Transient Study in Diesel Synchronous Generator

By

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Submitted to the Department of Electrical Engineering, Electronics, Computers and Systems

in partial fulfilment of the requirements for the degree of

Erasmus Mundus Master Course in Sustainable Transportation and Electrical Power Systems

at the

UNIVERSIDAD DE OVIEDO

September 2017

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Abstract

Diesel generators have multiple uses in nowadays applications and they will play an important role in the electrification of future. These generators can be used in islanded grids, small grids, as backup systems, as ship generators or as auxiliary generators in nuclear power plants, reason why they are versatile and of particular importance.

Transient response of the machine when short-circuits occur at the generator terminals or when loads are connected and disconnected from the system, are a key factor to know in order to identify the safety working limits, to calculate the necessary protections and to not affect the other elements connected to the grid.

The system under analysis in the master thesis is a diesel generator composed by a main salient pole synchronous generator, which is connected in the rotor to a three-phase diode bridge rectifier. The rectifier is connected with the rotor of a main exciter. The system is controlled by an automatic voltage regulator (AVR), which is fed by a permanent magnet pilot exciter. Main and pilot exciter are rotative. Their rotative parts are placed in the same shaft as the main generator. Their static parts are placed in the frame of the main generator.

The scope of the master thesis is to calculate and simulate the transient and post-transient response of the diesel generator system in their most influencing events; which are short circuit phenomenon and sudden connection or disconnection of loads.

The tool used for the calculation and simulation during the development of the final master's work is the software Matlab / Simulink. This software allows simulations in a reduced time and with high precision. Besides, it is a software massively used in the industry and in research and development on electrical design departments of the companies. Therefore, the tool that is going to be developed will save time and resources for analysing transient performance than other tools used in the industry.

The output of the simulated model will be a graphical representation of the evolution of the currents during the short-circuit time for the short-circuit phenomenon. On the other hand, another simulated graphical representation output will be the evolution of the voltage dip when sudden connection or disconnection of loads exits.

Keywords: Synchronous generator, Transient, Short-circuit, Voltage dip, Exciter, Automatic voltage control, Speed control.

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Acknowledgments

I would like to express my sincere gratitude to my dissertation supervisor and program coordinator of EMMC STEPS master course Dr. Pablo García Fernández for his continuous support and guidance throughout the last two years.

Furthermore, I would like to thank my internship supervisor, Jaime Peredo Argos engineering manager of Rotating Machines Department at Gamesa Electric for giving me the opportunity to develop my master thesis and to work in an innovative company.

Moreover, I am also grateful to Alvaro Martinez Saez, Sr. engineer at Gamesa Electric, who facilitated all the information and literature needed to successfully develop this master thesis and my internship stay. I would like to thank him for the valuable explanations, interpretations and engagement though all this time.

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List of Acronyms and Definitions

Acronyms	Definitions
AVR	Automatic voltage regulator
DC	Direct current
AC	Alternating current
p.u.	per unit
e.m.f, E_0	Electromagnetic field
P_n	Total three-phase apparent power
V_n	RMS line-to-line voltage
f_n	Frequency
p	Number of pole pair
R_s	Stator resistance
L_l	Stator leakage inductance
X_l	Stator leakage impedance
X_2	Negative sequence reactance
R_r	Rotor resistance
X_d	Direct axis synchronous reactance
X'_d	Direct axis transient synchronous reactance
X''_d	Direct axis subtransient synchronous reactance
X_q	Quadrature axis direct synchronous reactance
X''_q	Quadrature axis subtransient synchronous reactance
T'_d	Direct axis transient short-circuit time constant
T''_d	Direct axis subtransient short-circuit time constant
T''_q	Quadrature axis subtransient short-circuit time constant
T_a	Armature time constant
T_i	Stator short-circuit time constant
I_{ccp}	Permanent current
I'_d	Transient current
I''_d	Direct axis subtransient current
I''_q	Quadrature axis subtransient current
T_B and T_C	Time constant of lead-lag
K_A	Gain of the exciter regulator
T_A	Time constant of exciter regulator.
K_E	Gain of the exciter
T_E	Time constant of exciter regulator
K_C	Coefficient of rectifier commutation impedance
K_F	Gain of the damping filter
T_F	Time constant of the damping filter
R_E	Stator winding resistance of the exciter
L_E	Stator winding inductance of the exciter
K_d	Demagnetizing factor

Acronyms	Definitions
R_f	Rotor winding resistance of the synchronous generator
L_f	Rotor winding inductance of the synchronous generator
M	Mutual inductance between the rotor and stator windings of the synchronous generator
K_g	Gain of the synchronous generator
V	Voltage at generator terminals
V_f	Field/Rotor voltage of generator
I_a	Armature current
I_f	Filed/Rotor current of generator

Introduction

1.1. Background

Diesel generators have an important presence in nowadays world, they are used in multiple applications and they will develop and an important role in the future

Diesel is used broadly in developing countries as a primary generation system and in developed countries as backup generation system. Besides, it is used in islanded grids, small grids, as ship generators or as auxiliary generators in nuclear power plants.

The extensive and diverse usage of diesel is due to the advantages of the diesel powered generation systems. Those systems are reliable, simple, have a fast response and low cost in comparison with other powered solutions such as renewable energies, gas engines or microturbines. The technology is mature and does not need complicated maintenance. In addition, diesel generator sets are very compact, small in size and almost permanently available. Therefore, diesel is widely used and good for faraway areas.

The main drawbacks in the use of diesel are the price and availability of the fuel in some areas and the emissions due to the burning of the diesel. It is true that, diesel may not be an affordable solution for electrification to remote areas where the resource it is not available due to the high prices. Referring to the emissions, the technology has been developed in the last period of years to reduce the emissions and improve the efficiency.

Despite of the aforementioned drawbacks, diesel power is growing due to its versatility, reliability, fast response, efficiency and low emissions, which guarantee an important role of the technology in future power generation mix. [1]

Diesel generator manufacturers have to present the technical characteristics of the generators in order to provide, not only, all the necessary information to run the machine, but also, important information to size the protection elements connected to the grid.

The most harmful situation that a generator can experiment is a short-circuit event and the performance of the generator is a key factor to study to preserve the stability in the system. Besides, when connecting and disconnecting loads that are fed by the generation system, the voltage of the system changes and cannot exceed certain limits due to safety performance.

Therefore, to know the performance of diesel generating sets when harmful situations such us short-circuit events and connection and disconnection of loads, is necessary to define the electrical protections of the grid.

The information available on the data sheets is used by power system grid designers to select the protections according to the requirements of each power installation. [1]

1.2. Objectives

This dissertation focuses on the calculation and simulation of the transient response when short-circuits phenomena occur at diesel generator terminals and the voltage dip at diesel generator terminals when high inductive loads are connected and disconnected from the generation system.

The system under study is a power generation system composed by a main salient pole synchronous generator, which is connected in the rotor to a three-phase diode bridge rectifier. The rectifier is connected with the rotor of a main exciter. The system is controlled by an AVR, which is fed by a permanent magnets pilot exciter.

The steps to comprehensive the objectives are as follows:

- Searching and understanding the state of the art
- Searching and understanding simulation blocks available to characterize the generation system in Matlab/Simulink
- Modelling of the main salient pole synchronous generator block and comparison with the theoretical calculated results for a short-circuit event at generator terminals
- Addition of the rectifier, main exciter and AVR to the model and modelling the system composed by the main salient pole synchronous generator, rectifier, main exciter and AVR. Comparison with the theoretically calculated results and the previous simulations.
- Addition of the speed regulation to the model. Comparison with the theoretically calculated results and the previous simulations.
- Perform transient system response when high inductive loads are connected and disconnected from the generation system.

1.3. State of the art

Electric power systems should be designed to serve loads in a safe, reliable and efficient way. Therefore, control of short-circuit faults is one of the major considerations when designing a power system, but it is not the only consideration to take into account. Another important consideration is to know the working limits of the present generation systems in the electric power system and their transient response when the load changes.

Short-circuit current is defined as an overcurrent produced as a result of fault between live conductors with different potential value and operating under normal conditions. If short-circuits happen and they are uncontrolled, then, the power system can be damaged and the electric power system can suffer of service outages with associated lost time and accompanied inconvenience, interruption of essential facilities or vital services, extensive equipment damage, fire damage, and possibly human injury or fatality.

System and equipment design should be in a manner than faults in electric power systems should be avoided or minimized as much as possible. The consequences of short-circuits can be varied and serious:

- Electrical arcs, flashes and burning at the fault location with smoking from the fuel load of combustibles
- Increased current flows from different parts of the system to the fault, then all the components suffer of thermal and mechanical stress
- Voltage decrease in the system during the fault time, the voltage droop is proportional to the magnitude of the current. The maximum voltage droop happens at the fault point
- Enclosures in contact with live conductors may suffer the rising voltage and increase the hazard of electric shock

When a fault occurs, it should be fast removed from the power system to reduce as much as possible the undesired effects that the fault may cause in the power system. Therefore, the short-circuit test is an important tool to size properly protective devices, circuit breakers and fuses because they should be able to interrupt the maximum short-circuit current.

Transient performance of the generation system is necessary to know and to limit, because an uncontrolled transient response of the system due to the change in the loads of the power system may cause an undesirable situation that could drill into short-circuit faults. Therefore, the generation system transient response is tested to know the working limits of the generation system and to avoid undesirable hazardous situations.

Two ways have been presented to protect power systems, one is an active way about the operation of generation systems and another is a passive way about protecting the system. The idea is to avoid undesirable situations and to protect the system in case that undesirable situation occurs, as short-circuit on the power system. [2]

1.4. Thesis layout

The dissertation work is allocated in industrial collaboration at Rotating Electrical Machines Department of Gamesa Electric. This work analyses transient response of diesel synchronous generator when short-circuits occur at the generator terminals or when loads are connected and disconnected from the system. Firstly, a simulation model of the system is going to be designed with the software Matlab/Simulink. Secondly, the model is going to be validated by comparison of theoretical and simulated transient performance results. Finally, transient performance output is going to be analysed.

The transient analysis is done for a real machine studied in company, the data provided in this master thesis report are the necessary data to perform transient analysis of the generation system. However, extra data are not provided and neither technical data sheets due to confidential reasons.

Chapter 1 offers an introduction into the subject, explaining the background, study objectives and state of the art of transient response of diesel synchronous generators when short-circuits occur at the generator terminals or when loads are connected and disconnected from the system.

Chapter 2 explains the usage and importance of the generation system and describes the composition elements of the generation system.

Chapter 3 deals with the transient performance of the system when short-circuit occurs at generator terminals. In here, short-circuit phenomenon is explained, the simulation model is built and validated by comparison of results with theoretical results and transient performance results are analysed for different cases.

Chapter 4 deals with the transient performance of the system when sudden connection and disconnection of loads occurs at generator terminals. In here, the test is described, the simulation model is built and transient performance results are analysed for different cases.

Chapter 5 enumerates the tasks realized during the internship at Rotating Machines Department.

Chapter 6 provides the conclusions of the covered elements of this master thesis report and the future work of the subject treated.

Chapter 2

Description of the electric generating set

2.1. Usage and importance applications

Electric generating sets are becoming more important due to different necessities in the actual world, such as, demand of energy in remote areas and/or developing countries, unreliable electric supply from some companies, mainly in developing countries, and backup electric supply to sensitive usages such as hospitals, telecommunications, security and power plants.

Due to the wide possibilities of applications, diesel generators can offer different power supplies for different applications. Mainly, the usage of electric generating set can be divided in two categories:

- Backup electricity supply usage

A diesel generating set used as a backup supply to warranty the electricity supply because it can produce electricity in a constant way and at whatever time, reason why its usage is important when faults and outages happen in the grid. Besides, due to the constant supply, the reliability of the electricity supply increases and the damage on the connected loads are reduced.

- Normal electricity supply usage

A diesel generating set used as normal supply to provide electricity supply to usages where the electricity is needed but is not available. This kind of usage is really wide, from ships or campsites to construction sector or mining sector, remote areas and developing areas.

2.2. Description of the complete equipment

An electrical generating set is a machine that moves an electric generator to produce electric energy. The production of the electric energy in the electric generating set starts when the chemical energy in the fuel changes into mechanical energy in the motor and then mechanical energy changes into electric energy in the generator, this electric energy is supplied to the grid of the application.

The generating set has two main electrical machines, a diesel motor in where the change of chemical energy into mechanical energy is produced and a synchronous generator. The mechanical energy produced by the motor is used to move the shaft line where the complete generating set is placed, in other words, the motor and the synchronous generator share the shaft and the mechanical energy produced by the motor is used to produce the rotating of the shaft line.

The generating set has other machines in between the motor and the synchronous generator: a pilot exciter which is a permanent magnets synchronous generator, an AVR, a main AC exciter which is a synchronous generator and a three phase non-controlled rectifier, also mounted on the same shaft as the motor and the synchronous generator. Since the excitation of the synchronous generator includes a pilot exciter, then the generation system is completely independent of external power sources.

The pilot exciter has the permanent magnet mounted on the shaft and, due to the rotating of the shaft produced by the motor, the magnetic field is generated and the excitation field is created by the permanent magnets and current is induced into the armature of the pilot exciter and AC voltage is supplied from the pilot exciter armature to the AVR.

The AVR is a voltage control device that regulates the appropriate voltage level at the synchronous generator terminals. The control is done by providing the correct DC voltage, according to the situation in the complete system, to the armature of the main exciter. The main exciter field circuit is located on its stator; the excited field in the stator induces AC voltage on the rotor.

Later on, the output voltage of the main exciter is rectified by a three phase diode bridge rectifier. The DC output voltage of the rectifier is applied to the field winding of the synchronous generator placed in its rotor. The rotating magnetic field produced in the rotor induces AC voltage in the stator windings.

2.2.1. Description of the generation system

Synchronous machines are made by two independent windings placed on the rotor and the stator of the machine. The rotor winding of the synchronous generator is a DC excitation winding and the stator winding is a three phase AC winding.

The excitation system of the generator is fed with a DC current in the rotor winding from a main exciter which turns with the generator shaft. The main exciter is another synchronous generator where the excitation winding is placed on the stator and the inductor winding is placed in the rotor, the opposite to the main synchronous generator of the system. The output of the exciter is a three phase output, which is rectified by a diode bridge rectifier; the rectifier rotates within the shaft. The advantages of this excitation system are that the system does not need slip rings neither brushes.

All this system is controlled by an AVR, which maintains the voltage at generator terminals by a control loop of the electromagnetic field (e.m.f.) at the synchronous generator. This control is done by acting on the excitation current of the generator. [3]

The AVR is fed by a permanent magnets synchronous generator, called pilot exciter. The pilot exciter supplies low power to the AVR, which feds the rotor winding of the main exciter with DC current.

As final purpose, the main generator is excited in an independent manner.

A scheme of the complete generation system can be seen in figure 2-1.

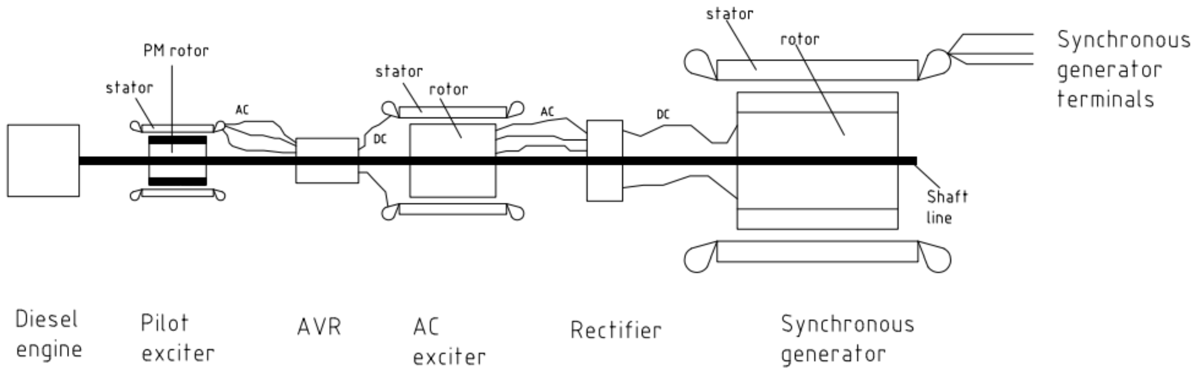

Figure 2-1: Complete generating set scheme

2.2.2. Description of the synchronous generator

Salient pole synchronous generator of the system is characterized, as many synchronous generators, by a uniformly slotted stator laminated core where AC three-phase winding is placed and concentrated DC excitation coil is hosted in the rotor slots. [4]

To produce an inductive voltage in the stator windings, a magnetic field should be produced in the rotor. The magnetic field induces voltage in the armature windings and, therefore, AC current flows through the armature windings.

Firstly, mechanical energy has to be applied to the machine axis to convert mechanical energy into electrical energy. The field winding of the rotor is fed by a DC voltage, so the rotating of the magnetic field generated by the rotor poles has relative movement to the stator windings. Since the relative movement and the magnetic field of the rotor is produced, then the magnetic field that crosses the stator windings will change with the time and three-phase sinusoidal waveforms of induced voltage in the stator windings will be produced.

Synchronous machines, motors or generators, are characterized for being an AC machine that under steady state conditions, its speed is proportional to the frequency of the armature current

The stator is the fixed part of the machine, it is built with ferromagnetic material and uniformly distributed winding along its circumference.

The design on the generator is made with the purpose of reducing the harmonics content of the voltage induced by the motion of the rotor. To do that, the stator slots have magnetic wedges that reduce the field space harmonics and consequently the electromagnetic force harmonics plus additional losses in the rotor damper cage.

In steady state operation, the currents in the rotor damper cage are zero. On the other hand, when any transient occur the effect on the damper cage is that eddy currents appear to mitigate the oscillations in the rotor due to the transient event.

Figure 2-2: Stator [5]

The rotor is the part of the machine that rotates inside the stator, it is built with ferromagnetic material and the field winding. The function of the field winding is to produce a constant magnetic field to interact with the field produced by the winding of the stator.

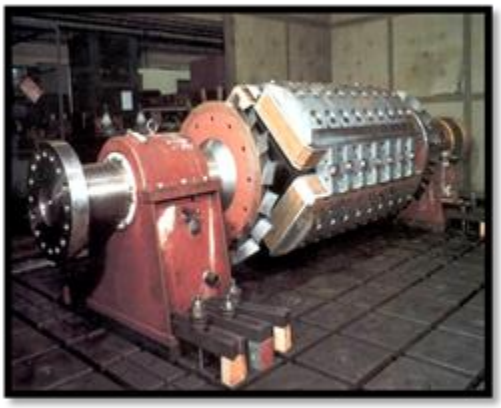

Figure 2-3: Rotor [5]

The per-phase equivalent circuit for a salient pole synchronous generator is in figure 2-4:

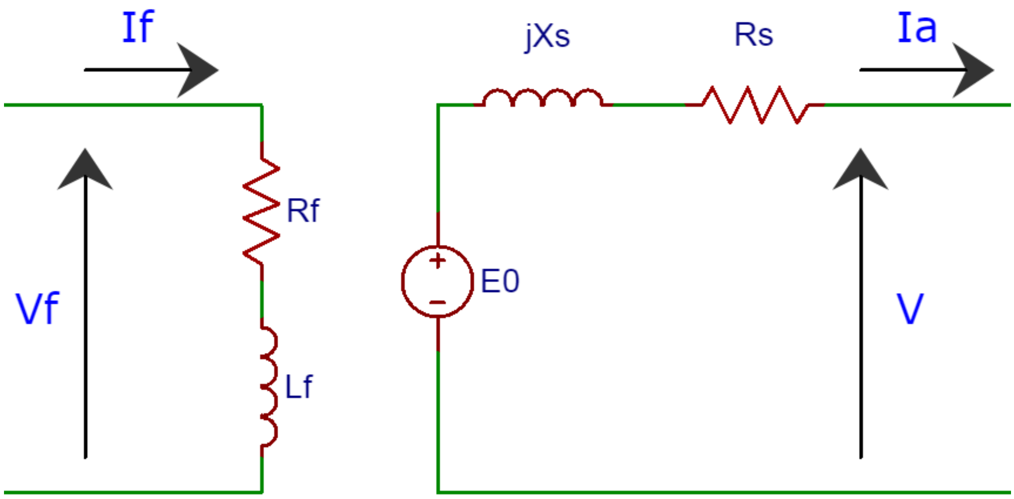

Figure 2-4: Equivalent circuit

where:

V_f: field/rotor voltage
I_f: field/rotor current
R_f: field/rotor resistance
L_f: field/rotor inductance
E_0: e.m.f.
X_s: synchronous reactance of the generator
R_s: stator resistance
I_a: current supplied by the generator
V: voltage at generator terminals

2.2.3. Description of the excitation system

The excitation system is composed by the AVR, the main exciter and the diode bridge rectifier, where the main element is the exciter. The exciter with the rectifier, provides the necessary DC current to generate the e.m.f. in the generator.

The purpose of the AVR is to maintain the voltage value at the generator terminals within the variation limits from the voltage reference value, even though load flow changes happen in the system. [3]

The excitation system used is a brushless excitation system; this type of excitation systems are very popular for big capacity synchronous generators, because the slip rings and brushes are eliminated. Therefore, the reliability of the generation system is increased and the maintenance is reduced.

The synchronous generator is excited by its rotor excitation windings when DC current is supplied to them by a rotating diode bridge rectifier placed on the shaft. The rectifier is fed with AC current provided by the main exciter, which is a synchronous generator with the rotating armature on the same shaft as the synchronous generator. The main exciter provides AC voltage to the rectifier by its rotor windings. The main exciter is supplied with DC voltage on its stator windings by the regulator. Besides, the voltage regulator power is taken from a pilot exciter, which is a permanent magnet generator and is not affected by external transients on the grid. [6]

2.2.4. Description of the pilot exciter

The pilot exciter is a permanent magnet AC generator which has permanent magnets rotor. It is similar to a synchronous generator, except that it has permanent magnets instead of field windings. [7]

In this type of alternators, the magnetic field is obtained from the permanent magnets and its relative movement. The field current of the exciter is produced by the permanent magnets, which in turn, produces the field current of the main synchronous generator.

The rotor is made with parallelepiped permanent magnets placed around the rotor. The stator contains laminated core with uniform slots to host the three-phase winding. [4]

Figure 2-5 shows a schematic of a non-salient pole PM rotor. This figure represents the eight poles permanent magnets pilot exciter of the system.

