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Fault Levels in Transmission Substations (Level 110 KV)

مستويات العطل في محطات النقل الجانبية (مستوى الـــ 110 ك.ف)

A Dissertation submitted in partial fulfillment for the requirements of the degree of M.Sc. in Electrical Engineering (Power)

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الآيـــــــــة

"وَيَنصُرَكَ اللَّهُ نَصْرًا عَزِيزًا"

صدق الله العظيم

سورة الفـــتح

الآيــة (3)

DEDICATION

I dedicate my simple effort to:

My Parents

The greatest pyramids in my life, the candles which burning to light my life, the warm hands which making me comfortable and happy all the time. God preserves you.

My brothers and sisters

Whose affections, love and prays make me able to get such success an honor.

My husband, Faris…

For his help, love and patience, despite the distance.

ACKNOWLEDGEMENT

First of all, I would like to express my gratitude to ***God*** *for granting me with wisdom and the opportunity of an education.*

It has been an honor and pleasure to me to have, ***Dr. Mohammed Osman Hassan*** *as my supervisor. I am grateful to him for the time given to me to make this requirement and for his valued suggestion. In addition to his huge knowledge and experience. I enjoyed his support and patience during the very tough moment of the research work and writing of the report.*

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ABSTRACT

The analysis of power systems under fault condition represents one of the most important and complex task in Power Engineering. The studies and detection of these faults is necessary to ensure that the reliability and stability of the power system do not suffer a decrement as a result of a critical event such as fault. This dissertation analyzed the behavior of a system under fault conditions for different fault scenarios .

A 110-kV level of Khartoum National Electrical Grid is implemented as case study. A short circuit analysis is applied to the system in order to assess and evaluate the short circuit currents. Short circuit currents are required in order to provide information for the selection of circuit breakers and switch of adequate short circuit capacity to maintain continuity of supply.

Calculations of short-circuit currents were carried out according to IEC 60909 standard using Electromagnetic Transient Analysis Program (ETAP). All the data used for analysis is real time and collected from Khartoum electric transmission grid. Results of the short-circuit currents were obtained. Maximum fault levels were found in “EID BABIKER” substation, the fault current in 110 KV bus bar was 15.527 KA for three phase faults and 18.771 KA for line to ground faults. The minimum fault levels were found in “ELSHAGARA” substation; the fault current in 110 KV bus bar was 7.395 KA for three phase faults and 9.212KA for line to ground faults.

المستخلص

تحليل أنظمة القدرة في حالة حدوث عطل يمثل واحدة من أهم المهام وأكثرها تعقيدا في أنظمة القدرة الكهربائية. لضمان موثوقية واستقرار نظام القدرة لابد من عمل دراسات للكشف عن هذه الأعطال وفي هذا المشروع تم دراسة سلوك النظام في ظل تلك الأعطال بأخذ سيناريوهات مختلفة لها.

تم عمل الدراسة لجزء من الشبكة القومية الكهربائية السودانية لمستوى جهد 110 كيلو فولت. تم تحليل الدوائر المقصورة للنظام لتحديد تيارات الدوائر المقصورة من أجل توفير المعلومات لاختيار سعات القواطع الكهربائية ومعدات الحماية للحفاظ على استمرارية التيار الكهربائي.

حساب تيارات القصر تم طبقاً للمواصفة IEC60909 وذلك باستخدام برنامج التحليل الكهرومغناطيسي العابر ايتاب . تم جمع بيانات شبكة النقل الكهربائية للخرطوم ومن ثم تم الحصول على نتائج تيارات القصر. أقصى مستويات عطل وجدت في محطة عد بابكر حيث كان تيار العطل في قضيب التوصيل 110 ك.ف يساي 15.527 كيلو أمبير لعطل ثلاثي الأطوار و 18.771كيلو أمبير لأعطال خط مع الأرض. أدنى مستويات عطل وجدت في محطة الشجرة حيث كان تيار العطل في قضيب التوصيل 110 ك.ف يساوي 7.395كيلو أمبير لعطل ثلاثي الأطوار و9.212 كيلو أمبير لأعطال خط مع الأرض.

