3
distinct loops can be seen, for which 3 equations could be derived. Since having an
expression for the current through resistors $R_{EE1}$ and $R_{EE2}$ is not essential for calculating
the current value through the short resistor, a further simplification can be applied to
the circuit. The Wye-Delta transform can be performed on the branch of the second
EE resistor, with the aim of obtaining one common node for the resistors that make up
$R_{EE2}$. The additional simplification of the reduced circuit after the transform has been
applied, can be seen in figure 4.3. A complete calculation of the resistances resulting
from the transform that leads to the final schematic of the reduced circuit, is presented
in Appendix A.1.

The total inductance, as well as the resistance of each loop, depends on the magnet
position where the short occurs. As an example, for a short that occurred between magnet
70 and ground, the total inductance before the position of the short is equal to $L_{bf} = 69L_{mag}$, while the inductance after the short position is equal to $L_{af} = (154 - 69)L_{mag}$. Similarly, since magnet 70 is positioned before the EE1 resistor, the total resistance
before the short is equal to $R_{bf} = R_{warm1} + R_1$ and the total resistance after the short
equal to $R_{af} = R_{warm2} + R_{warm3} + R_{warm4} + R_{EE2} + R_2$, where $R_1$ and $R_2$ the resistances
resulting from the transform and specified in Appendix A.1. Therefore, the values of
these parameters can be computed programatically, by specifying the position of the
magnet where the short occurred.
In a realistic situation, it can be the case that quenched magnets exist in the circuit. When this happens, the voltage drop across a quenched magnet is equal to the voltage drop over the diode connected in parallel to the magnet, as the magnet is bypassed. More specifically, this is equal to 6 V in cryogenic conditions and 1.2 V after heating up. Neglecting the time needed for the lower voltage to be obtained, the voltage drop over the quenched magnet can be considered as having a constant value. This is the reason that the quenched magnets are represented as voltage sources $Quenched_{bf}$ and $Quenched_{af}$ in figure 4.3, for the magnets that have quenched before and after the short respectively and a value that can be calculated as shown in equations 4.3 and 4.4.

$$Quenched_{bf} = \text{NumberOfQuenchedMagnetsBeforeShort} \cdot 1.2V$$ (4.3)

$$Quenched_{af} = \text{NumberOfQuenchedMagnetsAfterShort} \cdot 1.2V$$ (4.4)

For the magnet that has quenched, a constant voltage drop of 1.2 V is hence inserted in the place of the inductive voltage. This means that also the inductances $L_{bf}$ and $L_{af}$ need to be decreased by a number that depends on whether the quenched magnet is found before or after the position where the short occurred. Consequently, knowledge of the positions of the magnets that have quenched is required as input, in order to create an accurate representation of the state of the circuit at a specific time. This information can easily be obtained in a real scenario, since the quench detection system installed in the LHC main dipole circuit, records the voltages across the magnets that triggered it.

Taking into consideration the existence of quenched magnets in the circuit, the expressions for the inductors $L_{bf}$ and $L_{af}$ are presented in equation 4.5 and 4.6 respectively. In these equations the variable $shortPos$ represents the magnet number where the short occurred and $N_{mag}$ is the total number of magnets in the circuit.

$$L_{bf} = (shortPos - 1 - \text{NumberOfQuenchedMagnetsBeforeShort})L_{mag}$$ (4.5)

**Figure 4.3:** Further simplification of the reduced model using the Wye-Delta transform on the resistor branch of EE2.
\[ L_{af} = (N_{mag} - (\text{shortPos} - 1) - \text{NumberOfQuenchedMagnetsAfterShort})L_{mag} \quad (4.6) \]

The short resistor \( R_s \) can be seen connected to ground and effectively in series to \( R_g \), which represents the total resistance of the grounding subcircuit, presented in figure 3.7. The series connection of the two resistors obtains the values presented in expression 3.2, discussed in section 3.2.

A first simplification is made in the model regarding the above mentioned expression. More specifically, since the model does not consider the time dependent behaviour of the elements, the resistance of \( R_g \) can be considered as having a value of \( R_g = 8.66\Omega + R_3 \), where \( R_3 \) the resistor inserted in series as a result of the Wye-Delta transform (Appendix A.1). This means that the time needed for the 15 V threshold to be reached is neglected. Since the resistors \( R_s \) and \( R_g \) are effectively in series, without loss of generality it is possible to keep the value of resistor \( R_g \) constant and account for a potential blow up of the fuse using resistor \( R_s \), which would obtain a high value in that case.

The formula for the calculation of resistor \( R_{bf} \) can be seen in equation 4.7, while the one for \( R_{af} \) in equation 4.8. The equivalent resistances \( R_1 \) and \( R_2 \), derived using the Wye-Delta transform in Appendix A.1, are also included in the following equations.

\[
R_{bf} = \begin{cases} 
R_{warm1} + R_1, & \text{if shortPosition} \leq 77 \\
R_{warm1} + R_1 + R_{EE1} + R_{warm2} + R_{warm3}, & \text{if shortPosition} > 77 
\end{cases} \quad (4.7)
\]

\[
R_{af} = \begin{cases} 
R_{EE1} + R_{warm2} + R_{warm3} + R_{warm4} + R_2, & \text{if shortPosition} \leq 77 \\
R_{warm4} + R_2, & \text{if shortPosition} > 77 
\end{cases} \quad (4.8)
\]

After the simplification of the EE2 branch, two loops following the nodes 1 \( \rightarrow \) 2 \( \rightarrow \) 3 \( \rightarrow \) 6 and 3 \( \rightarrow \) 6 \( \rightarrow \) 5 \( \rightarrow \) 4 can be defined in the circuit. A solution needs to be found for the two unknown variables in the circuit, namely \( I \) and \( I_{\text{short}} \), with the first being the current circulating in the circuit before the short position and the second one, the current through the short. With a known value of the short resistor \( R_{g1} \) and a solution found for \( I_{\text{short}} \), it also becomes possible to obtain the voltage to ground of the magnet at which the short occurred.

Applying Kirchhoff’s voltage laws to the two aforementioned loops, the circuit behaviour can be described using two differential equations. The built-in ODE solver of MATLAB can be used to provide the analytical solution of their system. The differential equation for the first loop is shown in equation 4.9 and for the second one in equation 4.10. Initial values are defined as \( I(t_0) = I_0 \) for the circuit current and \( I_{\text{short}}(t_0) = 0 \) for the current through the short resistor. The solutions of the system for the variables \( I_{\text{short}} \) and \( I \) are then presented in figure A.3 of Appendix A.3 and the expressions of the \( \sigma \) variables included in the solutions, presented in figures A.4 and A.5.
4.2. ANALYTICAL SOLUTION OF SIMPLIFIED MODEL

\[ KVL_{1\rightarrow2\rightarrow3\rightarrow6} : \]
\[ R_{bf} \cdot I + L_{bf} \cdot \frac{dl}{dt} + R_{af} \cdot (I - I_{short}) + L_{af} \cdot \frac{d}{dt}(I - I_{short}) + Quenched_{bf} + Quenched_{af} = 0 \]  
\[(4.9)\]

\[ KVL_{3\rightarrow6\rightarrow5\rightarrow4} : \]
\[ L_{af} \cdot \frac{d}{dt}(I - I_{short}) + R_{af} \cdot (I - I_{short}) + I_{short}(R_s + R_g) + Quenched_{af} = 0 \]  
\[(4.10)\]