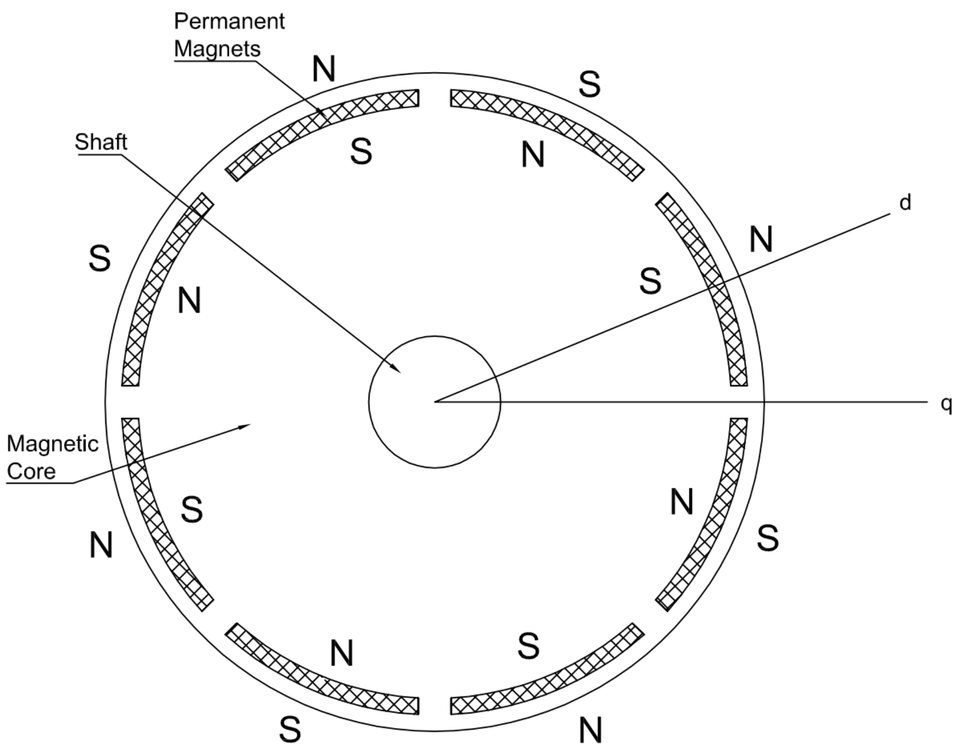

Figure 2-5: Schematic of a non-salient pole PM rotor

Chapter 3

Transient performance when short-circuit occurs at generator terminals

3.1. Introduction

Transient response of the diesel generator machine when short-circuits occur at the generator terminals, are a key factor to know in order to calculate the necessary protections and to not affect the other elements connected to the grid.

Asymmetric short-circuit events on the grids are more often than symmetric short-circuit events. According to production and distribution system operators, the frequency rate of three phase short-circuits in the grid is between 0% and 5% of the cases. Meanwhile, phase to phase short-circuit frequency rate is between 5% and 10% of the cases. For the phase to phase and ground short-circuit, frequency rate is between 10% and 15%. Finally, the most frequent short-circuit on the grid is the phase to ground short-circuit, with a frequency rate between 70% and 80%. [8]

Despite the high rates of the asymmetric short-circuit events on the grid, the worst case scenario is when a symmetric short-circuit happens because the most extreme current values are experienced during this type of short-circuits, consequently the protections designed to the grid have to insurance those extreme current values.

Therefore, three phase short-circuits are needed to be carefully studied to protect the grid elements to this phenomenon. Besides, due to the more often asymmetric phase to phase short-circuit events and, since this type, is the most extreme case of unbalance load sharing, it is interesting to study.

As it was previously mentioned, the diesel generator under study is by a main salient pole synchronous generator connected in the rotor to a three-phase diode bridge rectifier. The rectifier is connected with the rotor of a main exciter and the system is controlled by an AVR which is connected to a permanent magnets pilot exciter.

This section provides the information about the performance of a salient pole synchronous generator during a sudden three-phase short-circuit and a phase to phase short-circuit in the stator terminals. In accordance with this purpose, the performance of the generator is evaluated by analysing the current short-circuit waveforms which are obtained by two different methods. One method is based on the theory present in the literature and the other method is based on simulation of the generator performed with the software

Matlab/Simulink. This software allows simulations in a reduced time and with high precision.

Moreover, the current waveforms obtained by the theoretical method are verified by two different equations in order to corroborate the results. The first equation is the one explained in the book “Curso moderno de máquinas eléctricas rotativas” from M. Cortes Cherta [8] and the second equation is the one explained in the paper “Synchronous machine parameter determination using the sudden shot-circuit axis currents” from F. R. Blánquez [9]

Along this point 3.1., it has been mentioned the terms asymmetric short-circuit and symmetric short-circuit. Those concepts will be explained in the point 3.3. of this chapter. However, firstly the description of the short-circuit phenomenon will be achieved in the point 3.2.

3.2. Description of the phenomenon

The phenomenon under study are the transient currents of the stator of a synchronous machine when a quickly and abruptly short-circuit happens at the machine terminals.

All windings of the salient pole synchronous generator take an important part during the transient and must be taken into account.

For explaining the phenomenon, let’s assume that the synchronous machine is working under no-load conditions before the short-circuit. This means that the voltage RMS in the machine terminals and the e.m.f. are equal (3.1).

$$E_0 = V \tag{3.1}$$

Each stator phase current has a starting value of zero and ends with an RMS value of the permanent current I_{ccp} when the steady state is reached and where the current is a sinusoidal time dependent waveform. Due to the evolution of the current, the magnetic field of the generator will also change.

Since the generator windings are inductive, the flux and the currents cannot change instantly between both stages, no-load and short-circuit steady state. There is a transition time, called transient, for the state adaptation of the flux and currents.

Figure 3-1 shows an example of the evolution of the three phases currents during a sudden three phase short-circuit, one graph per phase. It is easy to see that the currents between the phases are shifted by 120º from each other. Besides, the three-phase short-circuit currents depend on the instant in the time when the fault occurs. [10]

Each phase current can be disregarded into a DC transient component, represented as a red line in figure 3-1, and as a symmetrical AC component, which is represented in figure 3-2. [11]

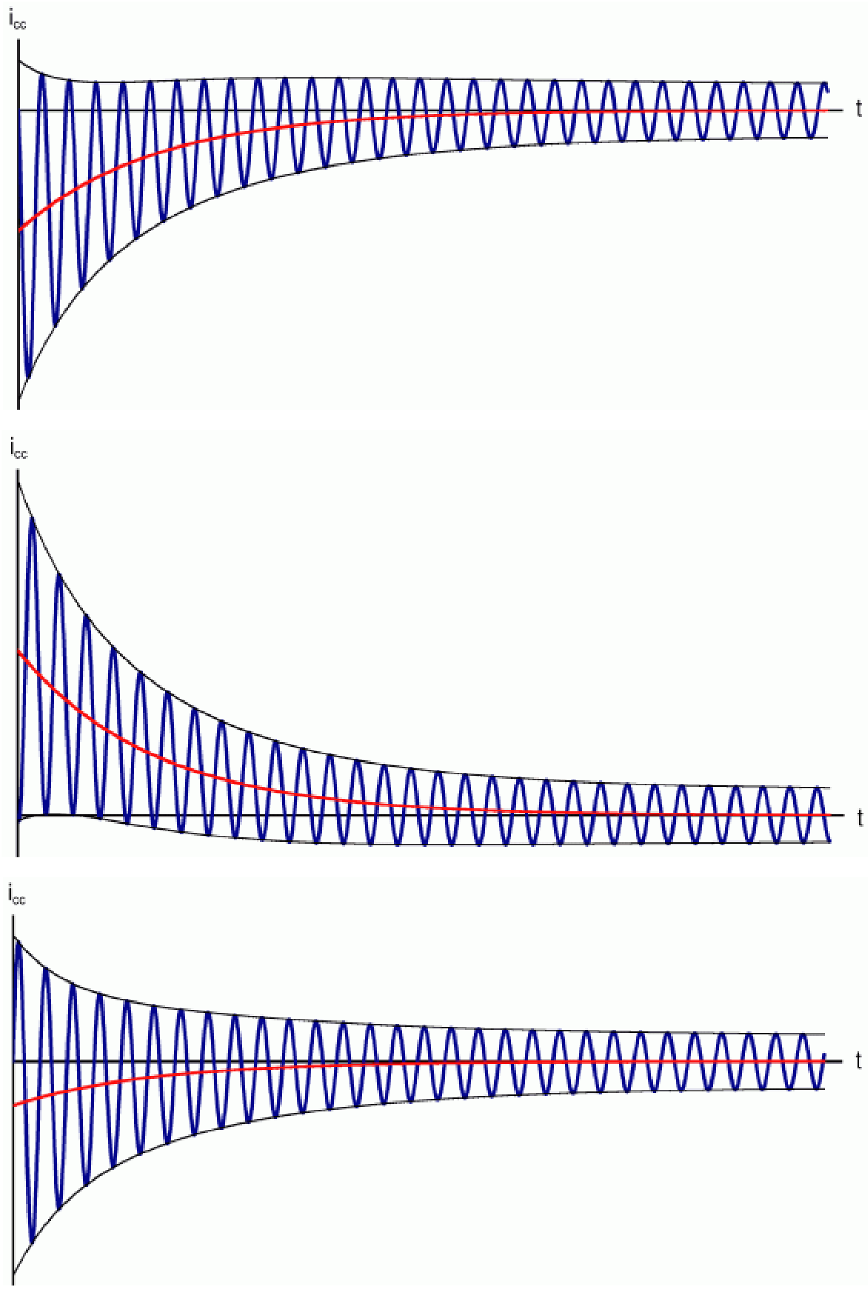

Figure 3-1: Currents of a sudden three-phase short-circuit between the three phases in salient pole synchronous generator terminals, one graph per phase. [10]

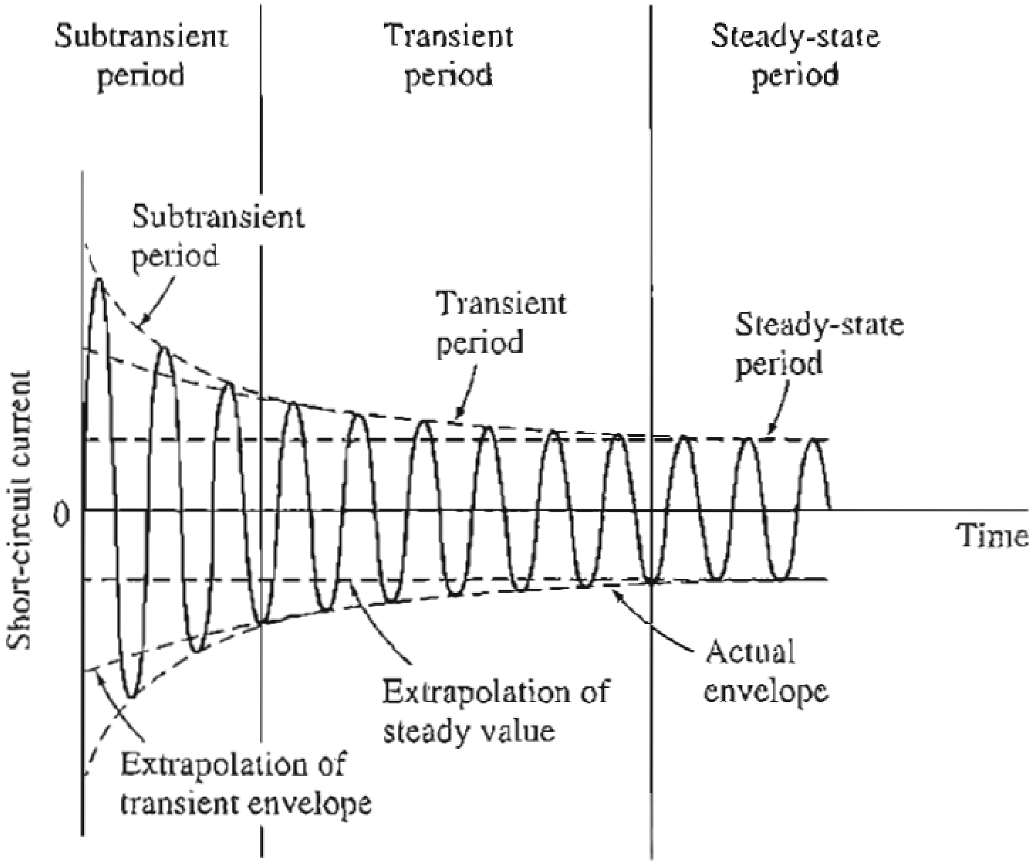

Figure 3-2: Symmetrical AC component of one phase current in a three-phase short-circuit situation in salient pole synchronous generator terminals. [11]

To analyse the phase current waveform it is very useful to decomposed it into different components. The decomposition criterion is to divide the waveform into several time periods in where a unique constant reactance is considered per period. [9]

The difference between the two theoretical methods, that are going to be analysed in the next points, is on the different time periods division proposed in each method.

3.3. Symmetrical and asymmetrical currents

In the previous points 3.1 and 3.2 the terms asymmetrical current and symmetrical current had been mentioned, but not explained. At this point both terms are going to be defined and explained.

The difference between asymmetrical and symmetrical current is on the displacement of the AC waves from the zero axis. Looking at the envelope of the peaks of the current waveforms, if the waves are symmetrical around the zero axis, then the current is called symmetrical current. However, if the envelopes of the peaks of the current waveforms are not symmetrical around the zero axis, then the current is called asymmetrical current.

The asymmetrical current reaches its maximum during the first cycles after short-circuit happens and by the next cycles it becomes gradually symmetrical. Since, in rotating machines, the current decays over time because of the flux in the machines is reduced after short-circuit, then the total short-circuit current decays with time and the highest values are reached during the first half cycle of the short-circuit event. These values are further increased by the DC component. However, DC component also decays with time.

This type of current is usually decomposed into two components to be analysed, symmetrical current component and DC current component. [12]

Figure 3-3 shows this decomposition and in figure 3-1 total asymmetrical current and DC component are plotted for each phase current.

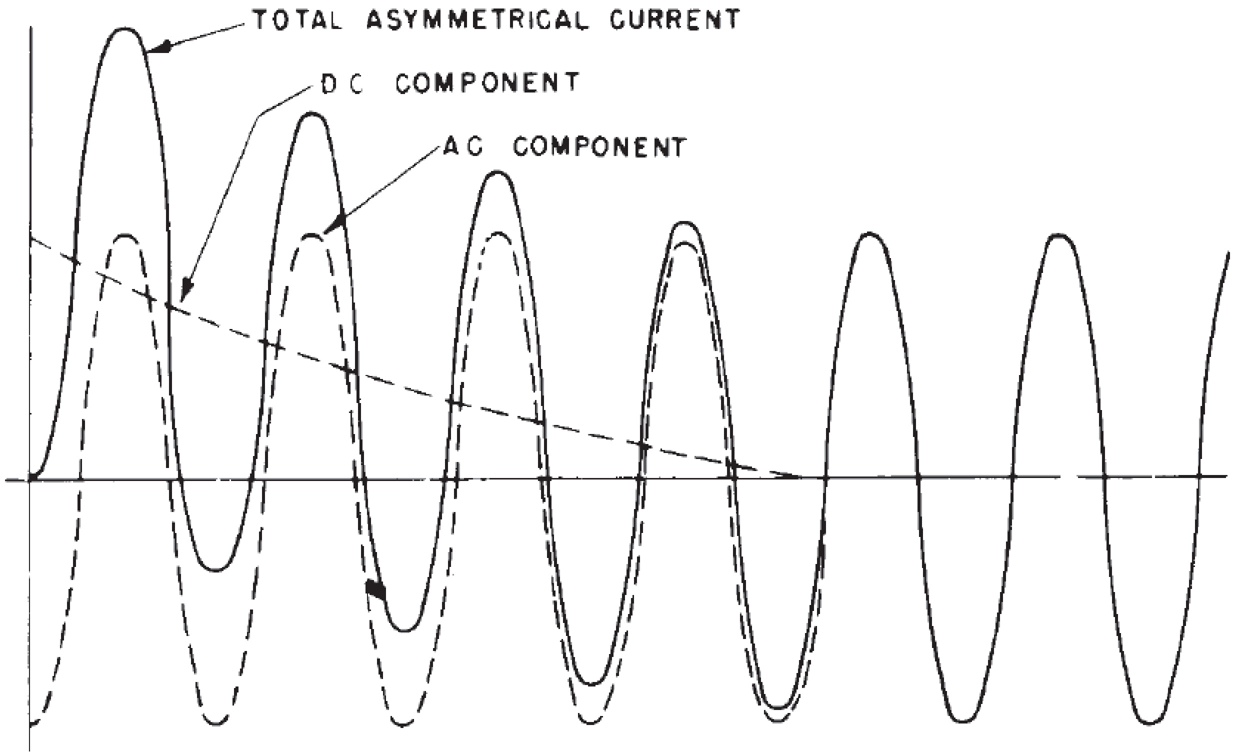

Figure 3-3: Total asymmetrical current and its decomposition into DC component and symmetrical AC component of one phase current in a three-phase short-circuit situation in salient pole synchronous generator terminals. [2]

The reason why the decomposition is usually done is that, the DC current component is dependent on the phase angle voltage when the short-circuit happens. So, by decomposing the waveform, it is possible to compare/analyse the symmetrical short-circuit waveform, no matter the phase voltage when the short-circuit takes place, and just by adding the DC component as whish, to analyse the complete short-circuit waveform.

It has been said that the DC current component is dependent on the phase voltage, so that phase affects to the current phase waveform in different conditions. Whereby, the current phase waveform could be at its maximum point, and then the DC component will be high during first cycles. The opposite happens if the current phase waveform is at its minimum point when short-circuit occurs, the DC component will be low during first cycles. Besides, if the current phase waveform has zero value at the time of short-circuit, then short-circuit waveform is symmetrical.

It can be observed in figure 3-1 that the DC component of the current waveforms for each phase are different. In one phase is positive and in the others is negative, also the absolute values of the DC components are different in the three phases. Those differences are because the phase currents are shifted by 120º from each other, so the phase angle voltage when the short-circuit happens is different for each phase and, due to that, the DC current component is different form one phase current to another.

On the other hand, the symmetrical short-circuit waveforms of three current phases have the same frequency and the same envelop curves, there is a phase shift of 120º between the three of them. A drawing of the envelop curves of the symmetrical short-circuit waveform of one phase current is shown in figure 3-2.

3.4. Current constant components

It is important to know that the mathematical expression of the phase current waveform decomposed into the different components and the mathematical expressions of the components, does not change depending on the type of short-circuit. However, firstly, some important concepts need to be explained in order to identify correctly the characteristics of the decomposed short-circuit current waveforms.

The concepts that need to be defined are I_{ccp}, I'_d, I''_d and I''_q. Besides, they are important because the difference for evaluating different types of short-circuit events is on the mathematical expression that defines those constants.

The constants are defined in the next paragraphs and their mathematical equations depending on the type of short-circuit in the system are:

- I_{ccp}: permanent current, is the RMS short-circuit current at the end of the transient period and is mathematically defined as (3.2) for a three phase short-circuit event and as (3.3) for a phase to phase short-circuit event.

Three phase short-circuit $$I_{ccp} = \frac{E_0}{X_d} \quad (3.2)$$

Phase to phase short-circuit $$I_{ccp} = \sqrt{3}\frac{E_0}{X_d + X_2} \quad (3.3)$$

- I'_d: transient current, is the maximum RMS of the AC component short-circuit current during the transient period and is mathematically defined as (3.4) and (3.5) for different short-circuit type events

Three phase short-circuit $$I_d^{'} = \frac{E_0}{X_d^{'}} \quad (3.4)$$

Phase to phase short-circuit $$I_d^{'} = \sqrt{3}\frac{E_0}{X_d^{'} + X_2} \quad (3.5)$$

- I’’$_d$: direct axis subtransient current component, is the RMS of the AC component short-circuit current at the beginning of the short-circuit and is mathematically defined as (3.6) and (3.7) for different short-circuit type events

Three phase short-circuit $$I_d^{''} = \frac{E_0}{X_d^{''}} \quad (3.6)$$

Phase to phase short-circuit $$I_d^{''} = \sqrt{3}\frac{E_0}{X_d^{''} + X_2} \quad (3.7)$$

- I’’$_q$: quadrature axis subtransient current component, is the RMS of the AC component short-circuit current at the beginning of the short-circuit and is mathematically defined as (3.8) and (3.9) for different short-circuit type events

Three phase short-circuit $$I_q^{''} = \frac{E_0}{X_q^{''}} \quad (3.8)$$

Phase to phase short-circuit $$I_q^{''} = \sqrt{3}\frac{E_0}{X_q^{''} + X_2} \quad (3.9)$$

Current mathematical expressions that just have been defined are based on some reactances that need to be explained:

- Subtransient reactance X’’$_d$: apparent reactance of the stator winding at the time the short-circuit occurs. It determines the current flow during the first few cycles after the short-circuit
- Transient reactance X’$_d$: determines the current during the period after the subtransient reactance is the controlling value.
- The synchronous reactance X_d: determines the current flow when steady-state condition is reached. It is not effective until seconds after the short-circuit occurs [2]

3.5. Theoretical short-circuit current

3.5.1. M. Cortes Cherta, “Curso moderno de máquinas eléctricas rotativas” [8]

In the first theoretical method, each phase current is decomposed into four components: subtransient, transient, permanent or steady state and DC. [8]

- Subtransient component: this component is due to the damper windings. It is an AC current which dies down until zero very fast. Phase current decreases as an exponential function with a constant time of hundredths of seconds. Figure 3-4 represents this component, which can be mathematically described as (3.10).

$$i_{subtransient} = \sqrt{2}\left(I_d^{''} - I_d^{'}\right)e^{\frac{-t}{T_d^{''}}}\sin(\omega t - \varphi) \tag{3.10}$$

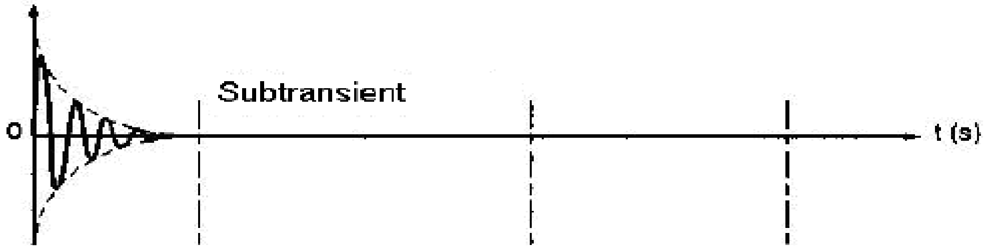

Figure 3-4: Subtransient component. [12]

- Transient component: this component is due to the stator windings. It is an AC current which dies down until zero, but not as fast as the subtransient component. Phase current decreases as an exponential function with a constant time of seconds. Figure 3-5 represents this component, which can be mathematically described as (3.11).

$$i_{transient} = \sqrt{2}\left(I_d^{'} - I_{ccp}\right)e^{\frac{-t}{T_d^{'}}}\sin(\omega t - \varphi) \tag{3.11}$$

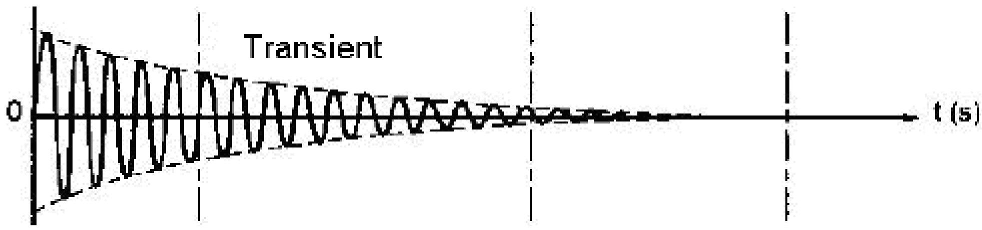

Figure 3-5: Transient component.[12]

- Permanent or steady state component: this component is a sinusoidal waveform produced with the generator terminal short-circuited in steady state operation. Figure 3-6 represents this component, which can be mathematically described as (3.12).

$$i_{permanent} = \sqrt{2}I_{ccp}\sin(\omega t - \varphi) \tag{3.12}$$

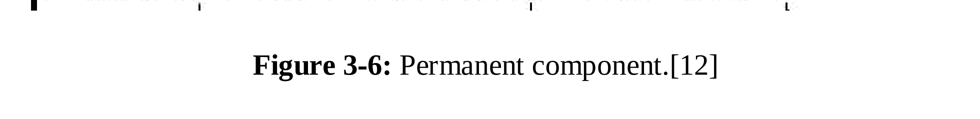

Figure 3-6: Permanent component.[12]

- DC component: this component is dependent on the phase voltage when the short-circuit occurs. Phase current decreases as an exponential function with a constant time of tens of seconds. Figure 3-7 represents this component, which can be mathematically described as (3.13).

$$i_{DC} = \sqrt{2} I_d^{"} e^{\frac{-t}{T_i}} \sin\varphi \tag{3.12}$$

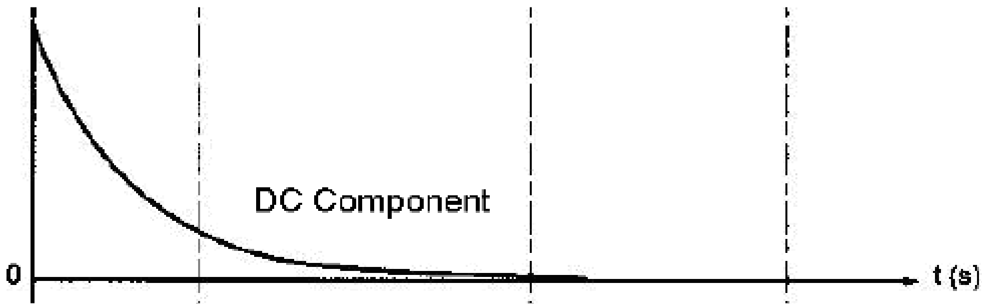

Figure 3-7: DC component.[12]

Therefore, the total short-circuit current in one of the phases is given by (3.14), the other two phase currents are phase shifted by 120 degrees from each other

$$i_{cc}(t) = i_{subtransient} + i_{transient} + i_{permanent} + i_{DC} \tag{3.14}$$

3.5.2. F. R. Blánquez, "Validation study of the use of Matlab/Simulink synchronous machine block for accurate power-plant stability studies" [9]

In the second theoretical method, each phase current it is composed up of subtransient, transient, permanent or steady state, DC and double frequency components. [9]

Subtransient, transient and permanent components are defined and described as in the previous point 3.5.1.