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LIST OF ABBREVIATIONS

ETAP	Electrical Transient Analyzer Program.
CTs	Current Transformers.
VTs	Voltage Transformers.
I_m	The Maximum Magnetizing Current.
X_d	Synchronous Reactance.
X_d'	Transient Reactance.
X_d''	Sub transient Reactance.
Z_0	Zero -Sequence Impedance
Z_1	Positive -Sequence Impedance
Z_2	Negative-Sequence Impedance
Z_s	Self Impedance.
Z_{s0}	Zero-Sequence Self Impedance.
Z_{s1}	Positive-Sequence Self Impedance.
Z_{s2}	Negative-Sequence Self Impedance.
Z_m	Mutual Impedance.
Z_{m0}	Zero-Sequence Mutual Impedance.
Z_{m1}	Positive-Sequence Self Impedance.
Z_{m2}	Negative-Sequence Self Impedance.
Z_f	Fault Impedance.
Z_g	The Impedance Towards The Ground.
I_{a0}	Zero-Sequence Current.
I_{a1}	Positive -Sequence Current.
I_{a2}	Negative-Sequence Current.
Z_{trf}	Transformer Impedance.
a	initial value of decaying dc component

i Generator

j Motor

$\Delta U''_{Gi}$ Initial voltage difference at connection to synchronous machine i

$\Delta U''_{Mj}$ Initial voltage difference at connection to synchronous machine j

$\frac{c\,Un}{\sqrt{3}}$ Equivalent voltage source at position of short circuit

I_a I''_k Symmetrical breaking current, initial symmetrical short circuit current considering all network inputs, synchronous machines and asynchronous machines

I''_{kGi} Initial symmetrical short circuit current of synchronous machine

I''_{kMj} Initial symmetrical short circuit current of asynchronous machine

μ_j Factor j for asynchronous machines

μ_i Factor i for synchronous machines

I_k'' Initial Symmetrical Short-Circuit Current.

I_k Minimum Symmetrical Short-Circuit Current.

I_b Symmetrical Short-Circuit Breaking Current.

i_p Peak Short-Circuits Current.

Chapter One

INTRODUCTION

1.1 Background:

Electrical power systems have to be planned, projected, constructed, commissioned and operated in such a way to enable a safe, reliable and economic supply of the load. The knowledge of the loading of the equipment at the time of commissioning and as foreseeable in the future is necessary for the design and determination of the rating of the individual equipment and of the power system as a whole. Faults, i.e., short-circuits in the power system cannot be avoided despite careful planning and design, good maintenance and thorough operation of the system. This implies influences from outside the system, such as short-circuits following lightning strokes into phase-conductors of overhead lines and damages of cables due to earth construction works as well as internal faults, e.g., due to ageing of insulation materials. Short-circuit currents therefore have an important influence on the design and operation of equipment and power systems [1].

Switchgear and fuses have to switch-off short-circuit currents in short time and in a safe way; switches and breakers have to be designed to allow even switch-on to an existing short-circuit followed by the normal switch-off operation. Short-circuit currents flowing through earth can induce impermissible voltages in neighboring metallic pipelines, communication and power circuits. Unsymmetrical short-circuits cause displacement of the voltage neutral-to-earth and are one of the dominating criteria for the design of neutral handling. Short-circuits stimulate mechanical oscillations of generator units which will lead to oscillations of active and reactive power as well, thus causing problems of stability of the power transfer which can finally result in system black-out. Furthermore, equipment and installations must withstand the expected thermal and electromagnetic (mechanical) effects of short-circuit currents [15].

1.2 Problem Statement:

The analysis of Power Systems under fault condition represents one of the most important and complex task in Power Engineering. The studies and detection of these faults is necessary to ensure that the reliability and stability of the power system do not suffer a decrement as a result of a critical event such a fault. This dissertation will analyze the behavior of a system under fault conditions and evaluate different scenarios of faults.

Sudanese national grid is not static but changes during operation (switching on or off of generators and transmission lines) and during planning (addition of generators and transmission lines), So the fault analysis is required in order to provide information for the selection of switchgear, setting of relays and stability of system operation to maintain continuity of supply. Thus, fault studies need to be routinely performed by utility engineers.

1.3 Dissertation Objectives:

This dissertation focuses on the following objectives:

- Selection of short circuit protective devices of adequate short circuit breaking capacity.

- Selection of circuit breakers & switches of adequate short circuit capacity.
- Selection of busbar size, busbar supports, cable & switchgear, designed to withstand thermal & mechanical stresses because of short circuit.

1.4 Methodology / Approach:

In this dissertation the fault level will be calculated at transmission bus bars level 110 KV for Sudanese transmission grid in 2017. The fault level will be calculated to 28 bus bars in Khartoum substations. To achieve the dissertation objectives, the data are collected with help Sudanese Electrical Transmission Company (SETCO), and then the transmission network is modeled by using ETAP software to simulate the outputs.

1.5 Dissertation Layout:

Chapter two presents the literature review of the dissertation, faults occurrences, protection system components, and the types of faults in power system. A review of short circuit analysis is presented and discussed. A general information about IEC 60 909 is also included.