Having obtained a solution for both current values in the circuit, it becomes possible to calculate the voltage drop over the magnets both before and after the short, presented in equations 4.11a and 4.11b respectively.

\[ U_{mag_{bf}} = L_{mag} \frac{dl}{dt} \]  
\[(4.11a)\]

\[ U_{mag_{af}} = L_{mag} \frac{d(I - I_{short})}{dt} \]  
\[(4.11b)\]

It then follows that the voltage to ground at each magnet position can also be calculated using the formulas presented in equations 4.12, 4.13, 4.14 and 4.15 with \( MagnetNumber \) a variable representing the electrical position of the magnet where the voltage is defined.

\[ U_{ground}(1) = \begin{cases} 
U_{mag_{bf}}, & \text{if } \text{shortPosition} < 1 \\
U_{mag_{af}}, & \text{if } \text{shortPosition} > 1 
\end{cases} \]  
\[(4.12)\]

\[ U_{ground}(78) = \begin{cases} 
U_{mag_{bf}} + R_{EE1}I, & \text{if } \text{shortPosition} < 78 \\
U_{mag_{af}} + R_{EE1}I, & \text{if } \text{shortPosition} > 78 
\end{cases} \]  
\[(4.13)\]

\[ U_{ground}(\text{MagnetNumber}) = \begin{cases} 
U_{ground}(\text{MagnetNumber} - 1) + U_{mag_{bf}}, & \text{if } \text{MagnetNumber} < \text{shortPosition} \\
U_{ground}(\text{MagnetNumber} - 1) + U_{mag_{af}}, & \text{if } \text{MagnetNumber} > \text{shortPosition} 
\end{cases} \]  
\[(4.14)\]

\[ U_{ground}(\text{MagnetNumber}) = \begin{cases} 
U_{ground}(\text{MagnetNumber} - 1) + 1.2, & \text{if } \text{MagnetNumber} \text{ is quenched} 
\end{cases} \]  
\[(4.15)\]

A first comparison between the current through the short \( I_{short} \) values calculated analytically and the signal obtained by simulating the complete model, is presented in
figures 4.4 and 4.5 for two different orders of magnitude of the short resistance values, namely 1 Ω and 100 Ω. In the specific simulation, a short occurred between magnet 70 and ground. The value of the current in the circuit at the time the short occurred was 11.32 kA and no magnets were quenched.

For a short at the specified magnet position, the analytical solution was computed in about 7 s, while the numerical simulation in PSpice required about 16 s to complete. It is important to mention that the same time grid was used in both simulations, which included 2000 equally spaced points between values 0 s to 400 s. Although an increase of the grid’s resolution requires additional computational time, the analytical solution was repeatedly computed in approximately half the time of the numerical simulation. It should also be noted that PSpice executes the simulation for certain initially specified parameters, while on the other hand the analytical solution of the differential equation contains symbolic variables for the different parameters. Computing the final result for the current after a change of parameters has taken place requires about 5 s, while on the other hand the time PSpice needs to complete the simulation remains the same.

After the signals have been interpolated, the relative difference of their datapoints can be calculated with the formula presented in equation 4.16, in order to measure the similarity of the two curves.

\[
\Delta_{\text{Relative}} = \frac{1}{N_{\text{VoltageFeelers}}} \sum_{i=1}^{N_{\text{VoltageFeelers}}} \frac{|(I_{\text{simulated}})_i - (I_{\text{analytical}})_i|}{|I_{\text{simulated}}|} \] (4.16)

From the figures it can already be seen that the signals overlap better for certain time regions, than others. The relative difference is plotted as a function of time in figures 4.6a and 4.6b for each short resistance value respectively. With a resistance of 1 Ω, it
4.2. ANALYTICAL SOLUTION OF SIMPLIFIED MODEL

Figure 4.5: Comparison of simulated and analytically computed signal for current through short when it occurs between magnet 70 and ground with a resistance value of 100 Ω.

Figure 4.6: Relative distances between simulated and analytically computed datapoints of the current in the circuit, plotted against time for two different short resistance values.

can be seen that the relative error obtains values less than 2% up to 150 s, after which its value increases eventually reaching a maximum of about 17%. For the case that the resistance of the short is equal to 100 Ω, the error has an average of about 1%, with a peak value of 2%. The maximum and mean relative distance values obtained for both resistances are presented in table 4.1. A possible cause for the higher error values observed for times larger than 150 s, in the case of the smaller short resistance, could be the fact that the equivalent resistance of the grounding lines does not maintain a constant value and instead as the current decreases, the diodes in parallel to the fuse resistor stop conducting, causing hence an increase of its value.
Table 4.1: Maximum and Mean Values Of Relative Difference Of Simulated And Analytically Calculated Signals For Different Resistance Values.

<table>
<thead>
<tr>
<th>$R_s$ [Ω]</th>
<th>Max Relative Distance</th>
<th>Mean Relative Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.1757</td>
<td>0.0639</td>
</tr>
<tr>
<td>100</td>
<td>0.0213</td>
<td>0.0130</td>
</tr>
</tbody>
</table>

4.3 Design Of Short Circuit Algorithm

From the simplified model of the LHC main dipole circuit, the solutions of the current in the circuit, as well as the current through the short can be found. In the previous section, equations for the voltage to ground values of the magnets in the circuit were presented, which make use of the analytical solutions of the currents. Expressions have also been provided for the calculation of the lumped element values that exist in the equivalent circuit.

An algorithm can hence be proposed that compares the analytically calculated voltage to ground values for each magnet in the circuit to the measured ones and draws conclusions about the short position and resistance value. More specifically, it calculates the mean distance between the measured voltages to ground of the magnets obtained by the voltage feelers and the analytically calculated ones at a specified time instance. The algorithm takes advantage of the reduced time needed to compute the result of the analytical expressions of the currents and calculates the voltage to ground values for all the possible short positions, as well as several short resistance values. It finally identifies the voltage values for which the minimum distance is obtained and returns the corresponding short position and resistance values as output.

A more detailed description of the steps followed by the algorithm in order to provide information regarding the short, follows next.

As a first step, the total number of magnets, the values of the warm resistances $R_{warm1}$, $R_{warm2}$, $R_{warm3}$ and $R_{warm4}$ and magnet inductance $L_{mag}$, as well as the values of the EE resistors $R_{EE1}$, $R_{EE2}$ are provided as inputs to the algorithm. Having these values specified as inputs is important for two main reasons. The first is the fact that the above mentioned resistance parameters model resistors that in the actual circuit tend to deviate from their specified nominal value, with their values even changing completely in the case they are replaced by different resistors. Second, leaving the freedom of manually inserting such parameters does not limit the proposed algorithm only to the LHC main dipole circuit, but makes it compatible with other accelerator circuits, which have different EE resistor and magnet inductance values or a different value for the total number of magnets in the circuit. The positions of the magnets that quenched, as well as the times at which each quench occurred are also provided to the algorithm.