- DC component: this component it is defined as in the previous point 3.5.1. However, the mathematical expression for the theoretical method is given by (3.15)

$$i_{DC} = -\frac{\sqrt{2}}{2}\left(I_d^{"} + I_q^{"}\right)e^{\frac{-t}{T_a}} \sin(\varphi) \tag{3.15}$$

- Double frequency component: this is a component due to a fixed axis magnetomotive force in the excitation winding created by the other four time-depending components. It can be mathematically described as (3.16). [9]

$$i_{double\_frequency} = -\frac{\sqrt{2}}{2}\left(I_d^{"} - I_q^{"}\right)e^{\frac{-t}{T_a}} \sin(2\omega t + \varphi) \tag{3.16}$$

Therefore, the total short-circuit current in one of the phases is given by (3.17), the other two phases of the current are shifted by 120 degrees from each other. [9]

$$i_{cc}(t) = i_{subtransient} + i_{transient} + i_{permanent} + i_{DC} + i_{double\_frequency} \quad (3.17)$$

3.6. Simulation performed with the software Matlab/Simulink

3.6.1. Simulation model scheme

Sudden short-circuit test is simulated by the software Matlab/Simulink.

To simulate the sudden short-circuit test the information collected in the standard IEEE Std 115[1] is taken into account. According to the standard, the sudden short-circuit test has to be performed at rated speed and it has to remain constant during the test. Also, the machine has to be operating under no-load conditions. [13]

The simulation is performed in the Simulink environment using its blocks from the library. The simulation system model is composed by a synchronous machine block, a fault breaker, an excitation system block, a speed-mechanical power regulator and a three phase load.

The three phase load block is necessary in order to be able to compile the model. According to the Matlab/Simulink requirements, it is necessary to add a low resistive three-phase load to avoid numerical oscillations and to preserve numerical stability [14]

The direct consequence of this software requirement is that the synchronous generator short-circuit test is not simulated under no-load conditions, as it is required in the standard. The solution used in this work was to use a small load connected to the generator and the short-circuit will occur after one period of time.

The Matlab/Simulink implemented simulation model is shown in the figure 3-8.

[1] International standard for synchronous machines test procedures

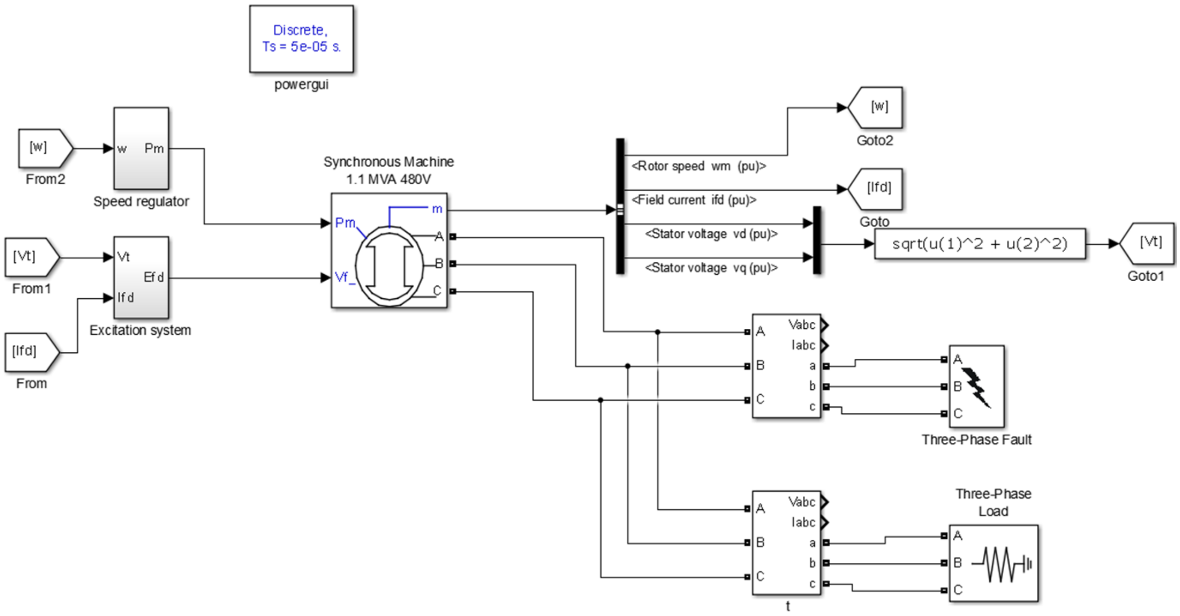

Figure 3-8: Simulation model of the generation system implemented for the sudden short-circuit test

The synchronous generator machine has two inputs, mechanical power and e.m.f.

3.6.1.1. Speed regulator scheme

The mechanical power is obtained by a speed regulator loop that has as input the rotor speed from the main synchronous generator in p.u. and as output the mechanical power in p.u. Figure 3-9 shows the loop schematics.

The speed reference is compared with the speed from the main synchronous generator. A proportional and integral gain (PI) is used by the speed regulator to adjust the torque reference. However, the torque reference is not sent to the synchronous generator. It is multiplied by the speed from the main synchronous generator to obtain the mechanical power reference. The mechanical power reference is sent to the synchronous generator to operate the generator at the specified mechanical power necessary to maintain the speed.

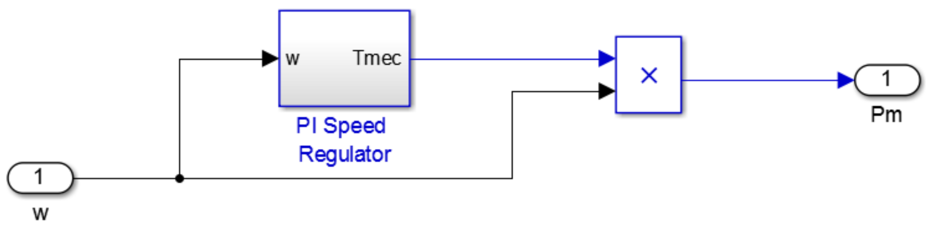

Figure 3-9: Schematics of the speed control loop

Ideally, the mechanical power should be obtained from diesel engine governor block from where mechanical power is obtained taking into account the characteristics of the diesel engine. However, due to lack of data the block cannot be used and the solution adopted for the Matlab/Simulink model was to use a speed control loop to obtain the mechanical power.

3.6.1.2. Excitation system scheme

To model different excitation systems for power systems stability studies the AC excitation model standardized in IEEE Std. 421.5[2] is used. In that standard, different excitation systems are explained and represented by their control loops.

- Type DC-direct current commutator exciters
- Type AC-Alternator-supplied rectifier excitation systems
- Type ST-Static excitation systems

For the generation system under study, the type AC is the one that better fits the real generation system. Because the excitation system uses an AC alternator and the DC field is produced by rotating or stationary rectifiers.

- Type AC1A—Alternator-rectifier excitation system with non-controlled rectifiers and feedback from exciter field current
- Type AC2A—High initial response alternator-rectifier excitation system with non-controlled rectifiers and feedback from exciter field current
- Type AC3A—Alternator-rectifier exciter with alternator field current limiter
- Type AC4A—Alternator-supplied controlled-rectifier exciter
- Type AC5A—Simplified brushless excitation system with rotating rectifier
- Type AC6A—Alternator-rectifier excitation system with non-controlled rectifiers and system-supplied electronic voltage regulator
- Type AC7B—Alternator-rectifier excitation system with high bandwidth inner loop regulating generator field voltage
- Type AC8B—Alternator-rectifier excitation system digitally based voltage regulator

The excitation system type selected for the simulation and modelling of the generation system is the type AC1A. The excitation system has been selected because it represents a field-controlled alternator-rectifier excitation system. The system consists of an alternator main exciter without self-excitation and a non-controlled rectifier. The power supplied to the voltage regulator is taken from a source that is no affected by external transients. [15]

Figure 3-10 represents the block diagram of the excitation model chose for the system under study as it is represented in the international standard IEEE Std. 421.5.

[2] International standard for excitation system models

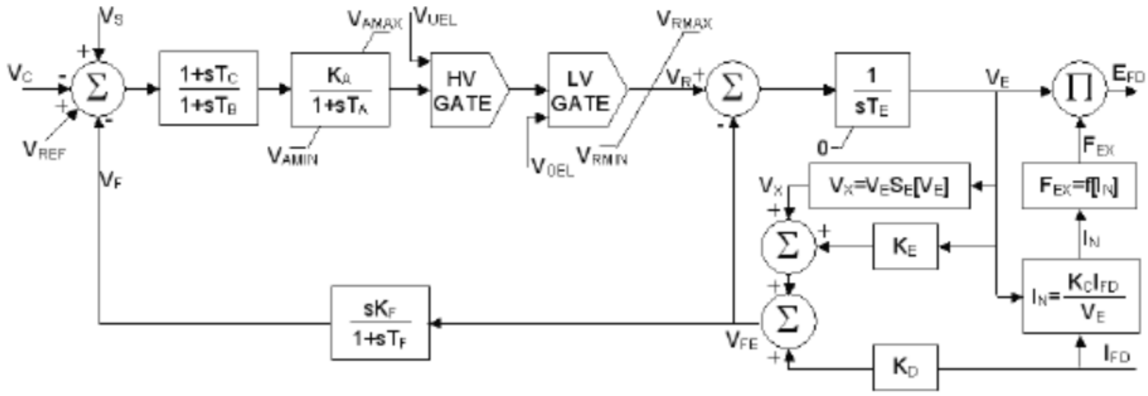

Figure 3-10: Type AC1A—Alternator-rectifier excitation system with non-controlled rectifiers and feedback from exciter field current [15]

The inputs of the blocks are the reference of the stator voltage from the main synchronous generator in p.u., the stator voltage from the main synchronous generator in p.u. and the filed current from the main synchronous generator in p.u.

The excitation model represents and AC type excitation system with lead-lag regulation and feedback stabilization. It is included in the model the excitation machine and the rectifier influence on the behaviour of the excitation system.

The excitation system used in the simulation model, models the terminal voltage V_c, compares with the reference voltage V_{ref} in signal mixer and then the voltage error is obtained. After a lead-lag block, it comes the voltage regulator and an output voltage limiter, the voltage error is modified to be the excitation regulator signal. Via the exciter block, the unload field voltage is obtained. [6]

The lead-lag block is defined as the mathematical expression (3.18), where time constant of lead-lag are defined as T_B and T_C.

$$\frac{1+sT_C}{1+sT_B} \tag{3.18}$$

The regulator block is defined as the mathematical expression (3.19), where K_A is the gain of the exciter regulator and T_A is the time constant of exciter regulator.

$$\frac{K_A}{1+sT_A} \tag{3.19}$$

The main exciter is defined as the mathematical expression (3.20) and the gain K_E, where K_E is the gain of the exciter and T_E is the time constant of exciter regulator.

$$\frac{1}{1+sT_E} \tag{3.20}$$

The block in figure 3-10 that represents a mathematical equation of F_{EX} (3.21) describes three different operating states of the rectifier. Those equations represent the output voltage drop due to rectifier regulation.

$$F_{EX} = 1 - 0.577\, I_N \qquad I_N < 0.433$$
$$F_{EX} = \sqrt{0.75 - I_N^2} \quad 0.433 < I_N < 0.75 \qquad (3.21)$$
$$F_{EX} = 1.732(1 - I_N) \qquad I_N > 0.75$$

Where, I_N is defined as the mathematical expression (3.22).

$$I_N = \frac{K_C I_{fd}}{V_E} \qquad (3.22)$$

Where K_c is the relation between the rectifier voltage and the exciting current in the rectifier and can be defined as the commutation reactance, which can be approximated to X''_d, in ohms, of the main generator. [16]

$$K_c \approx X''_d\text{: } 0.098 \text{ p.u.}$$

Besides, there is a block for the saturation of the AC exciter. The block is a function of the coefficient saturation, S_E, as unload voltage of the exciter, V_E, dependent.

Another block is used to damp the excitation feedback and provide stability to the system, defined as the mathematical expression (3.23), where K_F is the gain of the damping filter and T_F is its time constant.

$$\frac{sK_F}{1 + sT_F} \qquad (3.23)$$

3.7. Modelling of the simulation model

The transfer functions of the main elements in the control loop are going to be modelled for defining the complete system transfer function. The main elements are: regulator, exciter and synchronous generator.

The transfer function of those elements is defined by Laplace transformation. Therefore a variable change domain is necessary from time variable, t, to Laplace variable, s. The change of domain is due to use an important characteristic of Laplace transformation, which is known as the final value theorem (3.24). The theorem states that the value of a time dependent function in steady state, it can be found in the Laplace domain as a product of s and the transfer function, and taking its limit when s goes to zero. [3]

$$\lim_{t \to \infty} f(t) = \lim_{s \to 0} sF(s) \qquad (3.24)$$

3.7.1. Modelling of the synchronous machine

Synchronous machine block of the Simulink software is used.

The generator model takes into account the dynamic of the stator, field and damping windings and represents the machine with its equivalent circuit in *dq* reference frame, shown in figure 3-11, with all rotor parameters and electrical quantities referred to the stator side. [14]

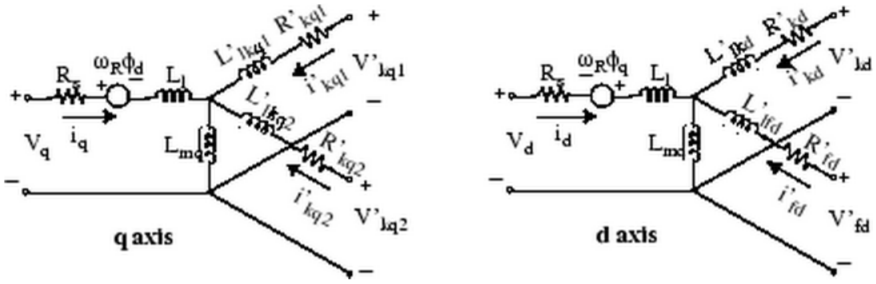

Figure 3-11: Quadrature axis and direct axis equivalent circuit [14]

The previous equivalent circuit is based on the following voltage equations:

$$V_d = R_s i_d + \frac{d\varphi_d}{dt} - \omega_r \varphi_q \tag{3.25}$$

$$V_q = R_s i_q + \frac{d\varphi_q}{dt} + \omega_r \varphi_d \tag{3.26}$$

$$V'_{fd} = R'_{fd} i'_{fd} + \frac{d\varphi'_{fd}}{dt} \tag{3.27}$$

$$V'_{kd} = R'_{kd} i'_{kd} + \frac{d\varphi'_{kd}}{dt} \tag{3.28}$$

$$V'_{kq1} = R'_{kq1} i'_{kq1} + \frac{d\varphi'_{kq1}}{dt} \tag{3.29}$$

$$V'_{kq2} = R'_{kq2} i'_{kq2} + \frac{d\varphi'_{kq2}}{dt} \tag{3.30}$$

And the previous voltage equations are based on the following flux quantities:

$$\varphi_d = L_d i_d + L_{md}(i'_{fd} + i'_{kd}) \tag{3.31}$$

$$\varphi_q = L_q i_q + L_{mq} i'_{kq} \tag{3.32}$$

$$\varphi'_{fd} = L'_{fd} i'_{fd} + L_{md}(i_d + i'_{kd}) \tag{3.33}$$

$$\varphi'_{kd} = L'_{kd} i'_{kd} + L_{md}(i_d + i'_{fd}) \tag{3.34}$$

$$\varphi'_{kq1} = L'_{kq1} i'_{kq1} + L_{mq} i_q \tag{3.35}$$

$$\varphi'_{kq2} = L'_{kq2} i'_{kq2} + L_{mq} i_q \tag{3.36}$$

where:

- V: voltage values
- i: current values
- φ: flux values
- R: resistance values
- L: inductance values
- $_{d,q}$: d and q axis quantities

$_{r,\,s}$: rotor and stator quantities
$_{l,\,m}$: leakage and magnetizing inductance
$_{f,\,k}$: field and damper winding quantities

3.7.1.1. Modelling of synchronous generator block

The rotor winding of the generator is supplied from the output of the rectifier, since it is the excitation winding of the generator. Where R_f is the rotor winding resistance of the synchronous generator and L_f is the rotor winding inductance. Therefore, the relation between the excitation voltage and the excitation current comes (3.37)

$$\Delta V_f = R_f \Delta I_f + L_f \frac{d}{dt}(\Delta I_f) \tag{3.37}$$

Besides, the e.m.f. of the synchronous generator is proportional to the rotor windings excitation current of the generator. The relationship comes mathematically defines as (3.38)

$$E = \left[(2\pi f) M I_f\right]/\sqrt{2} \tag{3.38}$$

Where M is the mutual inductance between the rotor and stator windings of the synchronous generator.

Therefore, with all the previous explanations, it can be said that the synchronous generator transfer function is defined as (3.39)

$$G_g(s) = \frac{K_g}{1 + sT_g} \tag{3.39}$$

Where the generator gain is defined as $\mathrm{K_g} = \frac{\omega \mathrm{M}}{\sqrt{2}\mathrm{R_f}} = \frac{\mathrm{X_d}}{\mathrm{R_f}}$ and the exciter time constant is defined as $\mathrm{T_g} = \frac{\mathrm{L_f}}{\mathrm{R_f}}$

Where R_f is the rotor winding resistance of the synchronous generator, L_f is the rotor winding inductance of the synchronous generator and X_d, in ohms, of the generator.

The designing characteristics of the synchronous generator are known because it had been developed in the company. Therefore, rotor winding resistance, rotor winding inductance of the synchronous generator and direct axis synchronous reactance of the synchronous generator have the following values:

R_f: 1.5975 p.u.
L_f: 4.4480 p.u.
X_d: 1.4510 p.u.

Therefore, for the synchronous generator transfer function, the gain and time have the values of:

K_g : 0.1898
T_g: 2.7844 s

3.7.2. Modelling of the excitation system

3.7.2.1. Modelling of the regulator block

To control the voltage levels in the AVR it is necessary to compare the reference of the voltage with the voltage output of the synchronous generator. The difference of their modules gives a voltage error at the output of the regulator. Since the signal experiments different changes, then the mathematical expression can be represented with incremental values (3.40)

$$\Delta \mathrm{e} = |\Delta \mathrm{V}|_{\mathrm{ref}} - |\Delta \mathrm{V}| \tag{3.40}$$

The voltage error is increased when a gain amplifier is used to have a higher voltage to be fed into the excitation winding of the main exciter. (3.41)

The regulator does not work instantly, it has a time delay that is modelled by the time regulator T_A and it also has a gain constant K_A that is calculated from the error of the measurements of voltage reference and voltage output.

Therefore, with all the previous explanations, it can be said that the regulator transfer function is defined as (3.41)

$$G_A(s) = \frac{\Delta V_R(s)}{\Delta e(s)} = \frac{K_A}{1 + sT_A} \tag{3.41}$$

The specification sheet of the AVR includes the values for the regulator gain and the time regulator. Those values are being used in the simulation and they have the following values:

K_A: 100
T_A: 4 ms

3.7.2.2. Modelling of the exciter block

The stator winding of the exciter is supplied from the output of the regulator with constant DC voltage V_R. Where R_E is the stator winding resistance of the main exciter and L_E is the stator winding inductance of the main exciter. Therefore, the relation between the excitation voltage and the excitation current comes (3.42)

$$\Delta V_R = R_E \Delta I_E + L_E \frac{d}{dt}(\Delta I_E) \tag{3.42}$$

Besides, the current from the rotor windings of the exciter is supplied to the diode full bridge rectifier to obtain the field voltage supplied to the synchronous generator. The relationship comes mathematically defined as (3.43)

$$\Delta V_f = K_d \Delta I_e \tag{3.43}$$

Where K_d is the demagnetizing factor, which is function of exciter reactances. [14]

Therefore, with all the previous explanations, it can be said that the exciter transfer function is defined as (3.44)

$$G_e(s) = \frac{\Delta V_f(s)}{\Delta V_R(s)} = \frac{K_E}{1 + sT_E} \tag{3.44}$$

Where the exciter gain is defined as $K_E = \frac{K_d}{R_E}$ and the exciter time constant is defined as $T_E = \frac{L_E}{R_E}$

The designing characteristics of the synchronous generator and the AC exciter are known because they had been developed in the company. Therefore, the values of commutation reactance of the rectifier and resistance and inductance of the AC exciter have the following values:

K_d: 0.782 p.u.
R_E: 0.032031 p.u.
L_E: 0.0035 p.u.

Therefore, for the exciter transfer function, the gain and time have the values of:

K_E : 24.4138
T_E: 0.1106s

3.7.2.3. Secondary blocks

Other blocks are present in the control loop that defines the excitation system, some of them are left as default and others have been modified.

The parameters left by default are:

- low pass filter constant (Tr available in matlab),
- voltage regulator internal limits (because the voltage regulator limits are modelled)
- damping filter gain and time constant (to avoid numerical oscillation and preserve numerical stability)
- exciter alternator voltage values (because the exciter had been designed without saturation and these voltage values do not affect)

The parameters to model according to the system are:

- voltage regulator output limits are defined as the voltage value in p.u. when the short circuit is maintained for 10 seconds
- time constant of lead-lag are defined as T_B=T_C=0, so the lead-lag block is simplified as a constant gain block of value 1.
- Exciter saturation multipliers are set to zero because the main exciter has no saturation.