The second set of inputs that are given as input to the algorithm are the measured signals that have been obtained during the short to ground event. The high resolution
data signal of the circuit current is stored in the Post-Mortem System [15], while the voltage feeler data signals of the event are found in the LHC Logging System [23]. The data can be accessed using queries that include the sector and magnet name, as well as the timestamp of the event. The voltage to ground signals are recorded by the voltage feeler sensors, connected to one every three magnets in the circuit, meaning that the voltages to ground of 52 out of the 154 magnets are measured. A list containing their exact position in the circuit and the electrical position of the magnets to which they are connected to, can be found in [24]. The measured signals are sampled with a frequency of 10 Hz, which works well for obtaining the general behaviour of the signal, but is at the same time not able to accurately capture all features of fast transients occurring in the circuit.

The fact that the signals of the circuit current and the voltage to ground are obtained from different systems and have different sampling frequencies, means that synchronisation needs to take place. This can be achieved by shifting both signals accordingly so that the time when the FPA occurs is positioned at $t = 0\text{s}$. A method is provided next for the algorithm to identify the time when the FPA is triggered in each of the signals.

As has been previously analysed, the current in the circuit follows an initial ramp-up to the nominal value with a constant $\frac{dI}{dt}$, after which it reaches a plateau. Hence the point where the FPA is triggered can be identified by the algorithm as the point when the ramp up rate of the current obtains a value close to zero. In absence of faults in the circuit, the behaviour of the signals is not characterized by sudden changes, apart from the region where the FPA occurs. Calculating the numerical derivative of the voltage to ground signals, reveals information on the points where abrupt changes occur, since its peak values are achieved at those points. The point in time at which a first peak is detected and which is followed by two other peaks for $t_{EE1}$ and $t_{EE2}$ is characterised as $t_{FPA}$, with the second criterion regarding the two follow-up peaks essential in order to differentiate between the peak of FPA and a peak caused by a short. After the peaks for $t_{FPA}$, $t_{EE1}$ and $t_{EE2}$ have been identified, the rest of the peaks can be considered shorts, making it possible to specify the times where these occurred.

Synchronisation can then be achieved for the input signals, by shifting all signals so that $t_{FPA}$ occurs at time zero. Their analysis hence becomes easier, as it allows for the voltage to ground values corresponding to a specific value of the current in the circuit, to be obtained simply by specifying a time instance, which is the same for both.

As has been thoroughly discussed in the first part of the thesis, the current $I$ in the circuit depends on the equivalent resistance of the circuit, meaning that its values depend on the two EE resistors, as well as the warm resistances. For resistors $R_{EE1}$ and $R_{EE2}$, only the nominal values are known, which are the ones given as input to the algorithm. Therefore it becomes important that the values of the resistors used in the model, do not deviate much from the ones that exist in the circuit. In case of a mismatch, at a specified time instance when the current in the circuit obtains a specific time value, an error due to a value mismatch would appear between the calculated and the measured voltage to ground values for each magnet. Since the algorithm looks for the closest fit between the calculated and measured voltage values, this could cause incorrect conclusions to be
In figure 4.7 the effect of the resistance values is shown on the obtained voltage to ground values with the short occurring at magnet 149 and a short resistance of 0.1 Ω. A linear behaviour relation can be seen existing between the resistance value and the final voltages obtained, with the slope of the curve changing. Since an analog circuit is considered, it can be said that a combination of resistance values exists, that minimises the distance of the voltage values from a certain reference. The error function, defined as a function of the resistances $R_{EE1}$ and $R_{EE2}$, can hence be considered continuous. For a time between the second EE and the time the short occurs, the analytically calculated voltage values will be optimised so that their distance to the measured ones becomes minimum. Therefore, a better match of the resistances used in the model with the values in the circuit can be achieved.

A method based on the Newton–Raphson scheme can then be used to find the roots of the error function. An initial guess is made for the two resistance values, which in this case is equal to their nominal values, and the total error of the voltages to ground is calculated. The value of the resistance to be used in the second iteration, as well as the iterations that follow, can be calculated using equation 4.17, with the numerical derivative of the error function shown in equation 4.18. These formulas are a function of the resistance and error values obtained during a specific iteration number for each resistance and will be computed iteratively, until the error value shows only small changes for successive iterations, which signifies that convergence has been reached.
4.3. DESIGN OF SHORT CIRCUIT ALGORITHM

\[ R_i = R_{i-1} - \frac{\text{error}(R_{i-1})}{\text{error}'(R_i)} \]  \hspace{1cm} (4.17)

\[ \text{error}'(R_i) = \frac{\text{error}(R_{i-2}) - \text{error}(R_{i-1})}{R_{i-2} - R_{i-1}} \]  \hspace{1cm} (4.18)

Two different methods can be used to compute the error function, namely the $\ell^1$-Norm and the $\ell^2$-Norm metric. Their formulas presented in equations 4.19 and 4.20, respectively. It is expected that the two methods will have different convergence rates, which is difficult to estimate however, since the shape of the error function is not known in advance. For this reason, further analysis will be provided on the two metrics during a case study. Both methods will be implemented in the algorithm, so that if convergence is not reached after 10 iterations, an alternative method exists.

\[ \text{error} = \sum_{r=1}^{N_{\text{VoltageFeelers}}} \left| V_{\text{measured}}(r) - V_{\text{analytical}}(r) \right| \]  \hspace{1cm} (4.19)

\[ \text{error} = \sqrt{\sum_{r=1}^{N_{\text{VoltageFeelers}}} \left| V_{\text{measured}}(r) - V_{\text{analytical}}(r) \right|^2} \]  \hspace{1cm} (4.20)

In order to analyse the voltage to ground behaviour after a short has occurred, the voltage to ground value at a time instance following the short can be chosen. It is also important that the algorithm chooses a time value not directly following the appearance of the short, since otherwise the fast transients caused by the short would be measured. It is also possible that at the chosen time more magnets have quenched, for which the algorithm is able to account for, using the input information on the quenched magnets.

The two differential equations are then solved. The solutions for the currents are saved, with the resistance and inductance parameters both before and after the short position, as well as the initial current in the circuit, kept as symbolic variables in the final solutions of $I$ and $I_{\text{short}}$. This allows for the values of the currents to be quickly computed for various parameter values as they can be easily substituted, without the need of solving the differential equations every time. In order to calculate the solution, the time vector of the measured signals is used, so that the analytical solutions can also be synchronised with the measured data, as previously discussed. In order to compute the solutions for a specific short, a time of about 1 s after its occurrence is chosen, when the transient oscillations have died off and is considered as $t_0$. The value of the current in the circuit at the chosen time, is also obtained and set as the initial current $I_0$ in the differential equation system.

The algorithm is then able to perform a parametric sweep of the short resistance, which is one of the free variables in the analytical equations. Resistance values at different orders of magnitude are chosen and more specifically $[0.1, 1, 10, 100, 1000, 10000] \, \Omega$. As was previously mentioned, resistor $R_g$ representing the total resistance of the grounding subcircuit is assigned a constant value in the model, which means that it is a change
in the value of the short resistor that has an effect on the equivalent resistance of the grounding part of the circuit. Therefore, a short resistor of a large value models the case when the fuse has blown up.

The voltage to ground values at the 52 positions of the voltage feelers are calculated analytically for a specified time after the short occurred and for each short resistance value. Due to the fact that another free parameter, namely the position of the short exists in the analytical solutions, the values need to be calculated for all 154 possible short to ground positions. The goal is for the algorithm to detect if for a specific resistance value, there exists a short position for which the average distance of the measured and calculated voltage values, becomes small. However, from the analysis performed in the first part of the thesis, it follows that for a fixed short resistance value, the peak voltages are obtained when the short occurs on the first and last magnet of the chain as well as the magnets before and after the EE1 resistor. Therefore, it will be sufficient to check whether the measured voltage values at a specific time instance fall in between the minimum and maximum voltages obtained for the measured magnet numbers in the case the short appears in one of the 4 magnet positions.

The method that the algorithm uses in order to determine the mean distance of the magnets for which measured signals exist is discussed next. Visually this process can be described as a comparison of the distance between two of the curves plotted in figure 3.4. Computing the relative mean difference would provide a better understanding of how much the analytically calculated values deviate from the measured ones, while taking into consideration the scale of the voltage values that are achieved. However, such a method is not ideal for the comparison of the measured and analytical voltages in this case, since at specific magnets, values around zero are obtained. When this is the case, the value of the relative difference does not provide a valid comparison, since it tends to infinitely high values.

As an alternative, the algorithm calculates the mean absolute difference between the voltages at each of the measured magnet positions where the \(i_{th}\) voltage feeler is placed and computes the mean distance for a specific short position and short resistance values by dividing their sum by the total number of voltage feelers. An expression is presented in equation 4.21, where \(N_{\text{VoltageFeelers}}\) is the total number of voltage feelers, or equivalently magnets for which measured signals exist.

\[
\Delta_{\text{Absolute}} = \frac{1}{N_{\text{VoltageFeelers}}} \sum_{i=1}^{N_{\text{VoltageFeelers}}} |(V_{\text{measured},i}) - (V_{\text{analytical},i})| \quad (4.21)
\]

Referring to the process of identification of the short resistance described above, if the mean absolute distance calculated for any of the 4 chosen short positions for a certain resistance has a small value, then the specific resistance value can be considered as belonging in the same range as the short resistance of the circuit. If a small distance value is obtained for multiple resistance values, then the algorithm considers the lowest and highest of these and returns a range of possible short resistance values for the short.

For the resistance values that the algorithm identified as belonging to the same range
4.4 Testing Of Algorithm And Results

As a first case study of the application of the short-circuit algorithm, the event which occurred in the dipole magnet of Sector 34 on 08/12/2016 is chosen. An investigation following the detection of the specific event starting from measured signal data recorded on the specified date, combined with the analysis of simulation data, has been presented in [25]. Shortly after the event, the electrical quality assurance team performed onsite visits in order to accurately locate the fault, eliminate it and perform specialised measurements. Further details on the event, such as the short resistance and its precise cause, have hence been provided [26]. Using this information, a first validation of the proposed algorithm can be performed and its accuracy when measured signal data are provided as input, can be determined.

It has been identified that the short occurred between magnet C12L4 and ground, which translates to the magnet at electrical position 149 of Sector 34. Regarding the exact point where the short occurred, using specialised diagnostic techniques [27], the short to ground was located at the bypass diode connected in parallel to magnet C12L4. A value of $\approx 0.47\Omega$ was determined for the resistance of the short [26]. Finally, although it has been reported that the fuse in the circuit did blow up, the specific time when this occurred is not known [27].

For the specific event, several magnets in the circuit quenched at times both preceding and following the occurrence of the short. The magnet positions, as well as the current

---

**Short Circuit Algorithm**

1: procedure Provide Short To Ground Information
2:   Input: circuit parameters
3:   Input: positions of quenched magnets and time at which they quenched
4:   Input: measured data of event (current $I_{FPA}$, voltage to Ground)
5:   Find $t_{FPA}$ for both signals and synchronise
6:   Optimise model for resistances $R_{EE1}$ and $R_{EE2}$
7:   Solve differential equation and save results
8:   Identify range where resistance belongs by finding resistance values where minimum distance between measured and calculated voltage values is achieved for the 4 extreme short positions
9:   Identify value of short position for which minimum distance between measured and calculated values is obtained
10: end procedure

---
levels at which the magnets quenched, are shown in table 4.2 and are provided as input to the algorithm. With the information regarding the current level at the time instance when the short occurred known, it can be seen that 4 out of the total 22 magnets quenched before the occurrence of the short, namely the magnets in electrical positions 5, 19, 149, 150.

The voltage to ground signals for the specific event have been obtained from the LHC Logging Database and are plotted in figure 4.8.

Comparing the measured signals of the figure to the simulated voltages to ground shown in 3.3a, where a single short to ground existed in the circuit, the effect of the low sampling frequency becomes visible in the fast transient regions. Although it is not possible to obtain an accurate voltage value for a time instance in between the two EE switch openings, due to a lack of datapoints, the times at which these events occur, can still be identified, since the behaviour of the signals is well understood. The times of the 3 events occurring during the FPA are indicated in figure 4.8. After the second EE switch opens in the circuit, the voltages are expected to slowly decay to zero with
4.4. TESTING OF ALGORITHM AND RESULTS

![Figure 4.8: Measured voltage to ground signals of 52 magnets obtained from the incident of 08/12/16.](image)

An almost exponential rate. An abrupt change that occurs after this event can hence be characterised as a short circuit. For the specific event, it becomes visible in the same figure that the short occurs \( \approx 1 \text{s} \) after EE2, with the current level in the circuit at the specific moment having a value of about 11.31 kA.

Next, the 52 measured voltage to ground signals are provided as input to the algorithm. The measured voltage to ground signal of magnet 10, as well as the numerical derivative of the signal are presented in figure 4.9, from which \( t_{\text{FPA}} \) can be found by identifying the peaks. In figure 4.8, the similarities between the plots of the different magnets can be seen for the regions where fast transients occur. Hence, it is true that the voltage to ground signal of any magnet can be used in order to find the time values of \( t_{\text{FPA}} \) and \( t_{\text{SHORT}} \) by calculating its numerical derivative. The first 3 peaks with the highest amplitudes reveal the times when the 3 events of the FPA occur, with the first event occurring at time \( t = 0 \), as shown in this figure. Since the numerical derivative is calculated as the difference between adjacent points, it is important to define the previous time point, as the time the event occurs, rather than the point where the peak is located at. A fourth peak can be seen at the time instance of about 1.42 s and hence since the previous time point needs to be considered, the time of the short occurrence is defined as \( t_{\text{SHORT}} = 1.4 \text{s} \). It should be mentioned that although the time axis in the plots has already been shifted so that the FPA occurs at 0 s, mainly to keep the plots uniform, this can only be achieved after its time has first been found, with the method described above.

The time when the FPA occurs in the signal of the current in the circuit, can be found by obtaining the time when it reaches its maximum value. In figure 3.4, it was shown that the current is initially ramped up to that point, after which it shortly reaches a plateau and starts decaying almost exponentially after the EE2 switch opens. Both signals are shifted so that \( t_{\text{FPA}} = 0 \text{s} \) and can hence be synchronised.
Figure 4.9: Measured voltage to ground of magnet 10 for the time window including the time where the FPA, the EE1 and EE2 and the short occurred. The peaks of the derivative of the signal indicated the times where the 3 events occur.