3.7.3. Modelling of the speed regulator system

The speed regulator system obtains the reference torque form the output of a PI controller that its input is the error between the actual speed of the synchronous generator and the reference speed.

To model the PI controller it is necessary to know the plant and it has been modelled at point 3.7.1.1. However, first of all, it is important to remember that the output of the PI gives us the reference torque, but that torque is multiplied by the speed to obtain the mechanical power reference to provide to the synchronous generator.

Since the speed in the system is in p.u. and it should be approximately the rated speed because the generator is a synchronous generator and it cannot work with other speed. Then, it can be approximated $T \approx P_m$.

The direct consequence of the approximation is that in the transfer function, the elements in the control loop are the PI controller and the synchronous generator.

3.7.3.1. Modelling of PI controller

The PI controller is obtained by testing the output of the plant when a step signal of value 1 is used as the input. The values of the proportional and integral gain had been tuned to have an output response of the system of steady state value 1 and a fast response but with low overshoot.

It has been found that the value of the proportional gain is K_p=100 and the value of the integral gain is K_i=40, the steady state value of the system with this PI is 1 and the overshoot is less than 0.4%.

3.8. Input parameters for theoretical calculation and simulation of short-circuit current

The modelling of the system is going to be verified by comparing the behaviour of the salient pole synchronous generator without excitation system with the results obtained from the theoretical analysis. The complete system, with excitation system, cannot be verified with the theory because the voltage regulator, exciter and rectifier influence in the short circuit current waveforms is not included in the theoretical calculations.

Firstly, the synchronous generator simulation performance when a sudden three phase short-circuit event and when a sudden phase to phase short-circuit event happens at generator terminals, is going to be compared with the theoretical calculated short-circuit current waveform. This will be the way to validate the simulation model.

Once the simulation with only the generator is performed and checked with the theoretical formulation, the next step will be to model the complete system, with excitation system and speed regulation, to analyse the system performance when a sudden short-circuit event occurs at generator terminals.

The necessary data to perform the theoretical current waveforms and the simulation are defined by the synchronous generator design parameters.

Following tables 3-1 and 3-2 show the necessary input parameters to calculate and simulate the performance of a salient pole synchronous generator during a sudden short-circuit in the stator terminals.

Table 3-1: Direct input parameters

DIRECT INPUT PARAMETERS	
Data	**Value**
P_n	1.1 MVA
V_n	480 V
f_n	60 Hz
p	2
R_s	$1.86\ 10^{-3}\ \Omega$
L_l	$5.43\ 10^{-5}$ H
X_l	0.0205 Ω
X_2	0.0234 Ω
R_r	$1.9\ 10^{-3}\ \Omega$
X_d	0.3033 Ω
X'_d	0.0405 Ω
X''_d	0.0205 Ω
X_q	0.1444 Ω
X''_q	0.0265 Ω
T'_d	0.3300 s
T''_d	0.0280 s
T''_q	0.0180 s
T_a	0.0360 s

Other important input parameters must be obtained indirectly from the direct input parameters according to the mathematical expressions (3.45), (3.2), (3.4), (3.6) and (3.8) respectively for a three phase short-circuit case and mathematical expressions (3.45), (3.3), (3.5), (3.7) and (3.9) for a phase to phase short circuit case.

$$T_i = \frac{X_2}{2\pi f_n R_s} \tag{3.45}$$

Table 3-2: Indirect input parameters obtained from the equations of direct input parameters

INDIRECT INPUT PARAMETERS		
Data	**Value for three phase short-circuit**	**Value for phase to phase short-circuit**
T_i	0.0335 s	0.0335 s
I_{ccp}	911.85 A	1.47 10^3 A
I'_d	6.82 10^3 A	7.49 10^3 A
I''_d	13.50 10^3A	10.91 10^3 A
I''_q	10.42 10^3A	9.59 10^3 A

Two other important input parameters for both theoretical calculation methods and for the simulation, those input parameters are the e.m.f. value and the displacement angle φ.

According to the standards, the synchronous generator short-circuit test has to be performed at rated speed and under no-load conditions before the short-circuit. [13] These requirements affect in two important points:

- The voltage RMS at the machine terminals: voltage RMS at the machine terminals and the e.m.f. are equal, as it was previously said (3.1).
- The displacement angle φ: the symmetrical AC component of one phase current is shifted 90º lagging from the no-load e.m.f.

In order to be able to compare the short-circuit currents obtained by the two theoretical methods and the simulation output; those previous aspects have to be taken into account.

As previously said in 3.6.1, for the simulation is necessary to connect a load to the system. As a design, a small load is chosen to try to have a system as close as possible to a no-load situation. The effects of the load on the e.m.f. value and the displacement angle have to be taken into account in the two theoretical methods to be able to compare the results with the simulation results.

The effect of the load on the e.m.f. value makes no true the equation (3.1). However, since this effect has not a big influence on the results, the modelling is considered valid.

The effect of the load on the displacement angle has to be taken into account, since the value of the load impedance and the load power factor modify the displacement angle between one phase current and the e.m.f. Besides, it is important to remember that the other two currents are phase shifted by 120 degrees from each other.

When simulating the complete system, with excitation system, those previous data and aspects need to be taken into account. Besides, some additional data are needed to implement the excitation system in the simulation model. Following table 3-3 show the necessary input parameters to simulate the performance of a salient pole synchronous generator and its excitation system.

Table 3-3: Excitation system input parameters

DIRECT INPUT PARAMETERS	
Data	**Value**
T_r	$20\ 10^{-3}$ s
K_A	200
T_A	$4\ 10^{-3}$ s
VAmin	-14.5 p.u.
VAmax	14.5 p.u.
VRmin	-10.57 p.u.
VRmax	10.57 p.u.
K_f	0.03
T_f	1 s
T_B	0 s
T_C	0 s
K_E	0.641
T_E	0.111 s
Ve1	4.18 p.u.
Ve2	3.14 p.u.
SeVe1	0 p.u.
SeVe2	0 p.u.
K_d	0.782
K_c	0.098

3.9. Validation of the synchronous generator model

Firstly, the short-circuit current in phase 'a' is obtained by the two theoretical methods and by the simulation. The resulted short-circuit currents in phase 'a' for the no-load test by each method are compared and discussed.

As it was previously said, a perfectly real no-load test is not possible to be performed by Matlab/Simulink. The simulation model must include a small resistive load connected in parallel within the synchronous generator and the fault. Therefore, the small load affects the initial conditions of the system.

To perform the simulation, the small resistive load chosen was a 2 ohms resistance. The initial conditions for the synchronous generator were:

- initial speed deviation (% of nominal speed): 0
- electrical angle of the rotor (degrees): -85.8647
- line current magnitudes i_a, i_b, i_c (pu): 0.104727; 0.104727; 0.104727
- phase angles ph_a, ph_b, ph_c (degrees): 2.59448e-13; -120; 120
- initial field voltage (pu): 1.00928

Those initial conditions must be taken into account to calculate the short-circuit current by the theoretical methods to be able to compare the results with the simulation outputs.

3.9.1. Three phase short-circuit current waveform of phase ‘a’

Following graphs in figure 3-12 represent the short-circuit current in phase ‘a’ obtained by the method exposed by M. Cortes Cherta [8], the method exposed by F. R. Blánquez [9] and the simulation output from Matlab/Simulink software. In order to be able to compare the three methods, the data from the two theoretical methods, were plotted using the Matlab/Simulink software. The graphs represent the evolution of one phase current in p.u. (RMS based) along the time.

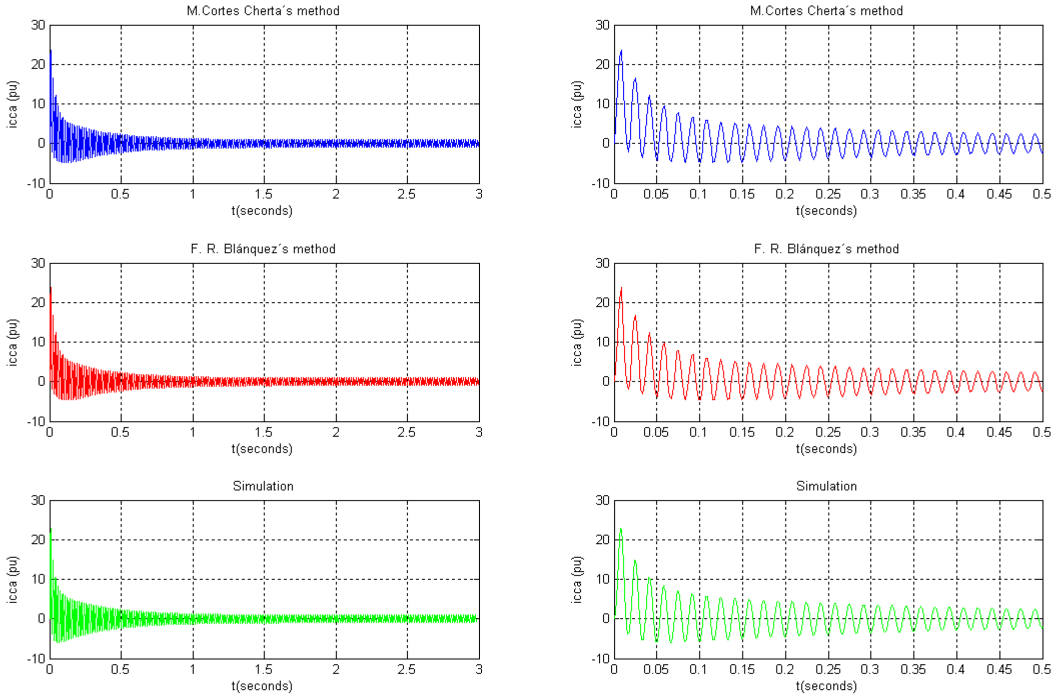

Figure 3-12: Short-circuit current in phase ‘a’ during a three-phase short-circuit at synchronous generator terminals under no-load conditions.

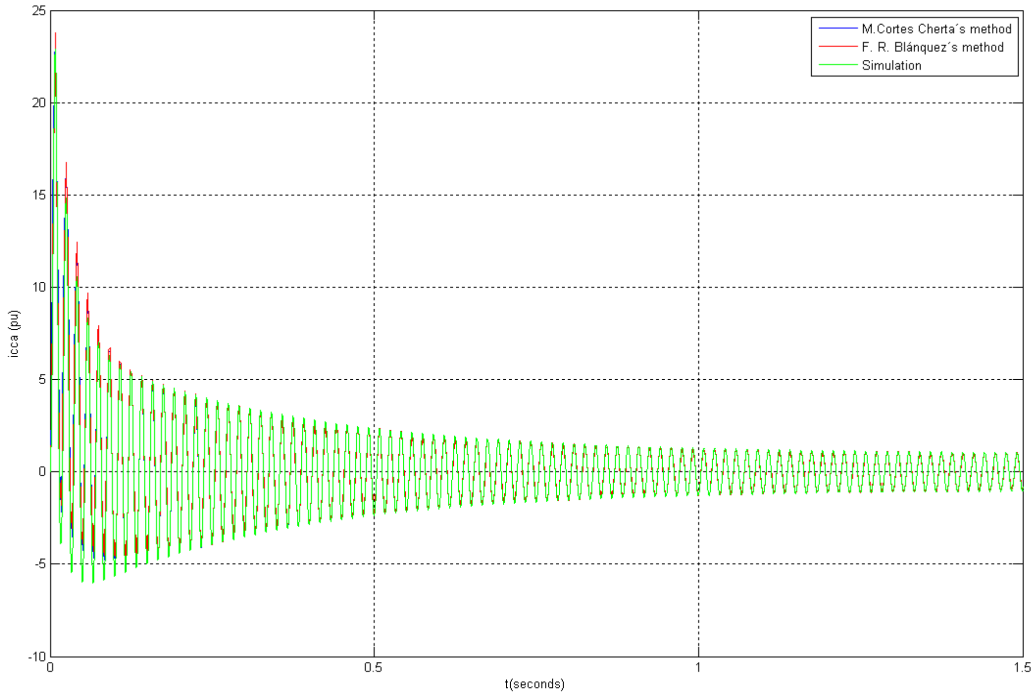

Figure 3-13: Comparison of short-circuit current in phase 'a' obtained by three different methods, during a three-phase short-circuit at synchronous generator terminals under no-load conditions

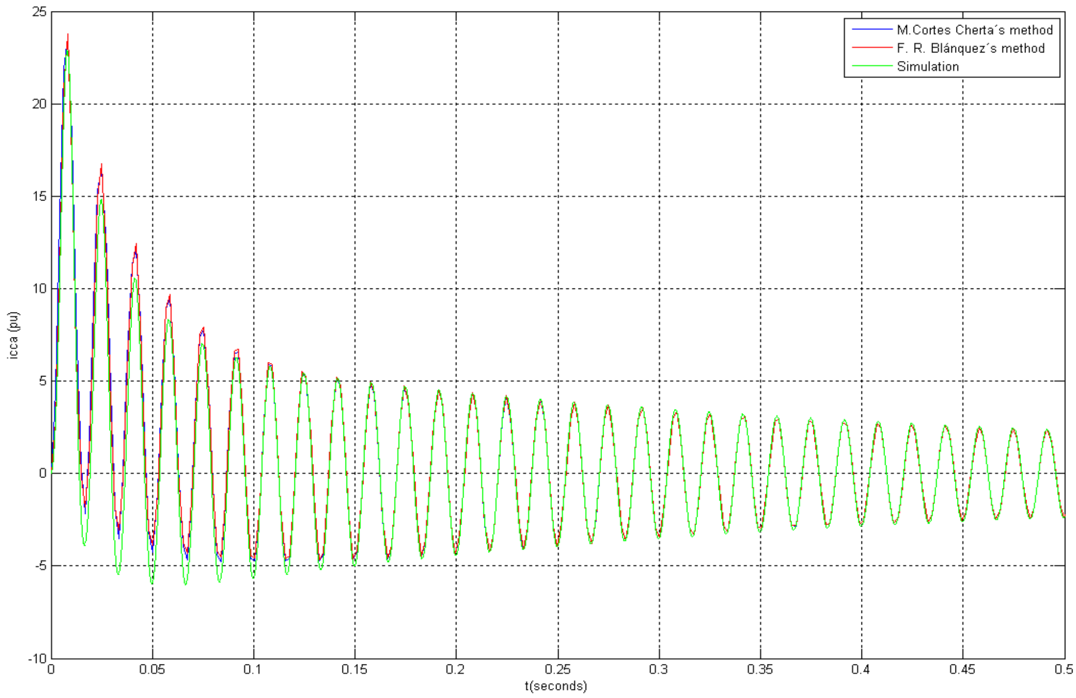

Figure 3-14: Zoom in of the comparison results of three-phase short-circuit current in phase 'a' obtained by three different methods

In previous figures 3-13 and 3-14 it is possible to compare the obtained values of the three-phase short-circuit in phase 'a'.

The simulated waveform matches the calculated waveforms for the steady-state period and for the transient period. However, the matching of the waveforms during the subtransient period does not happen.

The calculated waveforms match between them during the subtransient period, but not the simulated waveform. The waveform obtained by simulation is vertically down displaced, the displacement is the most noteworthy consequence of considering equation (3.1) as true, but it is not. However, the difference of the peak to peak waveforms between the simulated waveform and theoretical waveforms is 3.8%, which is a small error. Besides, in simulated waveforms, is hard to obtain an accuracy below the 3% of the graphical results during the subtransient period, as it is mentioned in the study made by Hydro-Québec of design a computer program to graphical analyse the sudden short-circuit of synchronous hydraulic generators [17]

3.9.2. Phase to phase short-circuit current waveform of phase 'a'

Following graphs in figure 3-15 represent the phase to phase short-circuit current in phase 'a' obtained by the method exposed by M. Cortes Cherta [8], the method exposed by F. R. Blánquez [9] and the simulation output from Matlab/Simulink software. In order to be able to compare the three methods, the data from the two theoretical methods, were plotted using the Matlab/Simulink software. The graphs represent the evolution of one phase current in p.u. (RMS based) along the time.

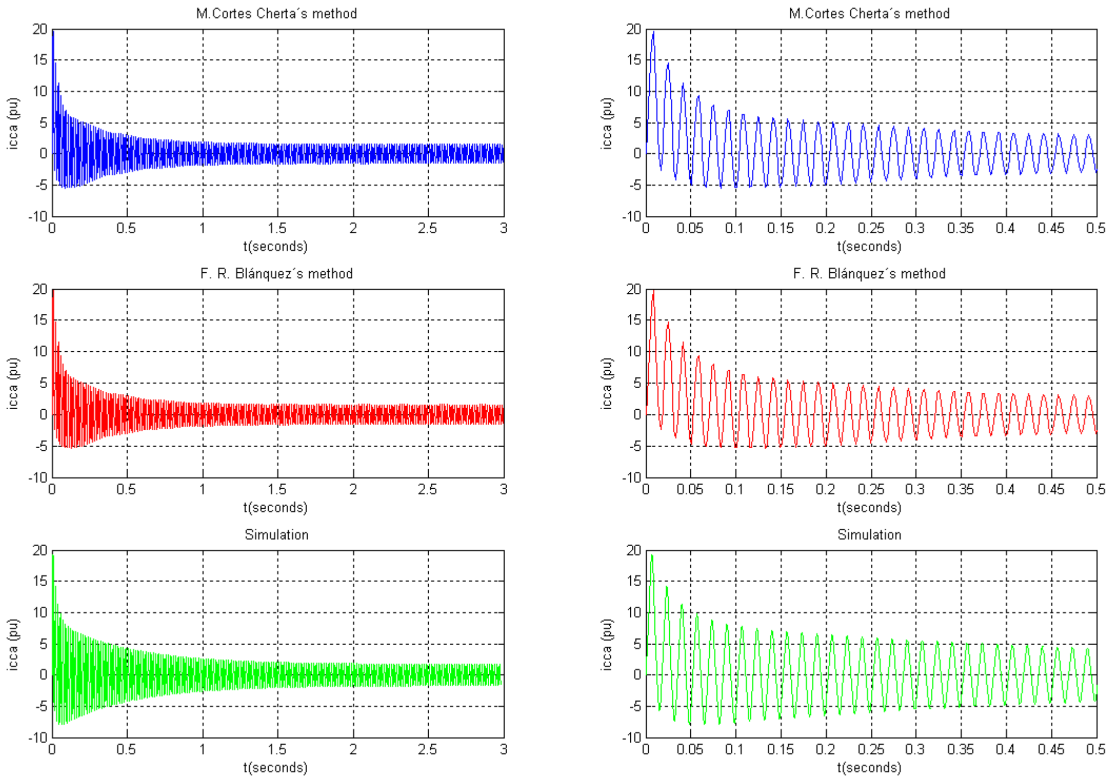

Figure 3-15: Short-circuit current in phase 'a' during a phase to phase short-circuit at synchronous generator terminals under no-load conditions.

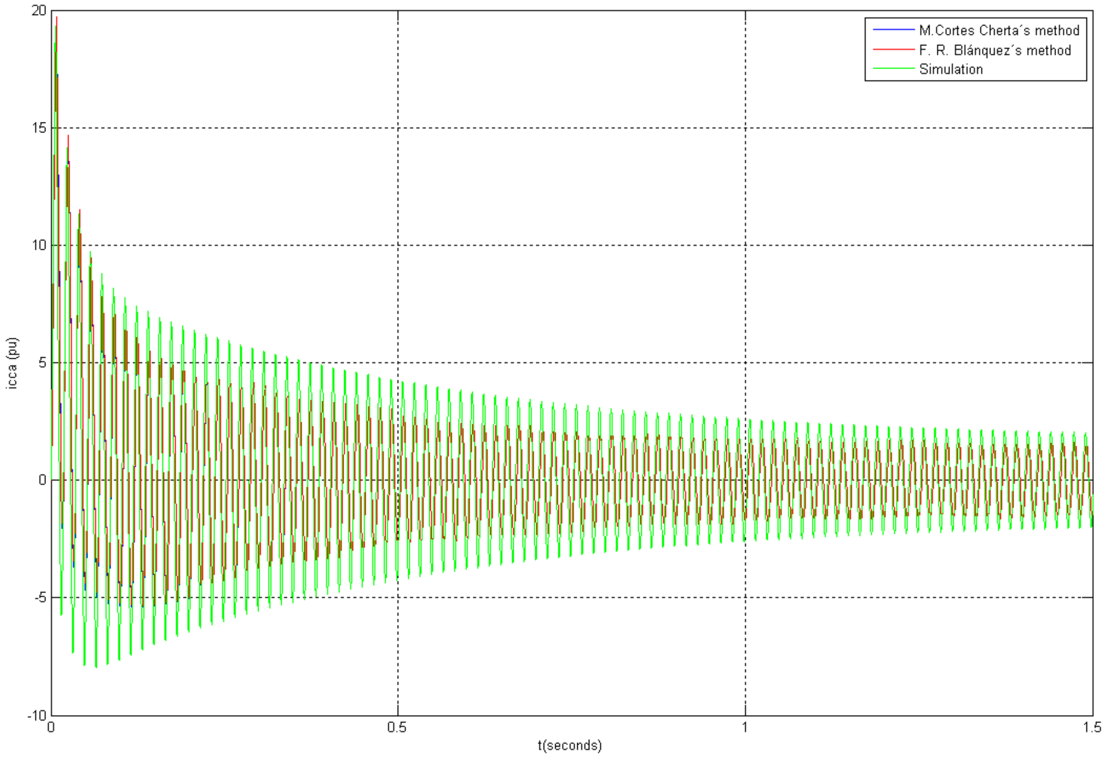

Figure 3-16: Comparison of short-circuit current in phase ‘a’ obtained by three different methods, during a phase to phase short-circuit at synchronous generator terminals under no-load conditions

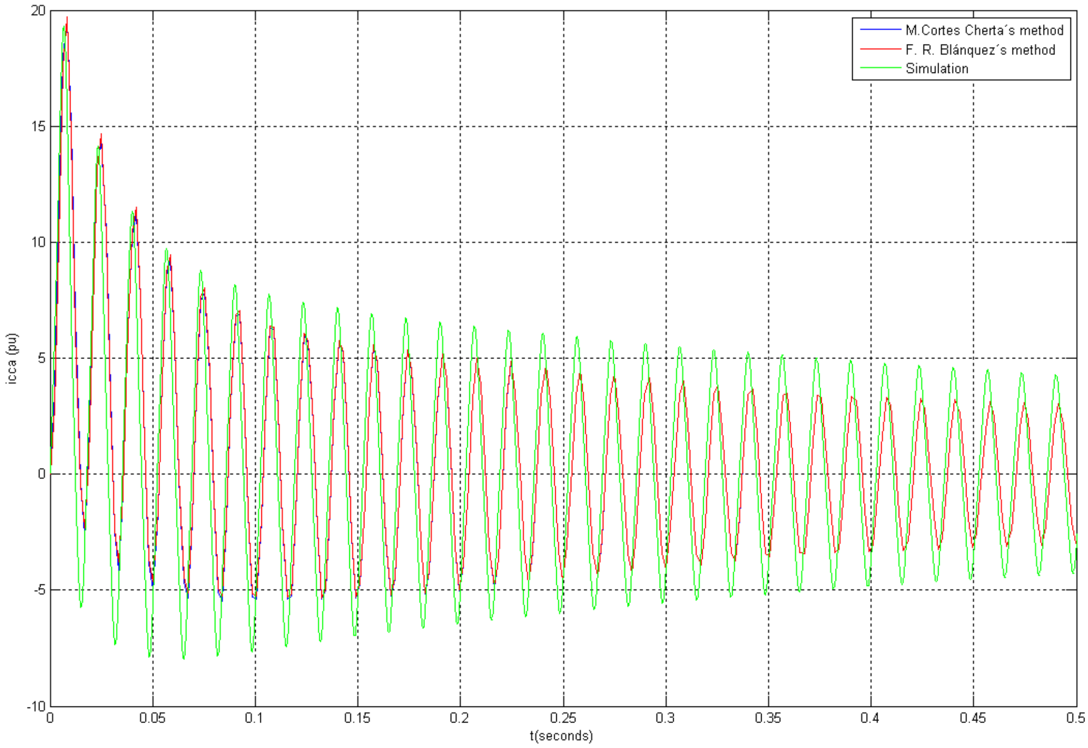

Figure 3-17: Zoom in of the comparison results of phase to phase short-circuit current in phase ‘a’ obtained by three different methods

In previous figures 3-15, 3-16 and 3-17 it is possible to compare the obtained values of the phase to phase short-circuit in phase ‘a’.