The values of $R_{EE1}$ and $R_{EE2}$ are then optimised for the circuit of the measured data that were provided as input. The algorithm picks a time instance of about 1.2 s after the FPA, which is a time that follows the openings of both EE resistors and precedes the fault occurrence. The initial values that are provided to the optimiser are the nominal values of the EE resistors, which for the LHC main dipole circuit have values of $R_{EE} = 71 \text{ m}\Omega$. The optimiser achieves convergence to the optimised values of $R_{EE1} = 70.2 \text{ m}\Omega$ and $R_{EE2} = 68.4 \text{ m}\Omega$ in 3 iterations, as seen in figure 4.10a, when the total error is calculated as presented in equation 4.19. In figure 4.10b, the convergence of the optimisation when the $\ell^2$-Norm is used can be seen, which converges slower to the same resistance values, requiring 6 iterations in total.

The final comparison of the measured voltage to ground values with the obtained values when the optimised EE resistance values are used, is presented in figure 4.11.

With all the required input parameters and the optimised resistance values, the algorithm solves the differential equation and computes the analytical solution for the current in the circuit as well as the current through the short. For the differential equations to be solved symbolically, a time of about 1.6 s is required. As has been mentioned before, the time required for the values of the solutions of the currents to be found, from which the voltage to ground values are calculated, depends on the time vector used in the formulas. It would be a logical step for the algorithm to compute the value of the currents for the part of the time vector of the measurements, starting from the specified point after the short and ending at a time when all the measured signals have decayed to zero. For this specific example, the part of the total vector containing those values, has a length of...
4.4. TESTING OF ALGORITHM AND RESULTS

(a) Error value as function of iteration number when $\ell^1$-Norm is used as metric

(b) Error value as function of iteration number when $\ell^2$-Norm is used as metric

Figure 4.10: Error value as function of iteration number for the cases that the error is calculated using the $\ell^1$-Norm and $\ell^2$-Norm metric.

Figure 4.11: Comparison of voltage to ground values over for all magnet positions with the nominal and the optimised $R_{EE}$ values.

2630 discrete time points.

A comparison of the time required for the calculation of the voltage to ground values for different time vector lengths, is shown in table 4.3. It can be seen that dividing the vector size in half, decreases the computational time also by a factor of two, with the calculation requiring 4 times less computational time, when the vector has 4 times less points. However, the same proportional decrease does not follow when the points are reduced by a factor of 10 and 100 respectively and it can be seen that calculating the voltage values at 5 individual time instances, requires approximately the same total time
as a time vector with 657 discrete points. Hence, a compromise has to be made regarding the length of the time vector, since achieving small values for the total computational time is essential. A time vector that consists of about 200 discrete points starting from the time chosen after the short up to the point where the voltages have decayed to zero, should be chosen hence over individual time points. It can also be seen that the time needed for the calculation of the solutions of the differential equations remains the same, since the equations don’t change. Finally, after the current values have been calculated for all times, there is no major advantage in computing the voltage to ground matrix only for individual time points and instead should be computed for the whole time vector.

The measured signal of the current in the circuit, obtained from the Post-Mortem system is compared to the analytically calculated one, with the two signals plotted in figure 4.12. From the figure, it becomes clear that although the two curves show good agreement until a current value of approximately 5 kA, they start diverging after that point with the relative difference reaching a maximum value of about 0.21 around 2 kA. It is known that in the actual circuit the time constant value of the current discharge changes over time, mainly due to the increase of temperature of the EE resistors, which alters their resistance values and consequently the equivalent resistance of the circuit. At the same time, this also reveals a first limitation of the proposed reduced model when the resistors used to solve the differential equations are defined as constants. However, with the short occurring at the current level value of 11.31 kA, good accordance in the results is expected for this case study.

In order to obtain voltage to ground values at this point, two free parameters exist in the analytical solutions, the resistance of the short to ground, as well as the position at which the short occurred. Starting with the resistance of the short, a range of values including the measured one needs to be identified. To achieve this, a parametric sweep of the short resistances can be performed for 5 resistance values at different orders of magnitude, namely $R = [0.1, 1, 10, 100, 1000] \ \Omega$. The algorithm calculates the distance between the measured and the analytically calculated voltages to ground for each of the 52 magnets. As a metric, the mean absolute distance is used, as previously analysed,
with the formula presented in equation 4.21.

Additionally, since the solutions of the differential equations have already been computed with symbolic variables, obtaining the voltages to ground for different short resistance values requires a value substitution for the parameter $R_s$. As has been discussed in the theoretical description of the algorithm, only the short positions where the peak values can be achieved will be calculated, namely magnets 1, 77, 78 or 154. This requires a total of about 20 s for the chosen time vector.

A time of about 1 s after the short has occurred in the circuit is chosen for the analysis to be performed, with a current value of 11.25 kA, which is considered $I_0$. Additionally, at the specified time and current value, 8 magnets have already quenched, namely the ones at positions [19, 149, 150, 5, 148, 146, 147, 151, 154, 153, 152, 8].

Applying this to the signals of the event, small distance values are obtained for short resistances $R_s = 0.1 \Omega$ and $R_s = 1 \Omega$, with the values increasing as the resistance takes larger values. Graphically this is presented in figures 4.13 and 4.14. It can be seen that in the case of the higher resistance, all curves deviate from the measured signal and since the extreme cases are plotted, it is expected that the curves for the short occurring at any other magnet will be in between these extreme cases. On the other hand, for resistance $R_s = 0.1 \Omega$, a good fit is observed, with the measured voltages even obtaining smaller values than those with a short at position 77. For a resistance value of $R_s = 1 \Omega$, a close fit was also achieved, with it being the first higher value for which the voltages were calculated larger than resistance $R_s = 0.1 \Omega$. The algorithm hence identifies that the short to ground in the circuit, obtained a resistance in the range between 0.1 - 1 \Omega.

The accuracy of these results can be verified, since the value of the short resistance
that appeared in the circuit was measured to have a value of about 0.4 Ω. The algorithm has hence correctly identified that the short resistance in the circuit has a low value and the specified range that was provided includes the actual value. The low value reveals that at the specified time, the fuse in the circuit has not blown up.
4.4. TESTING OF ALGORITHM AND RESULTS

Table 4.4: Smallest Mean Absolute Distance Values Achieved For A Resistance Of 0.1 Ω And Short Positions Where They Occurred

<table>
<thead>
<tr>
<th>Short Position</th>
<th>Distance [V]</th>
</tr>
</thead>
<tbody>
<tr>
<td>146</td>
<td>5.44</td>
</tr>
<tr>
<td>147</td>
<td>5.93</td>
</tr>
<tr>
<td>75</td>
<td>6.02</td>
</tr>
<tr>
<td>149</td>
<td>6.70</td>
</tr>
<tr>
<td>150</td>
<td>7.24</td>
</tr>
<tr>
<td>148</td>
<td>8.32</td>
</tr>
<tr>
<td>151</td>
<td>8.51</td>
</tr>
<tr>
<td>76</td>
<td>9.23</td>
</tr>
<tr>
<td>152</td>
<td>9.82</td>
</tr>
<tr>
<td>153</td>
<td>10.07</td>
</tr>
</tbody>
</table>

With a range for the short resistance containing values for which good accordance is achieved between the measured and analytically calculated signals, the last free variable is the magnet position where the short occurred. Since a good fit was achieved with a value of 0.1 Ω for the resistance, the voltage to ground values for every magnet are calculated for all 154 short positions. With the solutions of the differential equations already computed, this requires approximately 150 s, with the chosen time vector of about 200 points. The distance between the voltage to ground values for each case is computed using the formula in equation 4.21.

The 10 smallest distance values that were computed, as well as the corresponding short positions, are presented in table 4.4 and the voltages to ground for each of the measured magnets are plotted in figure 4.15. Looking at the smallest obtained magnet positions, it can be seen that a lot of the positions include magnets that have already quenched at the time the short occurred. This means that for those magnets at the time of the short, the voltage difference when moving from one magnet to the next, the voltage difference is equal to 1.2 V instead of the expected ≈ 11.1 V that is seen for the non quenched magnets in the chain. Since it is also know that an error exists in the calculated values of the current in the circuit, when compared to the measured ones, it would not be correct for the algorithm to claim that the short occurred in the short position with the smallest distance. Instead, a list of the possible positions with the highest probability is returned. With knowledge that the short position occurred at magnet 149, it is seen that the algorithm includes the correct short position in the range of possible values that it provides as output, despite the fact that it is not the one for which the minimum distance value was obtained.
Figure 4.15: Comparison of measured voltage to ground over magnet position curve and the analytically calculated ones for different short positions with a short resistance of $R_s = 0.1 \Omega$.

4.5 Discussion and Future Work

To conclude, the first test of the algorithm using measured data as input, shows promising results. For the analysed short to ground event, the fact that all magnets after position 146 had already quenched, results in a large number of curves that all have small distance values when compared to the measured curve and are all characterised as possible solutions. Despite this fact, the algorithm successfully identified the range of the short resistance, that includes the accurate value known following onsite measurements. The algorithm also narrowed the possible short positions to 10 magnets, with the actual short position included in the range. This information required a total time of about 250 s to be provided, after the measured data had been provided as input, which is significantly faster than the time that numerical simulations would require.

A first test of the algorithm has been performed in this thesis. Considering the promising results, further testing is deemed necessary using measurement data from different short to ground events. For the event analysed in this work, the magnet at which the short occurred had quenched before the appearance of the short. Additionally this was also the case for the magnets in positions directly following and preceding the short position. It would be interesting hence to test the algorithm on an event for which the magnet where the short occurs is not quenched and observe whether a smaller range of possible short positions can be identified by the algorithm due to larger deviations in the final distance values. It has been described that the algorithm reaches a conclusion regarding the position where the short occurred by calculating the voltage to ground values at a specific time instance. It would be of interest hence to investigate whether
and by how much the results provided by the algorithm change, when a time instance belonging to the time range where larger relative error values are obtained is provided. Finally, by reducing the time that is needed for computing the result of the symbolic solutions for the currents in the circuit, the algorithm could be run online. In this case, the results would be computed for time instances only a few seconds apart, meaning that information about the short could become available even more quickly.
The LHC main dipole circuit consists of 8 sectors, each including 154 superconducting main bending dipole magnets. During normal operation, the current in the circuit is ramped up to a nominal value after which it reaches a plateau, with the inductive voltage to ground values of the magnets following the same behaviour. In the event that a short to ground occurs in the circuit, among other cases, a fast power abort is triggered which is followed by the opening of two switches inserting two energy extraction resistors in the circuit, where voltage drops occur.

The first focus point of this thesis has been the analysis of the LHC main dipole circuit, in order for the worst cases to be identified for different parameters of the short to ground. After obtaining a better understanding of the circuit behaviour when a short occurs, an algorithm able to provide information on a short circuit that occurred has also been developed and tested.

In chapter 2, a general introduction to the models of the LHC main dipole circuit that can be used to perform numerical simulations has been provided. A short description of the process of the fast power abort, which can be triggered among other cases also when a short exists in the model, has been detailed. A brief analysis of the circuit behaviour during the abrupt events of the fast power abort is has also been provided.

In chapter 3, a short to ground has been modeled and its effect on the circuit and more specifically the voltage to ground values of different magnets in the circuit has been discussed. The blow up behaviour of the fuse that exists in the grounding lines of the circuit has been discussed, which when included in the model of the circuit, increases the accuracy of the model for the case that a short to ground has occurred. A simulation scheme has been proposed to achieve the modeling of the fuse by developing a common interface that combines PSpice simulations and numerical calculations in MATLAB. The results of the simulations after performing a parametric sweep for the short position and the short resistor value have been presented, in order to identify the worst cases of the obtained voltages to ground in the circuit. The chapter concludes with the identification
of three main extreme voltage to ground values that can appear at magnets, when different combinations of short resistance and short position are made. A maximum peak value of 2.2 kV has been determined for the circuit, which can occur at magnet positions 57-77 and 78-98 in the cases that the fuse blows up and the resistance of the short has a value less or equal to 10 Ω. For cases where the short to ground resistance has a value larger than 10 Ω, the worst case peaks obtain lower values.

In chapter 4, an algorithm able to provide information concerning a single short to ground that has occurred in the LHC main dipole circuit has been proposed. The differential equations of a simplified model of the LHC main dipole circuit, which reproduces the behaviour of the circuit under the existence of a fault, have been successfully derived and solved. During this process, a limitation has been revealed due to the fact that the discharge time constant value varies with time in the circuit, which reduces the accuracy of the algorithm for times far away from time $t_0$. At the same time, however this error reaches a value of about 17%, which can be considered relatively small, since the accelerator circuit is modeled while ignoring all the nonlinear effects and using only resistive and inductive elements. The algorithm has been tested using measured signal data from a short circuit to ground event that occurred in the circuit. The algorithm determines the 10 possible positions where the short to ground likely occurred with the correct position included in the range. Regarding the short resistance, the algorithm specified a range of possible resistance values that also included the value of the resistance previously determined from measurements performed on the magnet. Finally, with the reduction of the main dipole circuit to an equivalent circuit model consisting solely of resistive and inductive elements, the values of which are automatically calculated, it becomes possible to apply the algorithm to other accelerator circuits by simply changing its input parameters.
BIBLIOGRAPHY


APPENDIX A

A.1 Wye-Delta Transform

The Wye-Delta transform is used in order to simplify the resistor branch that models the second energy extractor of the circuit, namely Energy Extraction 2 (EE2). In this section of the Appendix, an analytic derivation of the equivalent resistances $R_1$, $R_2$, $R_3$ included in the circuit of figure A.1b as a function of the resistors $R_{EE21}$, $R_{EE22}$, $R_{EE23}$ and $R_{EE24}$ of the configuration shown in figure A.1a is detailed. The derived equivalent resistances are used to calculate the values of resistances $R_{bf}, R_{af}$ and inductances $L_{bf}, L_{af}$ of the lumped circuit of figure A.1c.