Simulated waveform has bigger amplitude than the calculated waveforms for all the periods (subtransient, transient and steady state). This differences between the waveforms are due to the difference between the testing conditions of the theory and the simulation.

The theoretical calculations have the statement of the generator is under no-load conditions before the short-circuit. As consequences, voltage RMS at the machine terminals and the e.m.f. are equal; and the phase not involved in the phase to phase short-circuit continues under no-load conditions during all the short-circuit event.

In the developed simulation model, it is necessary to include a small load to avoid numerical oscillations. The small load affects to the results of the simulation. Firstly the e.m.f. and the voltage RMS at the machine terminals are not equal. Secondly, whilst the short-circuit event, the phase not involved in the phase to phase short-circuit continues connected to that small load due to the necessity to avoid numerical oscillations.

Since the phase to phase short-circuit is an unbalance type, then the differences between the supposed theoretical short-circuit conditions and the model conditions are more evident. Errors of the peak to peak current values during the different periods are:

16.13% of error during subtransient period
22.41% of error during transient period
14.00% of error during steady state period

3.10. Results of the three phase short-circuit event

Several tests have been performed to analyse the behaviour of the simulation model and the behaviour of the synchronous generator under different operational conditions when a three phase short-circuit happens at the synchronous generator terminals.

The tests performed have been: no-load test, approximately half load (500kVA) with a power factor of 1, 0.8 lagging and 0.8 leading, and full load (1100kVA) with a power factor of 1, 0.8 lagging and 0.8 leading. Besides, all those tests have been done for a model without excitation system and with excitation system.

3.10.1. Test results for synchronous generator without excitation system

Three-phase short circuit test has been modelled without excitation system as a first step on the modelling of the diesel generator. For this test only the synchronous generator block and the fault block had been used. The reference values of e.m.f. and speed had been used as input parameters into the synchronous generator block.

Input data for the different load cases under study are presented in points 3.10.1.1 to 3.10.1.3 and the graphical representation of the short-circuit results are presented in point 3.10.1.4.

Since the short-circuit current at generator terminals is going to be deeply studied in the next points, the performance of the simulation model during a three-phase short-circuit event will be fast discussed below.

Firstly, it has to be taken into account that in this section the speed and field voltage applied to the synchronous generator model are constants because the model has no excitation system, neither speed regulation system. Therefore, the speed applied to the system is the reference speed in p.u. and the field voltage value in p.u. depends on the initial conditions of the simulated system.

The evolution of the voltage at generator terminals and of the field current under the short-circuit event situation is such that, just before the short-circuit event, the value of the voltage and the current are the rated values. When the short-circuit occurs, the voltage rapidly decreases to close to zero p.u. The field current undergoes a fast increase and later decreases to the rated value.

3.10.1.1. No-load test

Results of a three phase short-circuit test of a synchronous generator model without excitation system have been presented on the previous point 3.9.

3.10.1.2. 500kVA load test

In this section, the system has connected a load of 500kVA, approximately half load, and 480V, besides the system will be tested with that load with a power factor of 1, 0.8 power factor lagging and 0.8 power factor leading.

The initial conditions for the synchronous generator due to the kind of load connected are:

Load: 500kVA load test 1 PF

- initial speed deviation (% of nominal speed): 0
- electrical angle of the rotor (degrees): -72.6288
- line current magnitudes i_a, i_b, i_c (pu): 0.454546; 0.454546; 0.454546
- phase angles ph_a, ph_b, ph_c (degrees): 7.77212e-14; -120; 120
- initial field voltage (pu): 1.15516

Load: 500kVA load test 0.8 lagging PF

- initial speed deviation (% of nominal speed): 0
- electrical angle of the rotor (degrees): -78.2048
- line current magnitudes i_a, i_b, i_c (pu): 0.454546; 0.454546; 0.454546
- phase angles ph_a, ph_b, ph_c (degrees): -36.8699; -156.87; 83.1301
- initial field voltage (pu): 1.47678

Load: 500kVA load test 0.8 leading PF

- initial speed deviation (% of nominal speed): 0
- electrical angle of the rotor (degrees): -72.7051
- line current magnitudes i_a, i_b, i_c (pu): 0.454546; 0.454546; 0.454546
- phase angles ph_a, ph_b, ph_c (degrees): 36.8699; -83.1301; 156.87
- initial field voltage (pu): 0.737616

3.10.1.3. 1100kVA load test

In this section, the system has connected a load of 1100kVA, full load, and 480V, besides the system will be tested with that load with a power factor of 1, 0.8 power factor lagging and 0.8 power factor leading.

The initial conditions for the synchronous generator due to the kind of load connected are:

Load: 1100kVA load test 1 PF

- initial speed deviation (% of nominal speed): 0
- electrical angle of the rotor (degrees): -55.5921
- line current magnitudes i_a, i_b, i_c (pu): 1; 1; 1
- phase angles ph_a, ph_b, ph_c (degrees): -9.19285e-09; -120; 120
- initial field voltage (pu): 1.65229

Load: 1100kVA load test 0.8 lagging PF

- initial speed deviation (% of nominal speed): 0
- electrical angle of the rotor (degrees): -68.9392
- line current magnitudes i_a, i_b, i_c (pu): 1; 1; 1
- phase angles ph_a, ph_b, ph_c (degrees): -36.8699; -156.87; 83.1301
- initial field voltage (pu): 2.1675

Load: 1100kVA load test 0.8 leading PF

- initial speed deviation (% of nominal speed): 0
- electrical angle of the rotor (degrees): -46.7112
- line current magnitudes i_a, i_b, i_c (pu): 1; 1; 1
- phase angles ph_a, ph_b, ph_c (degrees): 36.8699; -83.1301; 156.87
- initial field voltage (pu): 0.898948

3.10.1.4. Peak short-circuit current decrement curves

It is interesting to compare the differences of the current during a short-circuit when the generator is, before the short-circuit event, operating under no-load conditions, approximately half load (500kVA) conditions at different power factor and full load (1100kVA) conditions at different power factor.

The comparison is done between the peak values of the different short-circuit current waveforms in phase ‘a’ with the system working under different load conditions before the short-circuit. As a standard conditions for all the calculations, the short-circuit starting time has been settled equal. If that was not the case, then only the AC symmetrical component could be compared, but since the time for starting the short-circuit is the same, then it is better to compare the complete short-circuit current waveform.

Following figure 3-18 represents the peaks short-circuit currents of the system with no- load and approximately half load (500kVA) of 1, 0.8 lagging and leading power factor. The graphs represent the evolution of one phase current in p.u. (RMS based) along the time.

Now it is easy to see that when the load connected to the generator has lagging power factor, the short-circuit current has bigger peak values than with a resistive load. This is due to the presence of the inductor in the load. However, the opposite happens when the load connected to the generator has leading power factor, in this case, due to the presence of the capacitor in the load.

Besides, the no-load case is bigger, but really close to the short-circuit current peak values when a load of 500kVA and power factor of 1 is connected.

As a general conclusion to this figure, the four curves represented have close values between them.

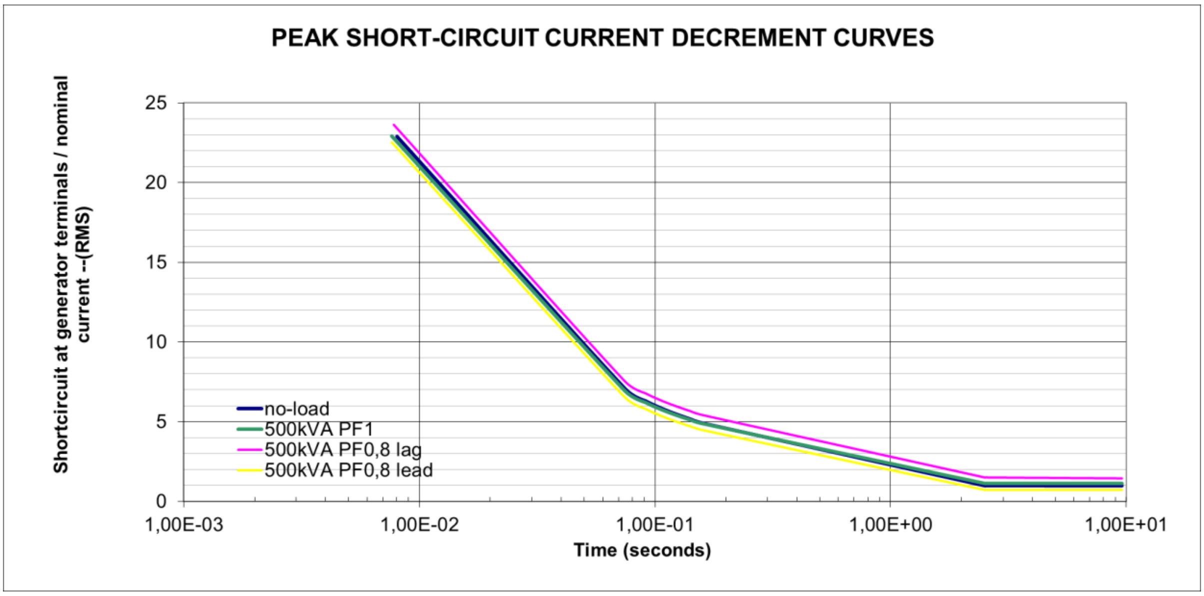

Figure 3-18: Comparison of peak short-circuit decrement curves under no-load and approximately half load with different power factor

Following figure 3-19 represents the peaks short-circuit currents of the system within no-load and full load (1100kVA) of 1, 0.8 lagging and leading power factor. The graphs represent the evolution of one phase current in p.u. (RMS based) along the time.

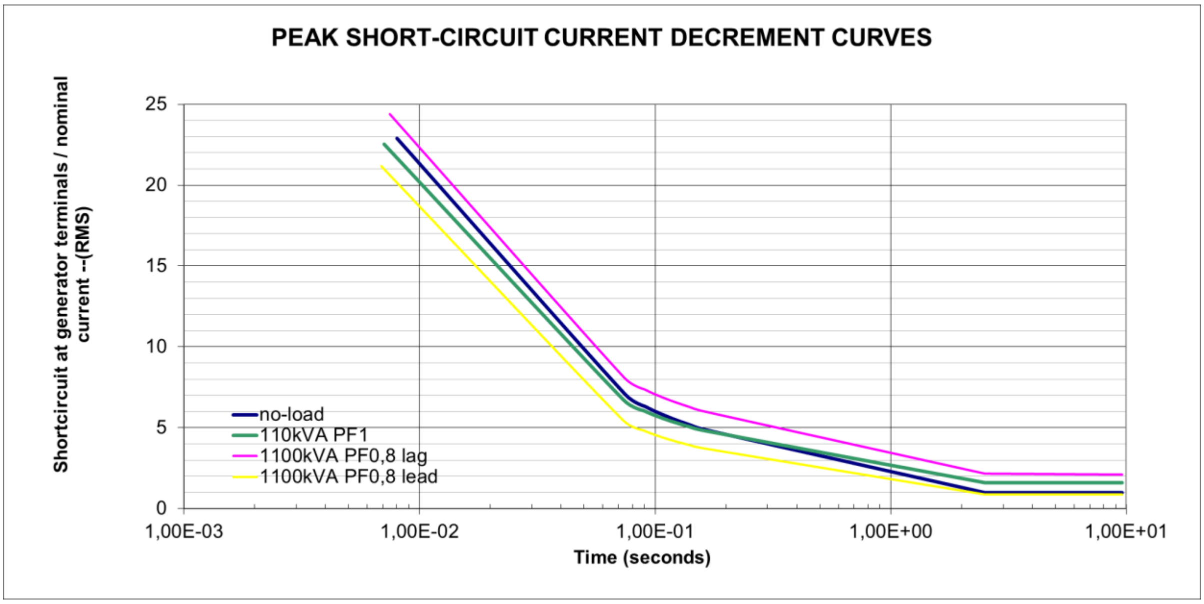

Figure 3-19: Comparison of peak short-circuit decrement curves under no-load and full load with different power factor

As in the previous figure 3-18, it can be seen that when the load connected to the generator has lagging power factor, the short-circuit current has bigger peak values than with a resistive load and the opposite happens when the load connected to the generator has leading power factor. Also, the no-load case is bigger than the short-circuit current peak values when a load of 1100kVA and power factor of 1 is connected.

However, for this figure 3-19 the four curves represented are farther away from each other than in figure 3-18, this is due to the increase of the apparent power in the load.

3.10.2. Test results for synchronous generator with excitation system

Three-phase short circuit test has been modelled with excitation system and speed regulator. Some differences in the current waveforms are going to be observed, mainly due to the action of the AVR.

Input data for the different load cases under study are presented in points 3.10.2.1 to 3.10.2.3 and the graphical representation of the short-circuit results are presented in point 3.10.2.4.

Since the short-circuit current at generator terminals is going to be deeply studied in the next points, the performance of the simulation model during a three-phase short-circuit event will be fast discussed below.

Firstly, it has to be taken into account that the mechanical power and field voltage applied to the synchronous generator model are coming from the speed regulator and from the excitation system respectively. Therefore, they will change with the time because a comparison between the reference and measured values is done in those control systems.

The evolution of the speed of the synchronous generator under the short-circuit event situation is such that before the short-circuit event the value is 1 p.u. and when the event takes place, the speed decreases, but it fast turns into an increasing speed during the subtransient period and later it decreases to the reference value. The evolution of the mechanical power of the synchronous generator under the short-circuit event situation is such that before the short-circuit event the value is lower than 1 p.u. and when the event takes place, the power increases during the subtransient period and later it decreases until a low value.

The evolution of the voltage at generator terminals, of the field current and of the field voltage under the short-circuit event situation is such that, just before the short-circuit event, the value of the voltage and the current are the rated values. When the short-circuit occurs, the voltage rapidly decreases to close to zero p.u; the field current undergoes on a smooth increase until it reaches a constant value; and the field voltage also increases and suffers a small overshoot and later it decreases until reach a constant value.

3.10.2.1. No-load test

In contrast to the no-load test for synchronous generator without excitation system, the simulated results of the no-load test for synchronous generator with excitation system can only be obtained by simulation. The two theoretical methods cannot be used to compare the results of the simulation because they do not take into account the effects on the system of the excitation system.

During subtransient and transient period of the waveform for a system without and with excitation system have been compared and they are equal for those periods. Besides, since the model without excitation system has been compared with the theoretical methods and the results matched, hence the system with excitation is supposed to be acceptable as well.

To perform the simulation, the small resistive load chosen was a 2 ohms resistance. The initial conditions for the synchronous generator were:

- initial speed deviation (% of nominal speed): 0
- electrical angle of the rotor (degrees): -85.8647
- line current magnitudes i_a, i_b, i_c (pu): 0.104727; 0.104727; 0.104727
- phase angles ph_a, ph_b, ph_c (degrees): 2.59448e-13; -120; 120
- initial field voltage (pu): 1.00928

Following figure 3-20 represent the short-circuit current in phase ‘a’ obtained from Matlab/Simulink simulation. Figure 3-20.a represents the full simulation time and figure 3-20.b is a zoom in of the waveform in the time period from 0 s to 0.5s. The graphs represent the evolution of one phase current in p.u. (RMS based) along the time.

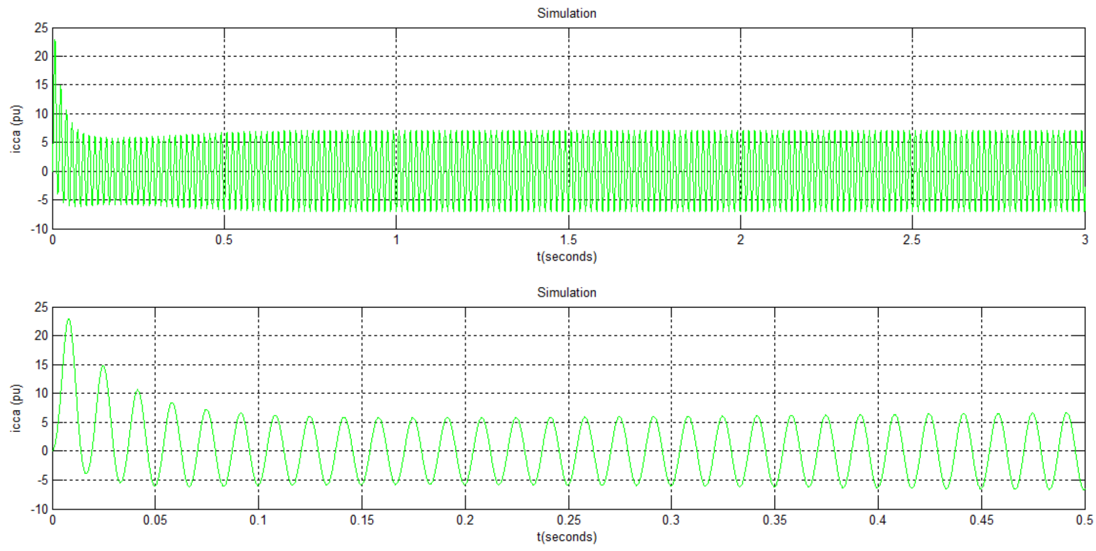

Figure 3-20: Short-circuit current in phase 'a' obtained by simulation, during a three phase short-circuit at synchronous generator terminals under no-load

3.10.2.2. 500kVA load test

In this section, the system has connected a load of 500kVA and 480V, besides the system will be tested with that load with a power factor of 1, 0.8 power factor lagging and 0.8 power factor leading.

The initial conditions for the synchronous generator due to the kind of load connected are:

Load: 500kVA load test 1 PF

- initial speed deviation (% of nominal speed): 0
- electrical angle of the rotor (degrees): -72.6288
- line current magnitudes i_a, i_b, i_c (pu): 0.454546; 0.454546; 0.454546
- phase angles ph_a, ph_b, ph_c (degrees): 7.77212e-14; -120; 120
- initial field voltage (pu): 1.15516

Load: 500kVA load test 0.8 lagging PF

- initial speed deviation (% of nominal speed): 0
- electrical angle of the rotor (degrees): -78.2048
- line current magnitudes i_a, i_b, i_c (pu): 0.454546; 0.454546; 0.454546
- phase angles ph_a, ph_b, ph_c (degrees): -36.8699; -156.87; 83.1301
- initial field voltage (pu): 1.47678

Load: 500kVA load test 0.8 leading PF

- initial speed deviation (% of nominal speed): 0
- electrical angle of the rotor (degrees): -72.7051
- line current magnitudes i_a, i_b, i_c (pu): 0.454546; 0.454546; 0.454546
- phase angles ph_a, ph_b, ph_c (degrees): 36.8699; -83.1301; 156.87
- initial field voltage (pu): 0.737616

3.10.2.3. 1100 kVA load test

In this section, the system has connected a load of 1100kVA and 480V, besides the system will be tested with that load with a power factor of 1, 0.8 power factor lagging and 0.8 power factor leading.

Load: 1100kVA load test 1 PF

- initial speed deviation (% of nominal speed): 0
- electrical angle of the rotor (degrees): -55.5921
- line current magnitudes i_a, i_b, i_c (pu): 1; 1; 1
- phase angles ph_a, ph_b, ph_c (degrees): -9.19285e-09; -120; 120
- initial field voltage (pu): 1.65229

Load: 1100kVA load test 0.8 lagging PF

- initial speed deviation (% of nominal speed): 0
- electrical angle of the rotor (degrees): -68.9392
- line current magnitudes i_a, i_b, i_c (pu): 1; 1; 1
- phase angles ph_a, ph_b, ph_c (degrees): -36.8699; -156.87; 83.1301
- initial field voltage (pu): 2.1675

Load: 1100kVA load test 0.8 leading PF

- initial speed deviation (% of nominal speed): 0
- electrical angle of the rotor (degrees): -46.7112
- line current magnitudes i_a, i_b, i_c (pu): 1; 1; 1
- phase angles ph_a, ph_b, ph_c (degrees): 36.8699; -83.1301; 156.87
- initial field voltage (pu): 0.898948

3.10.2.4. Peak short-circuit current decrement curves

It is interesting to compare the decrement of the current during a short-circuit when the generator is, before the short-circuit, operating under no-load conditions, approximately half load (500kVA) conditions at different power factors and full load (1100kVA) conditions at different power factors.

The comparison is done between the peak values of the different short-circuit current waveforms in phase 'a' with the system working under different load conditions before the short-circuit.

Following figure 3-21 represents the peaks short-circuit currents of the system within no-load and approximately half load (500kVA) of 1, 0.8 lagging and leading power factor. The graphs represent the evolution of one phase current in p.u. (RMS based) along the time.

As said in 3.10.1.4, when the load connected to the generator has lagging power factor, the short-circuit current has bigger peak values than with a resistive load due to the inductor action in the load. The opposite happens when the load connected to the generator has leading power factor due to the capacitor in the load.

In this study case, since the simulation includes the excitation system, when the current in the generator terminals reaches a certain low level, then the excitation system action, due to its voltage control loop action, makes the current to increase until certain maximum value fixed by the excitation system. Therefore, the short-circuit current in steady state period has the same constant value for all the load simulated study cases.

As a general conclusion to figure 3-21, the curves represented have close values between them.

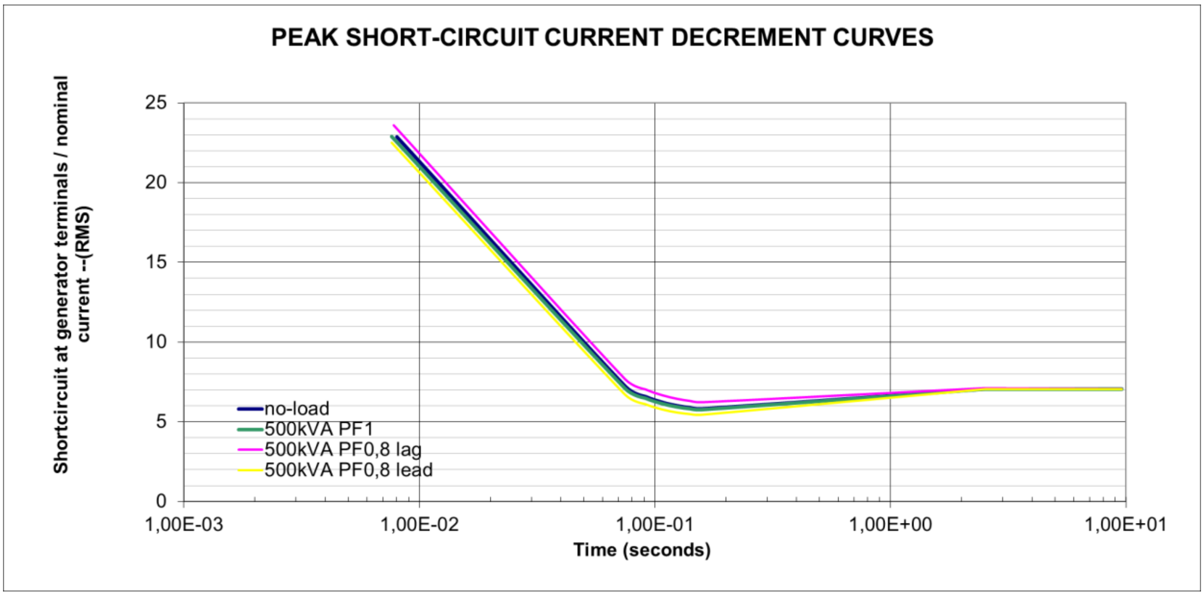

Figure 3-21: Comparison of peak short-circuit decrement curves under no-load and approximately half load with different power factor

Following figure 3-22 represents the peaks short-circuit currents of the system within no-load and full load (1100kVA) of 1, 0.8 lagging and leading power factor. The graphs represent the evolution of one phase current in p.u. (RMS based) along the time.

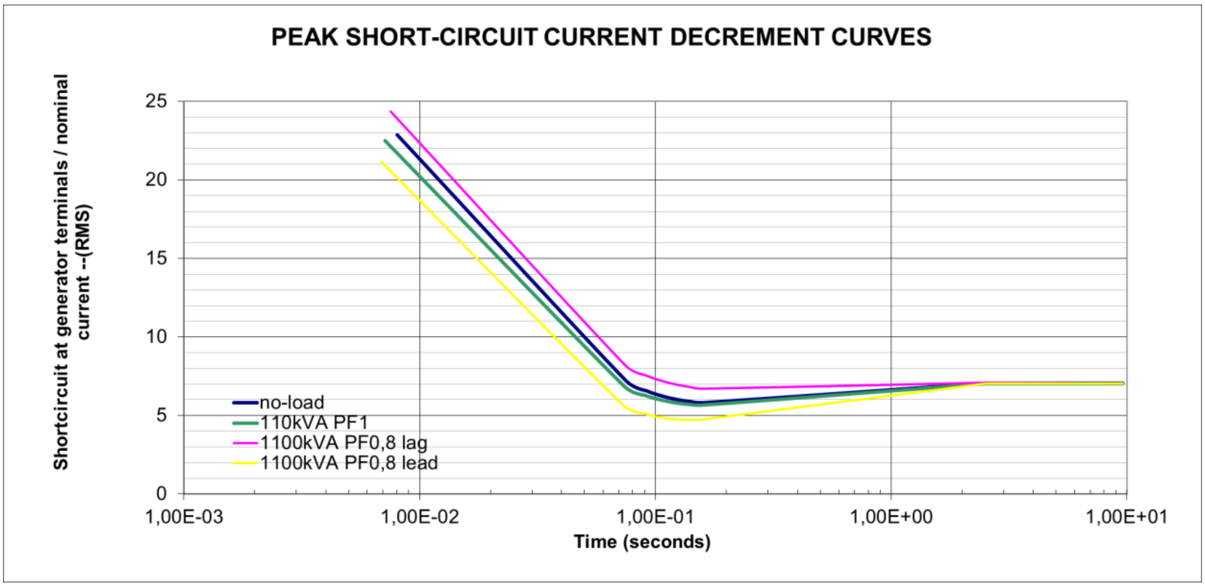

Figure 3-22: Comparison of peak short-circuit decrement curves under no-load and full load with different power factor

As in the previous figure 3-21, it can be seen that when the load connected to the generator has lagging power factor, the short-circuit current has bigger peak values than with a resistive load and the opposite happens when the load connected to the generator has leading power factor. However, for this figure 3-22 the curves represented are farther away from each other for subtransient and transient period, this is due to the increase of the apparent power in the load. Despite of the differences between the decrement curves during subtransient and transient period, due to the action of the AVR, the current curves are raising up until certain level characterized on the generating system working conditions.

3.11. Results of the phase to phase short-circuit event

The procedure to evaluate the behaviour of the simulation model and of the synchronous generator under different operation conditions when a phase to phase short-circuit event happens at the generator terminals, it is the same as in the previous point 3.10.

The tests performed have been: no-load test, approximately half load (500kVA) with a power factor of 1, 0.8 lagging and 0.8 leading, and full load (1100kVA) with a power factor of 1, 0.8 lagging and 0.8 leading. . Besides, all those tests have been done for a model without excitation system and with excitation system.

3.11.1. Test results for synchronous generator without excitation system

Phase to phase short circuit test has been modelled without excitation system as a first step on the modelling of the diesel generator. For this test only the synchronous generator block and the fault block had been used. The reference values of e.m.f. and speed had been used as input parameters into the synchronous generator block.

Input data for the different load cases under study are presented in points 3.11.1.1 to 3.11.1.3 and the graphical representation of the short-circuit results are presented in point 3.11.1.4.

Since the short-circuit current at generator terminals is going to be deeply studied in the next points, the performance of the simulation model during a phase to phase short-circuit event will be discussed below.

Firstly, it has to be taken into account that in this section the speed and field voltage applied to the synchronous generator model are constants because the model has no excitation system, neither speed regulation system. Therefore, the speed applied to the system is the reference speed in p.u. and the field voltage value in p.u. depends on the initial conditions of the simulated system. Besides, due to the unbalance short-circuit event, the drawback of the simulation is that the phase that is not affected by the short-circuit is connected to the small load used to avoid numerical oscillations and to preserve numerical stability. This condition affects to the system performance producing ripple on the waveforms.

The evolution of the voltage at generator terminals and of the field current under the short-circuit event situation is such that, just before the short-circuit event, the value of the voltage and the current are the rated values. When the short-circuit occurs, the voltage decreases, but not as fast and not as low as in the system without excitation system. The field current undergoes a fast increase and later decreases to the rated value.

3.11.1.1. No-load test

Results of a phase to phase short-circuit test of a synchronous generator model without excitation system have been presented on the previous point 3.9.2.

3.11.1.2. 500kVA load test

In this section, the system has connected a load of 500kVA and 480V, besides the system will be tested with that load with a power factor of 1, 0.8 power factor lagging and 0.8 power factor leading.

Load: 500kVA load test 1 PF

- initial speed deviation (% of nominal speed): 0
- electrical angle of the rotor (degrees): -72.6288
- line current magnitudes i_a, i_b, i_c (pu): 0.454546; 0.454546; 0.454546
- phase angles ph_a, ph_b, ph_c (degrees): 7.77212e-14; -120; 120
- initial field voltage (pu): 1.15516

Load: 500kVA load test 0.8 lagging PF

- initial speed deviation (% of nominal speed): 0
- electrical angle of the rotor (degrees): -78.2048
- line current magnitudes i_a, i_b, i_c (pu): 0.454546; 0.454546; 0.454546
- phase angles ph_a, ph_b, ph_c (degrees): -36.8699; -156.87; 83.1301
- initial field voltage (pu): 1.47678

Load: 500kVA load test 0.8 leading PF

- initial speed deviation (% of nominal speed): 0
- electrical angle of the rotor (degrees): -72.7051
- line current magnitudes i_a, i_b, i_c (pu): 0.454546; 0.454546; 0.454546
- phase angles ph_a, ph_b, ph_c (degrees): 36.8699; -83.1301; 156.87
- initial field voltage (pu): 0.737616

3.11.1.3. 1100 kVA load test

In this section, the system has connected a load of 1100kVA and 480V, besides the system will be tested with that load with a power factor of 1, 0.8 power factor lagging and 0.8 power factor leading.

Load: 1100kVA load test 1 PF

- initial speed deviation (% of nominal speed): 0
- electrical angle of the rotor (degrees): -55.5921
- line current magnitudes i_a, i_b, i_c (pu): 1; 1; 1
- phase angles ph_a, ph_b, ph_c (degrees): -9.19285e-09; -120; 120
- initial field voltage (pu): 1.65229

Load: 1100kVA load test 0.8 lagging PF

- initial speed deviation (% of nominal speed): 0
- electrical angle of the rotor (degrees): -68.9392
- line current magnitudes i_a, i_b, i_c (pu): 1; 1; 1
- phase angles ph_a, ph_b, ph_c (degrees): -36.8699; -156.87; 83.1301
- initial field voltage (pu): 2.1675

Load: 1100kVA load test 0.8 leading PF

- initial speed deviation (% of nominal speed): 0
- electrical angle of the rotor (degrees): -46.7112
- line current magnitudes i_a, i_b, i_c (pu): 1; 1; 1
- phase angles ph_a, ph_b, ph_c (degrees): 36.8699; -83.1301; 156.87
- initial field voltage (pu): 0.898948

3.11.1.4. Peak short-circuit current decrement curves

As in the previous point 3.10, for the phase to phase short-circuit event at the generator terminals, it is interesting to compare the decrement of the current during a short-circuit when the generator is, before the short-circuit event, operating under no-load conditions, 500kVA conditions at different power factor and 1100kVA conditions at different power factor.

The comparison is done between the peak values of the different short-circuit current waveforms in phase 'a' with the system working under different load conditions before the short-circuit.

Following figure 3-23 represents the peaks short-circuit currents of the system within no-load and approximately half load (500kVA) of 1, 0.8 lagging and leading power factor. The graphs represent the evolution of one phase current in p.u. (RMS based) along the time.

Now it is easy to see that when the load connected to the generator has lagging power factor, the short-circuit current has bigger peak values than with a resistive load. This is due to the presence of the inductor in the load. However, the opposite happens when the load connected to the generator has leading power factor, in this case, due to the presence of the capacitor in the load.

Besides, the no-load case is bigger, but really close to the short-circuit current peak values when a load of 500kVA and power factor of 1 is connected.

As a general conclusion to this figure 3-23, the four curves represented have close values between them.

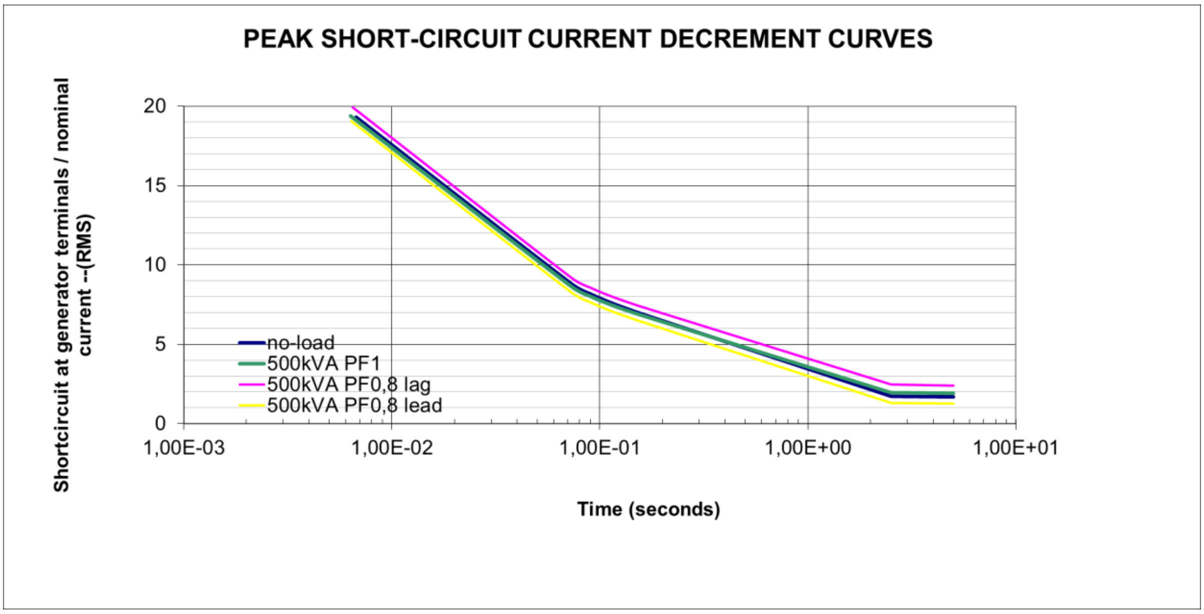

Figure 3-23: Comparison of peak short-circuit decrement curves under no-load and approximately half load with different power factor

Following figure 3-24 represents the peaks short-circuit currents of the system within no-load and full load (1100kVA) of 1, 0.8 lagging and leading power factor.

As in the previous figure 3-23, it can be seen that when the load connected to the generator has lagging power factor, the short-circuit current has bigger peak values than with a resistive load and the opposite happens when the load connected to the generator has leading power factor. Also, the no-load case is bigger than the short-circuit current peak values when a load of 1100kVA and power factor of 1 is connected.

However, for this figure 3-24 the four curves represented are farther away from each other than in figure 3-23, this is due to the increase of the apparent power in the load.

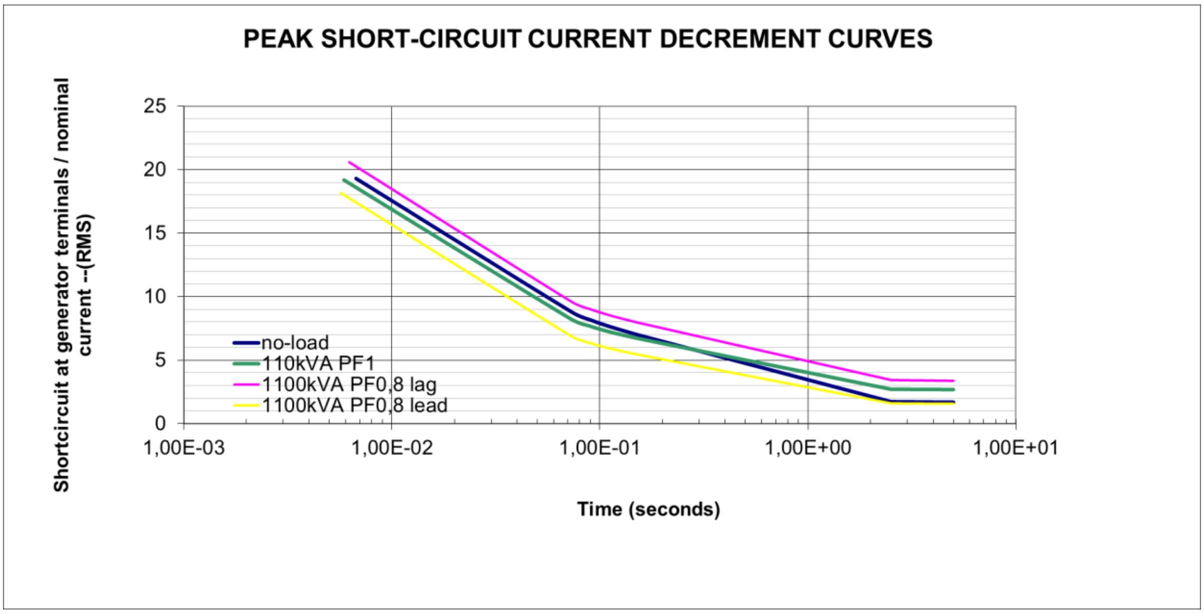

Figure 3-24: Comparison of peak short-circuit decrement curves under no-load and full load with different power factor

3.11.2. Test results for synchronous generator with excitation system

Phase to phase short circuit test has been modelled with excitation system and speed regulator. Some differences in the current waveforms are going to be observed, mainly due to the action of the AVR.

Input data for the different load cases under study are presented in points 3.11.2.1 to 3.11.2.3 and the graphical representation of the short-circuit results are presented in point 3.11.2.4.

Since the short-circuit current at generator terminals is going to be deeply studied in the next points, the performance of the simulation model during a phase to phase short-circuit event will be discussed below.

Firstly, it has to be taken into account that the mechanical power and field voltage applied to the synchronous generator model are coming from the speed regulator and from the excitation system respectively. Therefore, they will change with the time because a comparison between the reference and measured values is done in those control systems. Besides, due to the unbalance short-circuit event, the drawback of the simulation is that the phase that is not affected by the short-circuit is connected to the small load used to avoid numerical oscillations and to preserve numerical stability. This condition affects to the system performance producing ripple on the waveforms.

The evolution of the speed of the synchronous generator under the short-circuit event situation is such that before the short-circuit event the value is 1 p.u. and when the event takes place, the speed decreases, but it fast turns into an increasing speed during the subtransient period and later it decreases to the reference value. The evolution of the mechanical power of the synchronous generator under the short-circuit event situation is such that before the short-circuit event the value is lower than 1 p.u. and when the event takes place, the power increases during the subtransient period and later it decreases until a low value, but it is a higher one than in a three-phase short-circuit event.

The evolution of the voltage at generator terminals and of the field current under the short-circuit event situation is such that, just before the short-circuit event, the value of the voltage and the current are the rated values. When the short-circuit occurs, the voltage decreases at first, but later it increases its value, to a lower value than at the moment when the short-circuit happens, this performance is due to the condition of the not short-circuited phase. The field current undergoes a smooth increase until it reaches a constant value. The field voltage increases and suffers a small overshoot and later it decreases until reach a constant value.

3.11.2.1. No-load test

As previously stated in point 3.10.2 for a three phase short-circuit case; in here, for a phase to phase short-circuit at synchronous generator terminals with excitation system; the simulated results of the no-load test for synchronous generator with excitation system can only be obtained by simulation and cannot be compared with the two theoretical methods because they do not take into account the effects on the system of the excitation system.

During subtransient and transient period of the waveform for a system without and with excitation system have been compared and they are equal for those periods. Besides, since the model without excitation system has been compared with the theoretical methods and the results matched. Then, the system with excitation is supposed to be acceptable as well.

To perform the simulation, the small resistive load chosen was a 2 ohms resistance. The initial conditions for the synchronous generator were:

- initial speed deviation (% of nominal speed): 0
- electrical angle of the rotor (degrees): -85.8647
- line current magnitudes i_a, i_b, i_c (pu): 0.104727; 0.104727; 0.104727
- phase angles ph_a, ph_b, ph_c (degrees): 2.59448e-13; -120; 120

- initial field voltage (pu): 1.00928

Following figure 3-25 represent the short-circuit current in phase 'a' obtained from Matlab/Simulink simulation. Figure 3-25.a represents the full simulation time and figure 3-25.b is a zoom in of the waveform in the time period from 0 s to 0.5s. The graphs represent the evolution of one phase current in p.u. (RMS based) along the time.

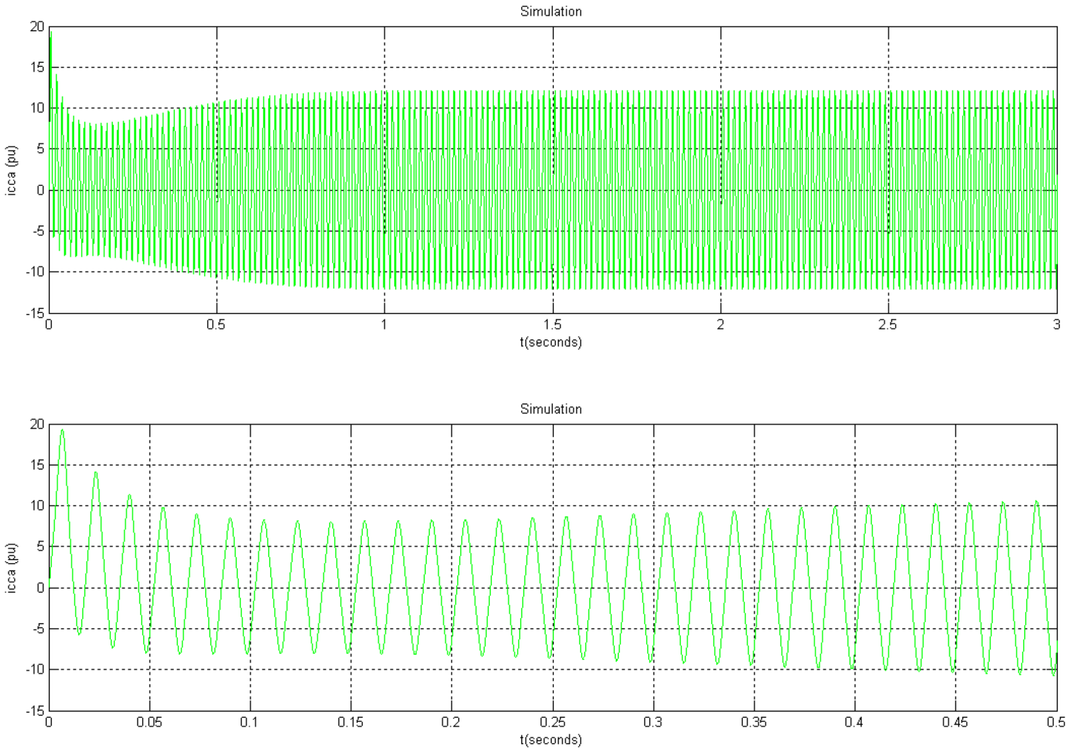

Figure 3-25: Short-circuit current in phase 'a' obtained by simulation, during a phase to phase short-circuit at synchronous generator terminals under no-load

3.11.2.2. 500kVA load test

In this section, the system has connected a load of 500kVA and 480V, besides the system will be tested with that load with a power factor of 1, 0.8 power factor lagging and 0.8 power factor leading.

Load: 500kVA load test 1 PF

- initial speed deviation (% of nominal speed): 0
- electrical angle of the rotor (degrees): -72.6288
- line current magnitudes i_a, i_b, i_c (pu): 0.454546; 0.454546; 0.454546
- phase angles ph_a, ph_b, ph_c (degrees): 7.77212e-14; -120; 120
- initial field voltage (pu): 1.15516

Load: 500kVA load test 0.8 lagging PF

- initial speed deviation (% of nominal speed): 0
- electrical angle of the rotor (degrees): -78.2048
- line current magnitudes i_a, i_b, i_c (pu): 0.454546; 0.454546; 0.454546
- phase angles ph_a, ph_b, ph_c (degrees): -36.8699; -156.87; 83.1301
- initial field voltage (pu): 1.47678

Load: 500kVA load test 0.8 leading PF

- initial speed deviation (% of nominal speed): 0
- electrical angle of the rotor (degrees): -72.7051
- line current magnitudes i_a, i_b, i_c (pu): 0.454546; 0.454546; 0.454546
- phase angles ph_a, ph_b, ph_c (degrees): 36.8699; -83.1301; 156.87
- initial field voltage (pu): 0.737616

3.11.2.3. 1100 kVA load test

In this section, the system has connected a load of 1100kVA and 480V, besides the system will be tested with that load with a power factor of 1, 0.8 power factor lagging and 0.8 power factor leading.