\[ R_{total} = R_{EE23} + R_{EE24} + (R_{EE22} + R_{EE21}) \]  \hspace{1cm} (A.1)

\[ R_1 = \frac{R_{EE23}(R_{EE22} + R_{EE21})}{R_{total}} \]  \hspace{1cm} (A.2)

\[ R_2 = \frac{R_{EE24}(R_{EE22} + R_{EE21})}{R_{total}} \]  \hspace{1cm} (A.3)

\[ R_3 = \frac{R_{EE24}R_{EE23}}{R_{total}} \]  \hspace{1cm} (A.4)
(a) Reduced circuit of the LHC main dipole circuit for the case when a short to ground has occurred

(b) Wye-Delta transform applied to circuit

(c) Final circuit simplification with minimum number of parameters

Figure A.1: Stages of equivalent circuit transformation of the initial circuit (top) to the final simplified LHC circuit diagram (bottom) using the Wye-Delta Transform.
A.2 LHC Magnet Crate Layout

<table>
<thead>
<tr>
<th>1 Pin</th>
<th>2 Pin</th>
<th>3 Pin</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>154</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>153</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>152</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>151</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>150</td>
<td>6</td>
</tr>
<tr>
<td>149</td>
<td>7</td>
<td>148</td>
</tr>
<tr>
<td>8</td>
<td>147</td>
<td>9</td>
</tr>
<tr>
<td>146</td>
<td>10</td>
<td>145</td>
</tr>
<tr>
<td>11</td>
<td>144</td>
<td>12</td>
</tr>
<tr>
<td>143</td>
<td>13</td>
<td>142</td>
</tr>
<tr>
<td>14</td>
<td>141</td>
<td>15</td>
</tr>
<tr>
<td>140</td>
<td>16</td>
<td>139</td>
</tr>
<tr>
<td>17</td>
<td>138</td>
<td>38</td>
</tr>
<tr>
<td>137</td>
<td>19</td>
<td>156</td>
</tr>
<tr>
<td>20</td>
<td>135</td>
<td>21</td>
</tr>
<tr>
<td>134</td>
<td>22</td>
<td>133</td>
</tr>
<tr>
<td>23</td>
<td>132</td>
<td>24</td>
</tr>
<tr>
<td>131</td>
<td>25</td>
<td>150</td>
</tr>
<tr>
<td>26</td>
<td>125</td>
<td>27</td>
</tr>
<tr>
<td>128</td>
<td>28</td>
<td>127</td>
</tr>
<tr>
<td>29</td>
<td>126</td>
<td>30</td>
</tr>
<tr>
<td>125</td>
<td>31</td>
<td>124</td>
</tr>
<tr>
<td>32</td>
<td>123</td>
<td>33</td>
</tr>
<tr>
<td>122</td>
<td>34</td>
<td>121</td>
</tr>
<tr>
<td>35</td>
<td>120</td>
<td>38</td>
</tr>
<tr>
<td>119</td>
<td>37</td>
<td>118</td>
</tr>
<tr>
<td>38</td>
<td>117</td>
<td>39</td>
</tr>
<tr>
<td>116</td>
<td>40</td>
<td>115</td>
</tr>
<tr>
<td>41</td>
<td>114</td>
<td>42</td>
</tr>
<tr>
<td>113</td>
<td>43</td>
<td>117</td>
</tr>
<tr>
<td>44</td>
<td>111</td>
<td>45</td>
</tr>
<tr>
<td>110</td>
<td>46</td>
<td>109</td>
</tr>
<tr>
<td>47</td>
<td>108</td>
<td>48</td>
</tr>
<tr>
<td>107</td>
<td>49</td>
<td>106</td>
</tr>
<tr>
<td>50</td>
<td>105</td>
<td>51</td>
</tr>
<tr>
<td>104</td>
<td>52</td>
<td>103</td>
</tr>
<tr>
<td>53</td>
<td>102</td>
<td>54</td>
</tr>
<tr>
<td>101</td>
<td>55</td>
<td>100</td>
</tr>
<tr>
<td>56</td>
<td>99</td>
<td>57</td>
</tr>
<tr>
<td>98</td>
<td>58</td>
<td>97</td>
</tr>
<tr>
<td>59</td>
<td>96</td>
<td>60</td>
</tr>
<tr>
<td>95</td>
<td>61</td>
<td>54</td>
</tr>
<tr>
<td>62</td>
<td>93</td>
<td>63</td>
</tr>
<tr>
<td>92</td>
<td>64</td>
<td>91</td>
</tr>
<tr>
<td>65</td>
<td>90</td>
<td>66</td>
</tr>
<tr>
<td>89</td>
<td>67</td>
<td>88</td>
</tr>
<tr>
<td>68</td>
<td>87</td>
<td>69</td>
</tr>
<tr>
<td>86</td>
<td>70</td>
<td>85</td>
</tr>
<tr>
<td>71</td>
<td>84</td>
<td>72</td>
</tr>
<tr>
<td>83</td>
<td>73</td>
<td>82</td>
</tr>
<tr>
<td>74</td>
<td>81</td>
<td></td>
</tr>
<tr>
<td>75</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td>76</td>
<td>75</td>
<td></td>
</tr>
<tr>
<td>77</td>
<td>78</td>
<td></td>
</tr>
</tbody>
</table>

Figure A.2: Electrical position of magnets included in each of the 54 crates.
A.3 Expressions For $\sigma$ Parameters Of Analytical Solutions

The solutions for currents $I$ and $I_{\text{SHORT}}$ that are obtained by analytically solving the differential equations 4.9 and 4.10 are presented in figure A.3. The equations also contain 42 $\sigma$ parameters which are a function of the elements of circuit 4.3 and are presented in figure A.4 and A.5 respectively.

A.4 GitLab Repository

The MATLAB scripts and the netlist models that were used to perform the parametric analysis for different short positions and resistance values, as well as model the fuse can be found in the Fault Analysis repository on the STEAM GitLab page. The short circuit algorithm described in the second part of the thesis is also included in the repository. The link is provided below. It should be mentioned however, that a CERN account is required to access the repository.

https://gitlab.cern.ch/steam/fault-analysis
\[ I = -e^{-\frac{\tau c_3}{2L a f L b f}} \left( \sigma_{34} - \sigma_{33} - L a f \ Quenchedbf \sigma_{42} + L b f \ Quenchedbf \sigma_{42} - \sigma_{22} + \sigma_{21} + \sigma_{20} - \sigma_{19} + \sigma_{18} - \sigma_{17} - I_0 \ L a f \ R b f \sigma_{42} + \right) \]
\[ + I_0 \ L b f \ R a f \sigma_{42} - L a f \ L b f \ Quenchedbf \ R a f + L a f \ L b f \ Quenchedbf \ R b f - L a f \ L b f \ Quenchedbf \ R g + L a f \ L b f \ Quenchedbf \ R g - \sigma_{35} \sigma_{42} \]
\[ - L a f \ L b f \ Quenchedbf \ R s + L a f \ L b f \ Quenchedbf \ R s + \sigma_{16} - \sigma_{15} + \sigma_{14} - \sigma_{13} - \sigma_{26} + \sigma_{25} - \sigma_{34} + \sigma_{32} + \]
\[ + \frac{e^{\sigma_{25}+\sigma_{23}+\sigma_{26}+\sigma_{28}+\sigma_{27}+\sigma_{30}+\sigma_{29}}}{2 L a f L b f \ (R g \ (L a f + L b f) - \sigma_{12} + R s \ (L a f + L b f) + L a f \ R b f + L b f \ R a f) \ \sigma_{42}} \]
\[ \left( \frac{\sigma_{35}}{2 \ \sigma_{41}} \right) - e^{-\frac{\tau c_3}{2L a f L b f}} \left( \sigma_{34} - \sigma_{33} - L a f \ Quenchedbf \sigma_{42} - L b f \ Quenchedbf \sigma_{42} - \sigma_{22} + \sigma_{21} + \sigma_{20} - \sigma_{19} + \sigma_{18} - \sigma_{17} + \right) \]
\[ + \frac{e^{\sigma_{32}+\sigma_{31}+\sigma_{36}+\sigma_{38}+\sigma_{37}+\sigma_{40}}}{2 L a f L b f \ (\sigma_{22} + R g \ (L a f + L b f) + R s \ (L a f + L b f) + L a f \ R b f + L b f \ R a f) \ \sigma_{42}} \]