Load: 1100kVA load test 1 PF

- initial speed deviation (% of nominal speed): 0
- electrical angle of the rotor (degrees): -55.5921
- line current magnitudes i_a, i_b, i_c (pu): 1; 1; 1
- phase angles ph_a, ph_b, ph_c (degrees): -9.19285e-09; -120; 120
- initial field voltage (pu): 1.65229

Load: 1100kVA load test 0.8 lagging PF

- initial speed deviation (% of nominal speed): 0
- electrical angle of the rotor (degrees): -68.9392
- line current magnitudes i_a, i_b, i_c (pu): 1; 1; 1
- phase angles ph_a, ph_b, ph_c (degrees): -36.8699; -156.87; 83.1301
- initial field voltage (pu): 2.1675

Load: 1100kVA load test 0.8 leading PF

- initial speed deviation (% of nominal speed): 0
- electrical angle of the rotor (degrees): -46.7112
- line current magnitudes i_a, i_b, i_c (pu): 1; 1; 1
- phase angles ph_a, ph_b, ph_c (degrees): 36.8699; -83.1301; 156.87

- initial field voltage (pu): 0.898948

3.11.2.4. Peak short-circuit current decrement curves

As in the previous point 3.10.2, for the phase to phase short-circuit event at the generator terminals, it is interesting to compare the decrement of the current during a short-circuit when the generator is, before the short-circuit, operating under no-load conditions, approximately half load (500kVA) conditions at different power factors and full load (1100kVA) conditions at different power factor.

The comparison is done between the peak values of the different short-circuit current waveforms in phase 'a' with the system working under different load conditions before the short-circuit.

Following figure 3-26 represents the peaks short-circuit currents of the system within no-load and approximately half load (500kVA) of 1, 0.8 lagging and leading power factor. The graphs represent the evolution of one phase current in p.u. (RMS based) along the time.

For this study case, as in the case in point 3.10.2, when the load connected to the generator has lagging power factor, the short-circuit current has bigger peak values than with a resistive load and the opposite happens when the load connected to the generator has leading power factor. Besides, the action of the voltage control loop action of the excitation system can be seen in the short-circuit current in steady state period.

As a general conclusion to this figure, the four curves represented have close values between them.

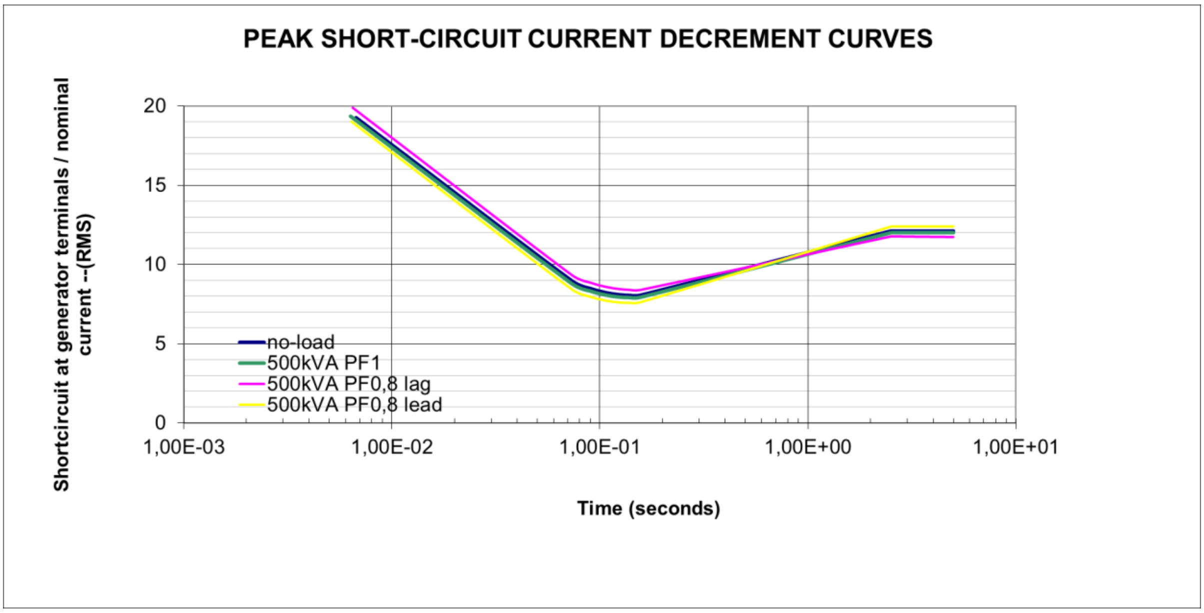

Figure 3-26: Comparison of peak short-circuit decrement curves under no-load and approximately half load with different power factor

Following figure 3-27 represents the peaks short-circuit currents of the system within no-load and full load (1100kVA) of 1, 0.8 lagging and leading power factor. The graphs represent the evolution of one phase current in p.u. (RMS based) along the time.

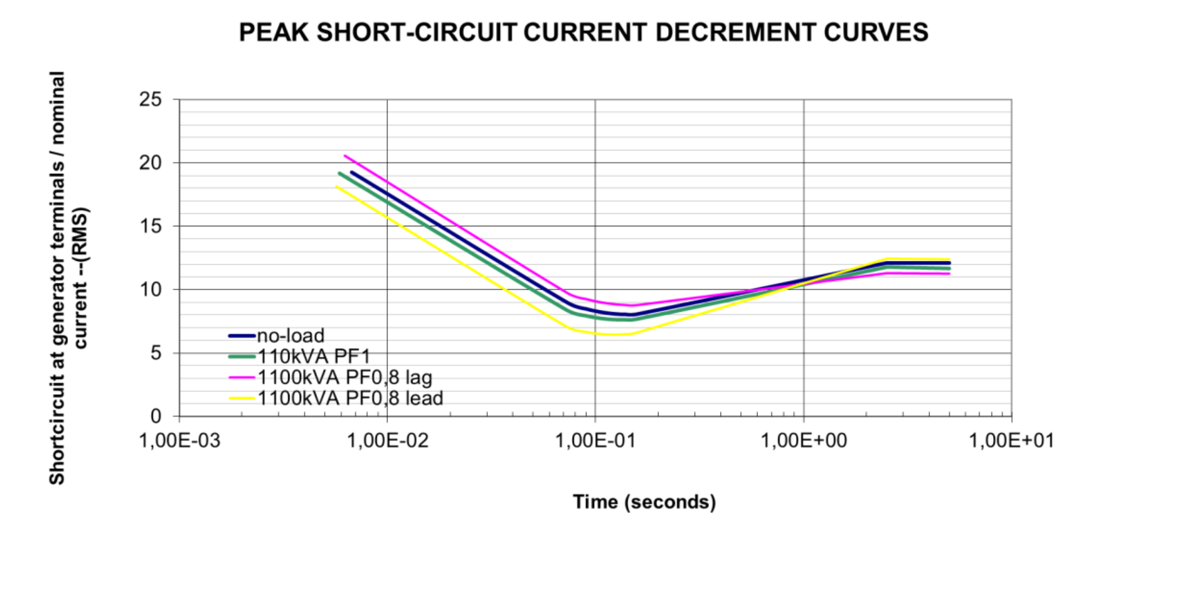

Figure 3-27: Comparison of peak short-circuit decrement curves under no-load and full load with different power factor

As in the previous figure 3-26, it can be seen that when the load connected to the generator has lagging power factor, the short-circuit current has bigger peak values than with a resistive load and the opposite happens when the load connected to the generator has leading power factor.

However, for this figure 3-27 the four curves represented are farther away from each other, this is due to the increase of the apparent power in the load.

3.12. Symmetrical short-circuit current decrement curve

To analyse and present the synchronous generator characteristics when a short-circuit occurs, it is interesting and a common practice in the industry, to plot in a figure the evolution along the time of the symmetrical AC component of the short-circuit current in phase ‘a’ during a three-phase short-circuit and a phase to phase short-circuit at the generator terminals.

Only the results of the no-load test have been analysed by obtaining the symmetrical short-circuit current decrement curves.

The Matlab/Simulink software output is the total short-circuit current in phase ‘a’, but what it is required is the symmetrical short-circuit current.

The symmetrical short-circuit current can be disregarded into subtransient component, transient component and permanent component of the total short-circuit current (3.46).

$$i_{symmetrical}(t) = i_{subtransient} + i_{transient} + i_{permanent} \tag{3.46}$$

Since, the software only provides the total short-circuit current, not the components of the waveform, the procedure used for obtaining the symmetrical current from the total short-circuit current is to calculate mathematically the polynomial equations which fit with the upper and lower envelopes of the peaks of the current waveforms. Once the polynomial equations are known, the solution of them through the time has to be found. Later, the AC symmetrical component is determined by the equation (3.47) [13]

$$i_{symmetrical}(t) = \frac{\lfloor I_{upper}(t) - I_{lower}(t) \rfloor}{2\sqrt{2} I_n} - \frac{I_{ss}}{I_n} \tag{3.47}$$

where

I_{ss}: is the steady-state current reached after the short-circuit
I_n: is the base current of the synchronous generator

Following figure 3-28 represents phase ‘a’ symmetrical short-circuit current during a three-phase short-circuit and a phase to phase short-circuit at the generator terminals operating under no-load conditions when the generation system has no excitation system.

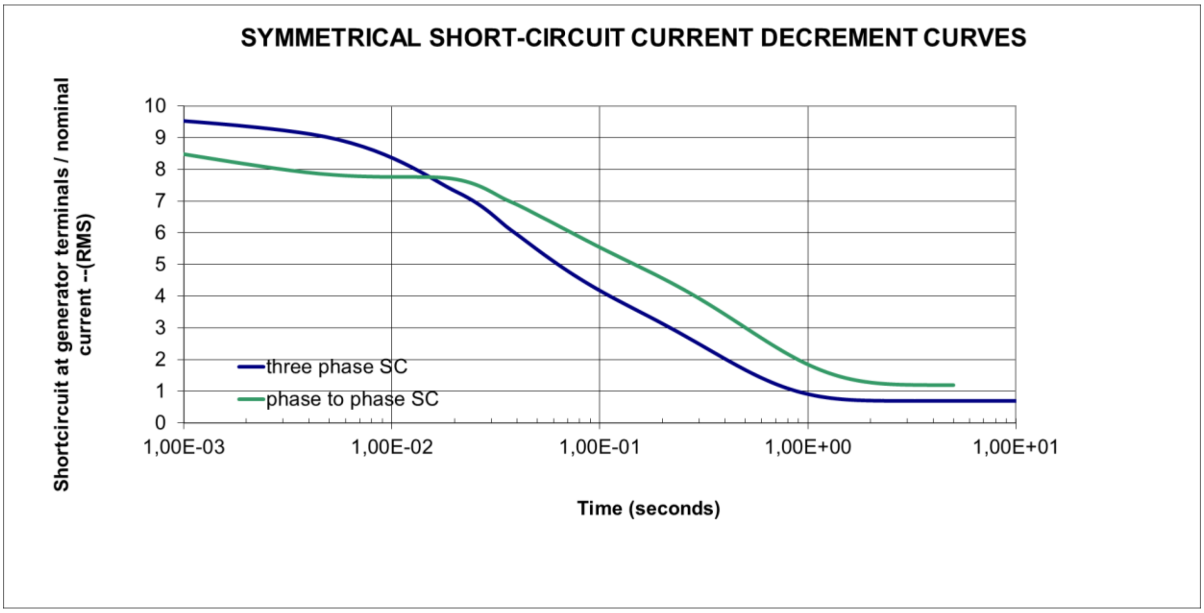

Figure 3-28: Symmetrical short-circuit decrement curves under no-load operation for a generation system without excitation system

It can be observed than the three phase short-circuit current has bigger values for the subtransient period and smaller for the transient and steady state period.

Following figure 3-29 represents phase 'a' symmetrical short-circuit current during a three-phase short-circuit and a phase to phase short-circuit at the generator terminals operating under no-load conditions. It can be observed the effect of the excitation system and its inner voltage control loop. Due to the influence, the curves start to decrease until a certain value, after the minimum value, the voltage control loop of the excitation system makes the system to increase the short-circuit current and to not pass a certain limit defined by the excitation system.

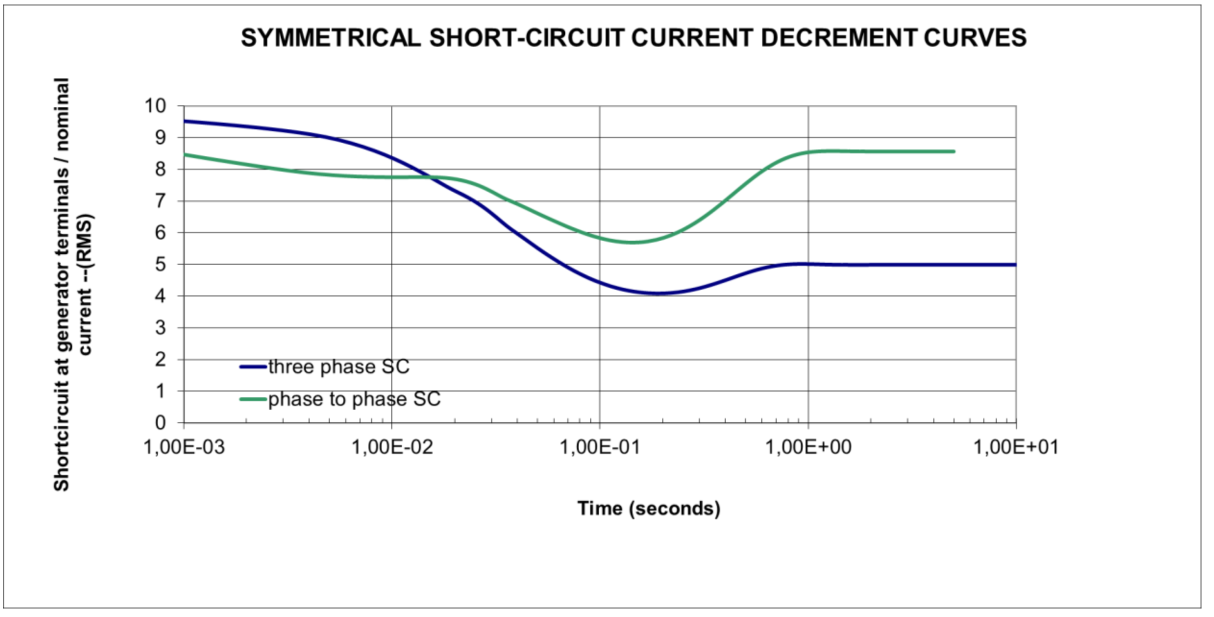

Figure 3-29: Symmetrical short-circuit decrement curves under no-load operation for a generation system with excitation system

Another interesting information needed for analyse completely the short-circuit event is to know the maximum instantaneous current value during the fault. The maximum instantaneous value of the current is the first peak value of the asymmetrical short-circuit current. For the cases studied in this work, the maximum instantaneous short-circuit current values are:

- Three-phase short circuit: 22.89 p.u.
- Phase to phase short-circuit: 19.30 p.u.

3.12.1. Importance of the decrement curve and key aspects

The short-circuit decrement curves represent the synchronous generator's fault current for subtransient, transient and steady state periods of the fault condition. The graphical representation of the synchronous generator performance is done when the system is under a fault situation produced at, or very close to the terminals of the electrical generating set.

The fault current represented from the subtransient and transient periods is the result of the energy within the e.m.f. strength, in association with the electromagnetic circuits of the synchronous generator and the excitation system working to maintain the rated output voltage. During the first moments of the fault, the stored energy is becoming to be dispersed, as consequence, the current reaches high values for subtransient and transient periods.

The short circuit performance of the electrical generating set during a fault at its terminals is represented by the short-circuit decrement curves. That information is necessary to correctly design the electrical protection system and to determine the electromagnetic and mechanical stresses on the generating set.

For the viewing of a decrement curve, some points are important and explain key aspects to take into account when designing the electrical protections.

- Subtransient period

In this region, the key aspect is the maximum current value of the asymmetrical current waveform. The reason why this value is important is that the power source capability has to be considered for designing the proper rupturing capacity of the electrical conductor assemblies, bus-bar chambers and switchgears.

- Transient period

In this region, the key aspect is that the short circuit decrement curve reaches its minimum current and after that point, it increases to a constant point for the steady state period.

The behaviour of the system is due to the action of the AVR, which is supplied by a permanent magnets generator, a dedicated source.

The AVR recognises the synchronous generator voltage and it immediately detects that is under the rated value and actuates on consequence. However, the effect of the AVR in the system is not instant, because the AVR acts by increasing the excitation and there is a certain time needed by the main exciter and synchronous generator rotor to reach the proper e.m.f. level that produces an increasing in the output voltage of the system.

- Steady state period

In this region, the current level is a multiple of the rated output current and it is defined for each electrical generating set design.

Another important issue represented in the short-circuit curves is the duration of the short-circuit. The time represented in the curves is the maximum duration than the alternator can tolerate each type of fault event. The maximum duration of a three-phase short-circuit is less than 10 seconds and for a phase to phase short-circuit the maximum time is less than 5 seconds.

The importance of the limit established with the maximum duration of a fault is a key factor, because it is considered to trip the circuit breakers. Thereby, a generator under a fault can be removed from the grid. The generator depends for it on the effective fault discrimination that circuit breakers do in the grid.

Chapter 4

Transient performance when sudden connection and disconnection of a load occurs at generator terminals

4.1. Description

Transient performance of the alternator is studied for the system when suddenly a load is connected to the system and when suddenly a load is disconnected to the system.

Transient performance of the generation system is an important part to study due to the impact on the system of connection and disconnection of high inductive load, which affect the behaviour of the generation system.

The system performance, when sudden connection and disconnection of high inductive load takes place on it, is focused to preserve the power stability in the system.

The electrical power is generated by the synchronous generator, which is a rotating machine with rotational inertia. The system maintains the frequency, and therefore the speed, by balancing the power generated with the power demanded by the loads connected to it. If there is a mismatch between the demanded and generated power, then the rotating machine, that is the generator, accelerates or decelerates trying to balance the addition or reduction of the demanded power by the load. The generator will accelerate if the power demanded is increased by connecting a load and it will decelerate if the power demanded is reduced by disconnecting a load. [18]

Now let's assume that the generator is operating at rated voltage and taking into account the preservation of power stability in the system. When a load is suddenly applied to the generator terminals, there is a fast decrease in the generator terminals voltage level. Due to the falling of the voltage, the AVR acts to maintain the voltage level on its rated value.

Since the voltage level is going down rapidly, the gradient of the voltage has a marked angle and due to the action of the AVR, the angle is reduced. However, the voltage level continues falling but not as fast as before. The AVR will continue acting on the excitation system until the voltage level at synchronous generator terminals recovers its rated value. The recovery of the rated voltage it is not instantaneous due to the inductance of the main exciter, synchronous generator and load.

Besides, the disconnection of a high inductive load also affects to the voltage at alternator terminals. In this situation, instead of having a reduction of the voltage level, a voltage rise or overshoot occurs upon removal of the electrical load. After the moment of load rejection there is a fast excitation increase, which takes some time to be reduced and the excitation level to reach again the rated voltage. In this case, also the AVR action plays an important role to recover the rated voltage level at alternator terminals.

At first sight, it seems that the generation system has no voltage limits when a high inductive load is connected to the system. However, if the voltage level decreases to extremely low levels, a short-circuit at the generator terminals could happen. The same way of thinking can be applied to the disconnection of high inductive load situation, but in this case an overvoltage situation could be the consequence in the generation system.

In order to avoid those unlikely situations, standards establish the voltage variation limits when a load is connected or disconnected to the generation system.

On the standard ISO 8528[3], the operating limits for transient voltage when the load is increased and decreased are classified according to the generator performance class. According to the standard, the classification is:

- Class G1: general purpose loads such as lighting
- Class G2: similar requirement to the public electricity supply and may include load such as pumps, fans and hoists
- Class G3: telecommunications and thyristor controlled loads
- Class G4: data processing or computer systems where the demands on the quality of the supply may be particularly severe.

To analyse the transient performance of the system, it is assumed that the generator performance class is G2. For that performance class, the generator operating limits are: [19]

- Transient voltage deviation on load increase :24% of rated voltage
- Transient voltage deviation on load decrease :25% of rated voltage

Induction motors are usually loads with more impact on the system when they are connected, because their starting currents are high, between 5 and 7 times the rated current value. In addition, the voltage dips in the diesel synchronous generator caused by the connection of this type of loads, are noteworthy. If the voltage dip is high, then the starting time of the motor increases. In the worst case scenario, it could even do not start if the resulting voltage causes a motor torque, which is proportional to the square of the voltage, is lower than the resistive torque of the motor when it starts.

Besides, on the standard the recommended test conditions to demonstrate the motor starting performance of a synchronous generator, exciter and AVR are mentioned. For that, the motor

[3] International standard for internal combustion engine driven alternating current generating sets

has to be represented by a load with constant impedance, which means that is non-saturable reactive load, and with lagging power factor less or equal to 0.4.

Figure 4-1 represents the evolution in the time of voltage at alternator terminals when a load is connected to the system. Figure 4-2 represents the evolution in the time of voltage at alternator terminals when a load is disconnected of the system. These figures are presented to show graphically what has been said about voltage dip evolution when the transient performance of the generation system test is performed. In figure 4-1 the decrease and recovery of voltage are shown and in figure 4-2 the rise and recovery of voltage.

In both example figures the load connected and disconnected is the same load of 1.1MVA (rated power) and PF=0.

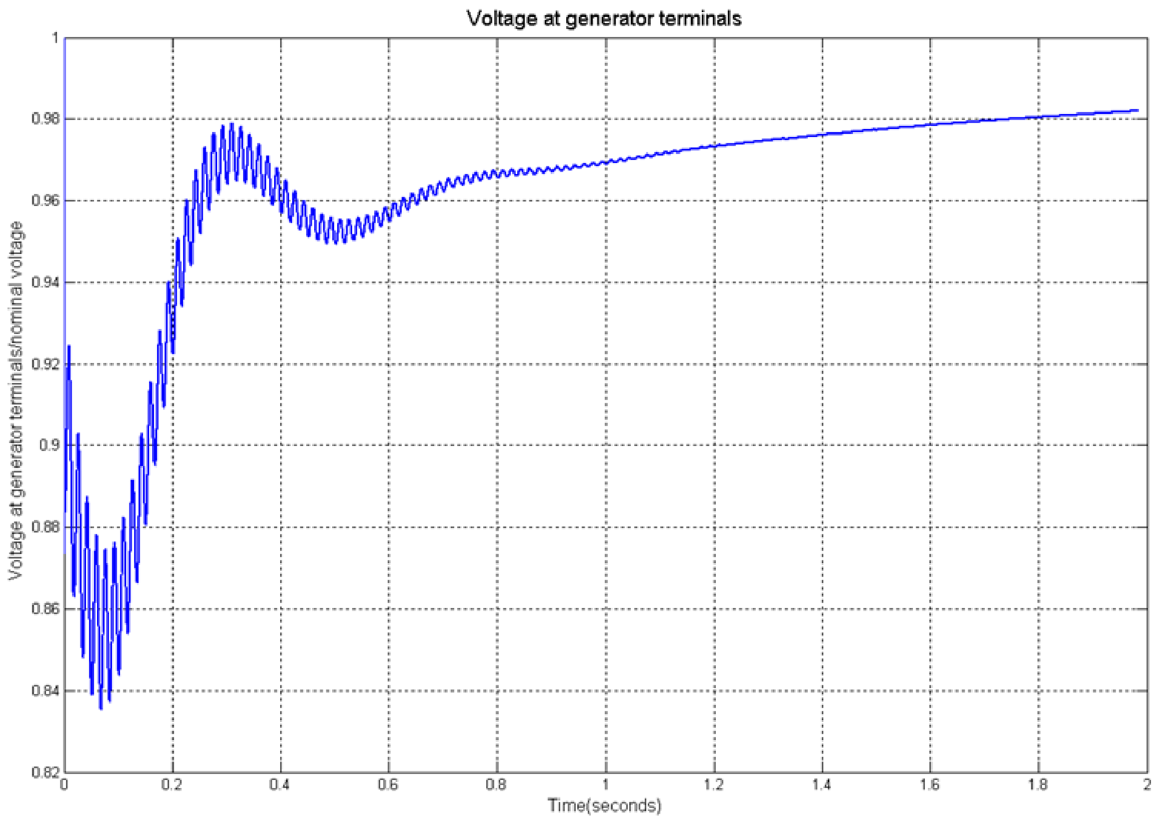

Figure 4-1: Voltage in p.u. at the generator terminals against time in seconds when a load is connected for transient performance generation system test

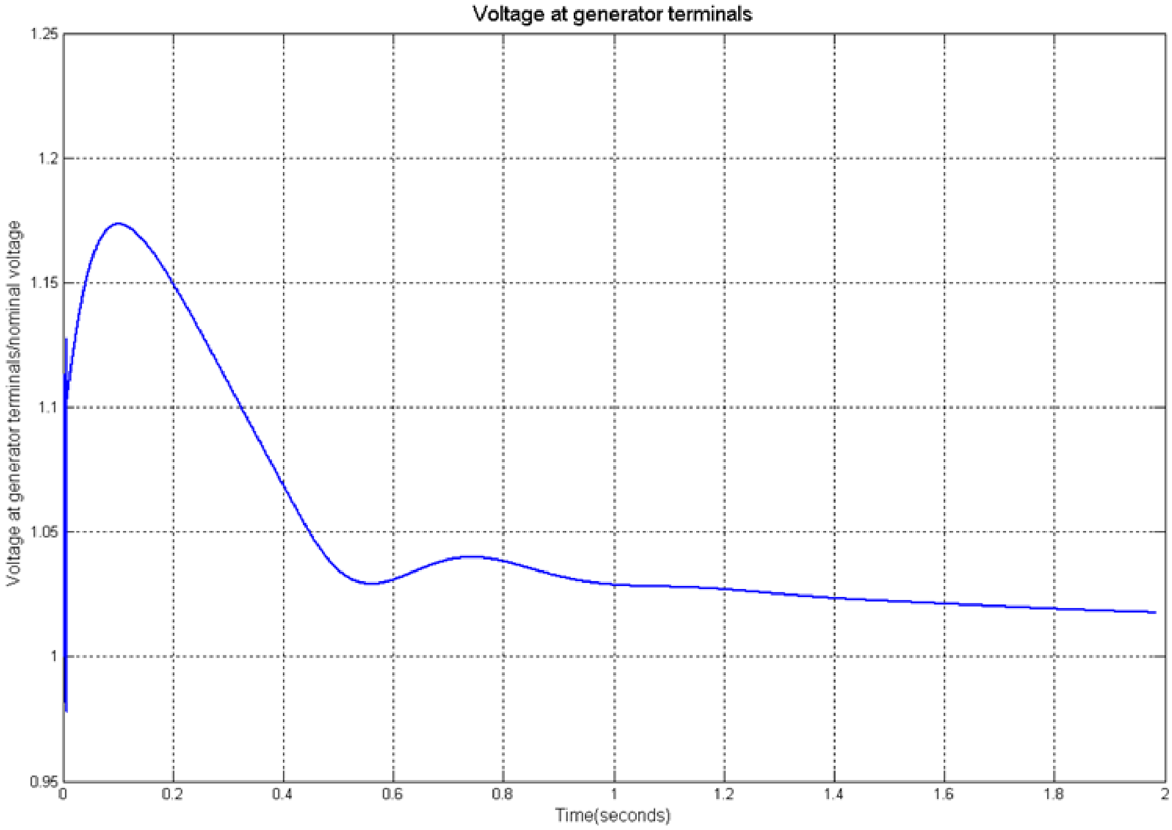

Figure 4-2: Voltage in p.u. at the generator terminals against time in seconds when a load is disconnected for transient performance generation system test

In both figures 4-1 and 4-2, is represented a zoom in of the evolution of the voltage at generator terminals in the time period from 0 s to 2s. The reason for the zoom in is to appreciate the voltage dip and rise evolution. It is not shown but it can be perceived, that the rated voltage will be reached after a time, due to the action of the AVR, as it was previously explained. In figure 4-1 the voltage tendency is to increase until reach the 1p.u. value and in figure 4-2 the tendency for the voltage id to decrease until reach 1 p.u. value.

4.2. Simulation performed with the software Matlab/Simulink

4.2.1 Simulation model scheme

The chosen load, to study the transient performance of the generation system, when connecting and disconnecting, is going to be a reactive load with power factor in the limits of the ISO 8528 standard.

The simulation is performed in the Simulink environment using its blocks from the library. The simulation system model is the same as the model used for the sudden short-circuit test. The difference between both models is that the fault breaker block has been substituted by a three phase load (typically an asynchronous motor).

The Matlab/Simulink implemented simulation model is shown in the figure 4-3.

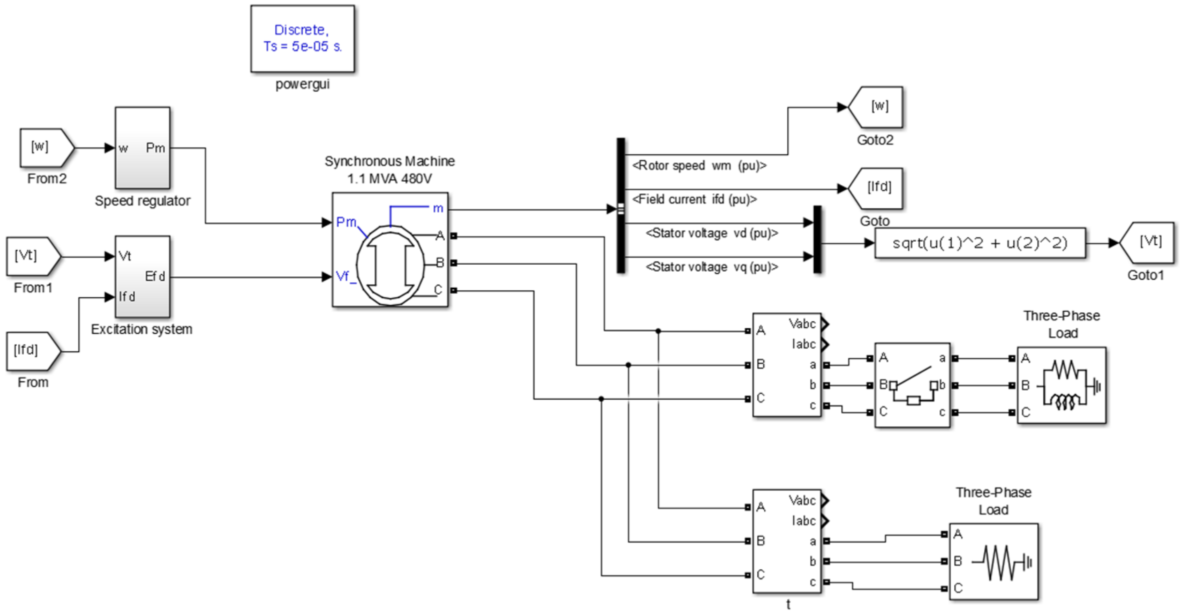

Figure 4-3: Simulation model of the generation system implemented for the motor starting and shut down test

4.3. Transient voltage dip with load application

The motors during their starting process, have a low power factor, but not when they are working at rated speed, at that time the power factor of the motor is high. When several motors are connected to the grid, the usual procedure is to connect them stepwise. Once few of them are at rated speed and the rated power factor, others are connected. By this way of proceed, the apparent power of the load experienced by the generator in the starting of the motors is not as big as if all the motors would start at the same time. Moreover, the voltage dip is also lower.

The synchronous generator performance under a sudden step load and the voltage dip is interesting, because it represents a starting motor study case. The loads have low power factor of PF=0 and PF=0.4 lagging, according to the ISO 8528 standard.

The simulation results are collected in curves in where the degree of voltage dip and the size of the load are represented.

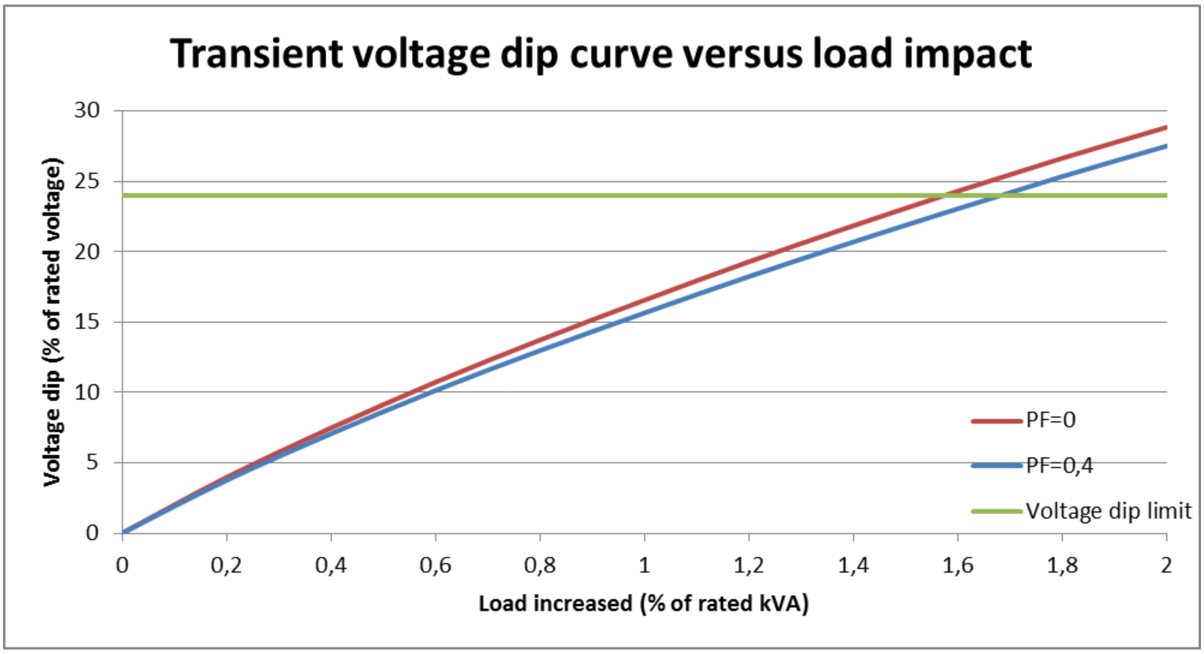

Figure 4-4: Transient voltage dip with load application

Previous figure 4-4 represents the maximum voltage dip when a load with certain power is connected to the generation system terminals.

The two power factor curves represented are the most extreme cases allowed by the standard [19]. If the load connected has an intermediate power factor, the curve should be between the extreme curves represented on the figure 4-4.

It can be observed on the figure 4-4 that if the load has high power and high power factor, the voltage dip is smaller than if the load has a low power factor. This is due to the resistive-inductive nature of the load.

4.4. Transient voltage rise with load rejection

The motors during their rated performance are working at rated speed, at that time the power factor of the motor is high. Therefore, when the motor is disconnected from the grid, the power factor of the motor is high. Usually, when several motors are disconnected from the gird, all of them are disconnected at the same time because the disconnection of the load is usually caused by some safety issues. The disconnection of the loads occurs with high power factors and in all the grid, usually it cannot be done step by step as the connection of the motors.

The synchronous generator performance under a sudden disconnection of load and the voltage rise is interesting. To represent the sudden disconnection, the loads disconnected have high power factor of PF=0.85 lagging and PF=1.

Therefore, the simulation results are collected in a curve in where the degree of voltage rise and the size of the load are represented.

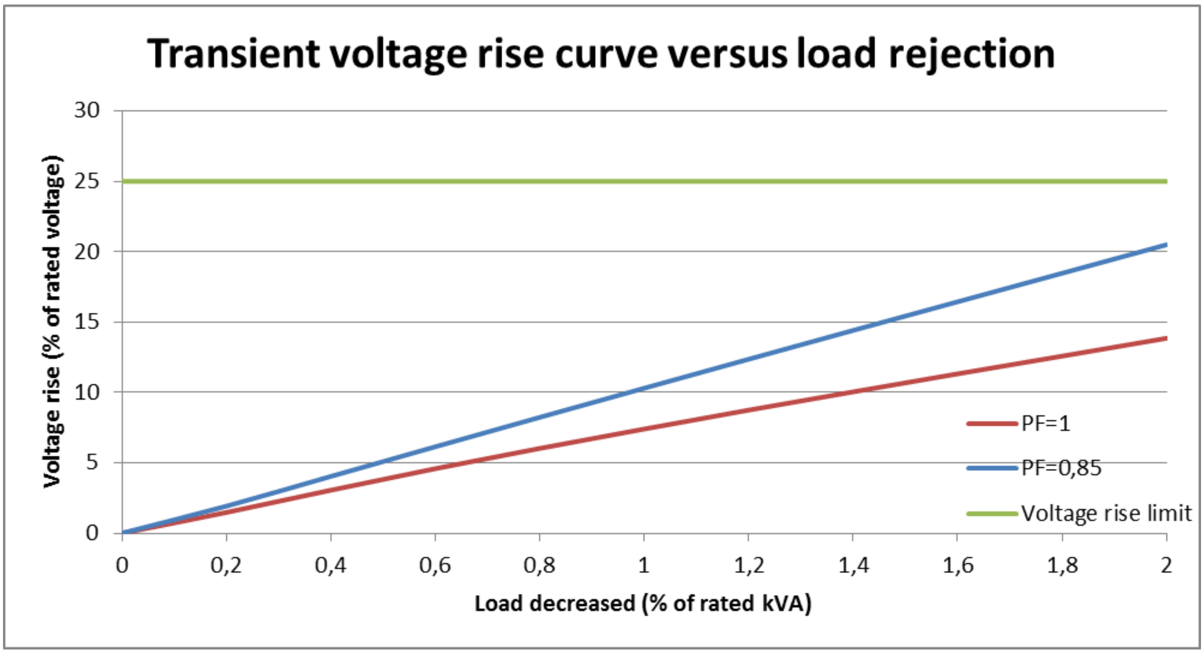

Figure 4-5: Transient voltage rise with load rejection

Previous figure 4-5 represents the maximum voltage rise when a load with certain power is disconnected to the generation system terminals.

The two power factor curves represented are representing the common situation of a disconnected toad. If the load disconnected has an intermediate power factor, the curve should be between the extreme curves represented on the figure 4-5.

It can be observed on the figure 4-5 that if the load has high power and high power factor, the voltage dip is smaller than if the load has a low power factor. The conclusion is the same than for the figure 4-4, the difference between the curves is due to the resistive-inductive nature of the load.

4.5. Importance of voltage dip and rise curves and key aspects

Electrical generating set's transient performance, when connecting and disconnecting loads from the system, is graphically represented by the maximum variation of the voltage against the power of the load.

The voltage dip curve represents a series of data points resulting of the instantaneous dip that happens when the AVR detects the change in the voltage, but before the excitation system answers recovering the voltage. The same is represented by the voltage rise curve, but the data points represent the instantaneous voltage rise.

Once the excitation system reacts, the voltage ends up returning to its rated value. The recovery time depends on the characteristics and performance capabilities of the elements of the system (synchronous generator, main exciter, voltage regulator, engine and connected loads).

The curves representations are used to know the maximum variation of the voltage due to the change in the load. Those changes in the load have a direct effect on the performance of the generation system, because the power stability could be compromised in case that the variation of the voltage would be higher than the maximum value represented on the curve for the corresponding load.

Besides, the standard settles limits to the variation of the load, those limits are different for the connection of load and for the disconnection of load. In addition, those limits cannot be exceeded. So, indirectly, the power of the load that can be connected and disconnected is defined by those limits.

Chapter 5

Task realized during the internship

Different tasks were assigned to me in the scope of diesel synchronous generator, during the internship at Rotating Machines Department of the EMMC STEPS' company partner Gamesa Electric. During my six months internship period in the company, I carried out different tasks that are going to be enumerated in the next lines.

Since I did not have experience in the designing and manufacturing aspects of the generators and neither in the transient test of the generators, I needed to spend significant time comprehending the state of the art. All the information and literature needed to head on the internship responsibilities were facilitated to me by my mentor.

During this time, I learned about transient importance and tests aspects and designing aspects of synchronous generators.

Other than developing and validating a tool for transient simulation during short-circuit and during connection and disconnection of motors, in the same scope I get familiar with the final user document consisting on the technical data sheet and performance curves of synchronous generators. Besides, I collaborated on the making of technical reports to external clients and I made technical reports to internal usage in the department in the same scope of diesel synchronous generators.

Chapter 6

Conclusion report

Conclusions

Transient response of the diesel synchronous generator is an issue of matter in the process of designing power systems. Electric power systems should be design to supply energy to the loads in a safe, reliable and efficient way. Therefore, to know the transient response of the generating elements of the grid is a key aspect to properly calculate the protections of the distribution system and to identify the safety working limits.

Along this master's work, a simulation tool has been designed using the software Matlab/Simulink, which is widely used in the industry and allows executing simulations in a short time and with precise results.

The tool designed is a model of a diesel synchronous generation set under the harmful situations that a generator could experiment. The objective pursued with the simulation is to obtain the necessary data to define the working limits of the generator and the electrical protections of the grid. The tool allows to know the data in a safe and fast way instead of performing real tests, which are risky and consume time and resources.

The most harmful situation that a generator could experiment is a short-circuit event. Besides, the performance of generator when connecting and disconnecting loads is necessary to preserve the stability of the system. Thus, it has been studied, by using the developed simulation model, the main sources of transients in a diesel application, which are short-circuit events and connection and disconnection of loads.

To fulfil with the objectives, the understanding of the generation system has been a key factor to develop the simulation model and to properly characterize the real elements of the system in the software.

The first part of this work has been the transient study of the diesel generator under a short-circuit event at its terminals has been simulated. The most harmful short-circuit types have been studied, those types are the three-phase and the phase to phase short-circuits. Even though they are less common than other types of short-circuit events, the extreme current values are experienced under those situations. Therefore, the protections for the grid have to insurance those current values, so no dangerous situations in the grid can be experienced for the connected loads and/or people.

During the short-circuit study of the generator, different current waveforms have been obtained. Short-circuit current waveforms at generator terminals when the system is under no-load before the short-circuit, when the system is under half load and under full load with different power factors had been analysed.

From the waveforms obtained, it can be concluded that the biggest peak values of the current are obtained when the generator is connected to a high load with lagging power factor. This behaviour is due to the presence of the inductor in the load.

Despite, the lowest peak values of the current are obtained when the generator is connected to a high load with leading power factor. The capacitor of the load makes to decrease the current waveform maximum peak values.

Apart from the nature of the load, the current short-circuit simulated waveforms have been treated to obtain the complete waveform, called asymmetrical waveform, and the symmetrical waveform. It is important to obtain the symmetrical short-circuit decrement curve, because it does not depend on the phase voltage when the event occurs.

Important points to have a look for proper sizing of the protection elements are shown in the short-circuit decrement curves.

- First point is the maximum current value of the system, which is experimented in the subtransient period of the waveform. This fault value is high because just after the short-circuit occurs, the stored energy in the generating system is becoming to be dispersed.
- Second point is the minimum current value of the system, which is experimented in the transient period of the waveform. The minimum value is at the moment that the AVR detects that the voltage is under the rated value, but the excitation system needs some time to act, reason why there is a minimum and afterwards the current starts to recover.
- Third point is the current constant level in the steady state period, which is a multiple of the rated current defined for each diesel generator.
- Fourth point is the duration of the fault. Each type of fault has its precise maximum time. The circuit breakers are selected to remove the faulty element from the grid in case that maximum duration time of fault is exceeded.

The second part of this work has been the transient study of the diesel generator performance when connecting and disconnecting loads has been achieved with the software. The aim is to know the working limits of the machine in order to preserve the stability of the system. The type of load selected for the transient study is an induction motor, because these motors are the loads with more impact on the system.

The diesel generator maintains the frequency, and therefore the speed, by balancing the generated and demanded power. When a mismatch between the power supplied and demanded happens, the generator accelerates or decelerates to balance the addition or reduction of the demanded power. Also, the voltage at generator terminals decreases when a load is connected to the system. On the other hand, the voltage increases when a load is disconnected. The AVR detects the variation on the voltage level and acts to maintain the rated value at generator terminals.

The maximum voltage dips have been represented in a curve composed by the voltage value at generator terminals when the AVR detects the change in the voltage due to the added load. To preserve the stability of the system, the maximum voltage dip is defined for different loads. Besides, the voltage limits established on the standards cannot be exceeded. Since the consider load is a starting induction motor, the simulation has been done for loads with low power factors. Induction motors are the most stressing loads which can be connected to the diesel". The reason for that is the low power factor and the high current (5 to 7 times nominal current) demanded by the motors when starting. These two factors reduce the voltage of the diesel in a great amount and can cause starting problems for the induction motors.

Similarly to the voltage dip when a load is connected, the voltage rise when a load is disconnected has been studied. The maximum voltage rise for each disconnected load had been found. These values and the voltage limit of the standards are key aspects to preserve the stability of the system. For the simulation it has been consider that the motors are suddenly disconnected from the grid due to safety reasons. Hence, the motors were working in normal conditions. So, the loads disconnected in the simulation to represent this situation have high power factors.

To conclude, the developed tool simulates the transient response that a diesel generating set could experiment. The output results of the simulation are used to properly design the protection elements of the grid and to preserve the stability of the system by defining the working limits of the generator.

The use of the simulation tool is approachable, since it has been done with the software Matlab/Simulink, which is widely used in the industry. Besides, the used of the simulation tool instead of performing real tests, provides the necessary data in a safe and fast way that reduces the resources and time needed.

Future work

Important transient performance curves of the diesel generating system had been obtained by using the developed tool. Other important information can be obtained by using the simulation model, such us torque transient performance curves and efficiencies curves. Also, the simulation performed to obtain those curves will save time and resources.

Torque transient performance curves represent the electrical torque produced by the synchronous generator when sudden short-circuit event occurs at generator terminals along the time. Efficiency curves represents the efficiency of the generator at different working percentages of rated power and at different power factor values. These two types of curves could be part of future work to develop in a short time.

The developed tool can be used, with small changes, to simulate the performance of a grid with power supplied from the generating system. Besides, the grid could be more complicated by connecting different power systems in parallel. Then an islanded grid could be simulated. Besides, the system can be connected to the main grid to analyse its performance.

Quality report

The starting point of this dissertation has been the understanding of the necessary theoretical concepts to successfully develop the topic. The design of the model has been checked with the theoretical values. All the necessary information has been provided by the Rotating Machines Department of Gamesa Electric.

Besides, the necessary explanations, valuable knowledge and support to develop this master thesis have been provided by the academic institutions that make up the EMMC STEPS and the co-workers of Rotating Machines Department of Gamesa Electric.

During the development of the EMMC STEPS master course, all the academic and administrative staff of the academic institutions of the master, all the professors and external professionals that where part of the modules and the co-workers of the master's partner company where approachable and supportive to help me to acquire the necessary skills to work in highly technical tasks related with electric power systems.

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