\[ I_{\text{short}} = e^{-\frac{\tau c_3}{2L a f L b f}} \left( \sigma_{34} - \sigma_{33} + L a f \ Quenchedbf \sigma_{40} - L b f \ Quenchedbf \sigma_{40} - \sigma_{22} + \sigma_{21} + \sigma_{20} - \sigma_{19} + \sigma_{18} - \sigma_{17} + \right) \]
\[ + I_0 \ L a f \ R b f \sigma_{40} - L a f \ L b f \ Quenchedbf \ R a f + L a f \ L b f \ Quenchedbf \ R b f - L a f \ L b f \ Quenchedbf \ R g + L a f \ L b f \ Quenchedbf \ R g - \sigma_{36} \sigma_{40} \]
\[ - L a f \ L b f \ Quenchedbf \ R s + L a f \ L b f \ Quenchedbf \ R s + \sigma_{16} - \sigma_{15} + \sigma_{14} - \sigma_{13} - \sigma_{26} + \sigma_{25} - \sigma_{34} + \sigma_{32} + \]
\[ + \frac{e^{\sigma_{25}+\sigma_{23}+\sigma_{26}+\sigma_{28}+\sigma_{27}+\sigma_{30}+\sigma_{29}}}{2 L a f L b f \ (R g \ (L a f + L b f) + R s \ (L a f + L b f) + L a f \ R b f + L b f \ R a f) \ \sigma_{40}} \]
\[ \left( \sigma_{35} \sigma_{40} \right) \]
\[ + I_0 \ L a f \ R b f \sigma_{40} + I_0 \ L b f \ R a f \sigma_{40} - L a f \ L b f \ Quenchedbf \ R a f + L a f \ L b f \ Quenchedbf \ R b f - L a f \ L b f \ Quenchedbf \ R g + L a f \ L b f \ Quenchedbf \ R g + \]
\[ \sigma_{35} \sigma_{40} \]
\[ + \frac{e^{\sigma_{32}+\sigma_{31}+\sigma_{36}+\sigma_{38}+\sigma_{37}+\sigma_{40}}}{2 L a f L b f \ (R g \ (L a f + L b f) + R s \ (L a f + L b f) + L a f \ R b f + L b f \ R a f) \ \sigma_{40}} \]

Figure A.3: Analytical solution of current $I$ and $I_{\text{short}}$ in the simplified circuit of figure 4.3.
Figure A.4: Analytical expression for parameters $\sigma_1$ to $\sigma_{16}$ and $\sigma_{18}$ to $\sigma_{34}$ included in the solution of $I$ and $I_{short}$ shown in figure A.3.
\[ \sigma_{35} = L_{af}^2 \text{Rbf Quenchedbf} \]
\[ \sigma_{36} = L_{af} \text{Quenchedbf} + L_{af} \text{Quenchedaf} - L_{af} \text{Quenchedbf} \]
\[ \sigma_{37} = L_{af} \text{Rbf} - L_{bf} \text{Raf} \]
\[ \sigma_{38} = 2 L_{af} L_{bf} \text{Quenchedbf} \sigma_{42} \]
\[ \sigma_{39} = 2 L_{af} L_{bf}^2 \text{Quenchedaf} \sigma_{42} \]
\[ \sigma_{40} = \frac{I \sigma_{42}}{2 L_{af} L_{bf}} \]
\[ \sigma_{41} = L_{af} \text{Rbf} - L_{bf} \text{Raf} \]
\[ \sigma_{42} = 2 L_{a} L_{bf} \left( \sigma_{35} + \sigma_{41} - \sigma_{33} - \sigma_{32} + \sigma_{34} + \sigma_{40} - \sigma_{20} - \sigma_{23} + \sigma_{27} + \sigma_{26} - \sigma_{25} - \sigma_{24} \right) \]
\[ - L_{af} L_{bf} \text{Raf Quenchedbf} - L_{af} L_{bf} \text{Raf Quenchedaf} + L_{af} L_{bf} \text{Raf Quenchedbf} \]
\[ + L_{af} L_{bf} \text{Rbf Quenchedaf} + \text{R} + L_{af} L_{bf} \text{Rg Quenchedbf} + L_{bf} \text{Rg Quenchedbf} \]
\[ + L_{bf} \text{Rg Quenchedaf} - \sigma_{23} + L_{af} L_{bf} \text{Rs Quenchedbf} + L_{bf} \text{Rs Quenchedbf} - \sigma_{22} \right) \]
\[ - 2 L_{af} L_{bf} \sigma_{36} \left( L_{af} \text{Rbf} + L_{bf} \text{Raf} + L_{af} \text{Rg} + L_{bf} \text{Rg} + L_{bf} \text{Rs} + L_{bf} \text{Rs} \right) \]
\[ \sigma_{42} = \sqrt{L_{af}^2 \text{Rbf}^2 + 2 L_{af}^2 \text{Rbf Rg} + 2 L_{af}^2 \text{Rbf Rs} + L_{af}^2 \text{Rg}^2 + 2 L_{af}^2 \text{Rg Rs} + L_{bf}^2 \text{Rs}^2} \]
\[ - 2 L_{bf} \text{Raf Raf Rbf} - 2 L_{af} \text{Lbf Raf Raf} - 2 L_{af} \text{Lbf Raf Rs} - 2 L_{af} \text{Lbf Rbf Raf Rg} - 2 L_{af} \text{Lbf Rbf Raf Rs} \]
\[ + 2 L_{af} \text{Lbf Raf Raf} + 2 L_{af} \text{Lbf Rg}^2 + 4 L_{af} \text{Lbf Rg Rs} + 2 L_{bf} \text{Lbf Rs}^2 + L_{bf}^2 \text{R Raf}^2 + 2 L_{bf}^2 \text{R Raf Rg} \]
\[ + 2 L_{bf}^2 \text{R Raf Rs} + L_{bf}^2 \text{Rg}^2 + 2 L_{bf}^2 \text{Rg Rs} + L_{bf}^2 \text{Rs}^2 \]

**Figure A.5:** Analytical expression for parameters \( \sigma_{35} \) to \( \sigma_{37} \), \( \sigma_{41} \) and \( \sigma_{42} \) included in the solution of \( I \) and \( I_{\text{SHORT}} \) shown in figure A.3.