Chapter three presents background theory and literature review on fault analysis in power systems and short circuit studies.

Chapter four presents a part of Sudan 110 kV system model. The short circuit analysis method is applied to the case study and discussion the results obtained by using ETAP.

Chapter five will go through the conclusion and recommendation for future dissertation. References cited and supporting appendices are given at the end of this dissertation.

Chapter Two

LITERATURE REVIEW

2.1 Introduction:

Electric power is generated, transmitted and distributed via large interconnected power systems. The generation of electric power takes place in a power plant. Then the voltage level of the power will be raised by the transformer before the power is transmitted. Electric power is proportional to the product of voltage and current this is the reason why power transmission voltage levels are used in order to minimize power transmission losses [1].

The primary objective of all power systems is to maintain the continuous power supply. During normal operating conditions, current will flow through all elements of the electrical power system within pre-designed values which are appropriate to these elements' ratings. However, natural events such as lightning, weather, ice, wind, heat, failure in related equipment and many other unpredictable factors may lead to undesirable situations and connection between the phases conductors of a transmission lines or the phase conductors to ground, these types of events are known as faults. A falling tree on a transmission lines could cause a three-phase fault where all phases share a point of contact called fault location. In different occasions, fault could be a result of insulation deterioration, wind damage or human vandalism [1].

Faults can be defined as the flow of a massive current through an improper path which could cause enormous equipment damage which will lead to interruption of power, personal injury, or death. In addition, the voltage level will alternate which can affect the equipment insulation in case of an increase or could cause a failure of equipment start-up if the voltage is below a minimum level. As a result, the electrical potential difference of the system neutral will increase. Hence, People and equipment will be exposed to the danger of electricity which is not accepted [2].

Any power system can be analyzed by calculating the system voltages and currents under normal & abnormal scenarios [2].

The fault currents caused by short circuits may be several orders of magnitude larger than the normal operating currents and are determined by the system impedance between the generator voltages and the fault, under the worst scenario if the fault persists, it may lead to long-term power loss, blackouts and permanently damage to the equipment. To prevent such an undesirable situation, the temporary isolation of the fault from the whole system it is necessary as soon as possible. This is accomplished by the protective relaying system [1].

The process of evaluating the system voltages and currents under various types of short-circuits is called fault analysis which can determine the necessary safety measures & the required protection system to guarantee the safety of public [1].

The analysis of faults leads to appropriate protection settings which can be computed in order to select suitable fuse, circuit breaker size and type of relay [2].

The severity of the fault depends on the short-circuit location, the path taken by fault current, the system impedance and its voltage level. In order to maintain the continuation of power supply to all customers which is the core purpose of the power system existence, all faulted parts must be isolated from the system temporary by the protection schemes. When a fault exists within the relay protection zone at any transmission line, a signal will trip or open the circuit breaker isolating the faulted line [1].

To complete this task successfully, fault analysis has to be conducted in every location assuming several fault conditions. The goal is to determine the optimum protection scheme by determining the fault currents & voltages. In reality, power system can consist of thousands of buses which complicate the task of calculating these parameters without the use of computer softwares such as MATLAB. In 1956, L.W. Coombe and D. G. Lewis proposed the first fault analysis program [1].

2.2 Faults Occurrences:

The nature of a fault is simply defined as any abnormal condition, which causes a reduction in the basic insulation strength between phase conductors, or between phase conductors and earth or any earthed screens surrounding the conductors. In practice, a reduction is not regarded as a fault until is it is detectable, that is until it results either in an excess current or in a reduction of the impedance between conductors, or between conductors and earth, to a value below that of the lowest load impedance normal to the circuit. Thus, a higher degree of pollution on an insulator string, although it reduces the insulation strength of the affected phase, does not become a fault until it causes a flashover across the string, which in turn produces excess current or other detectable abnormality, for example abnormal current in an arc-suppression coil [3]. Following are some of the main causes:

2.2.1 Lightning:

More than half of the electrical faults occurring on overhead power transmission lines are caused by lightning. The main conventional approaches for reduction of the lightning flashover faults on power lines are lowering of the footing resistance and employing of multiple shielding wires, and differential insulation [3].

2.2.2 Pollution:

Pollution is commonly caused by deposited soot or cement dust in industrial areas, and by salt deposited by wind-borne sea-spray in coastal areas. A high degree of pollution on an insulator string, although it reduces the insulation strength of the affected phase, does not become a fault until it causes a flashover across the string, which in turn reduces excess current or other detectable abnormality, for example abnormal current in an arc-suppression coil [3].

2.2.3 Fires:

The occurrence of fire under transmission lines is responsible for a great number of line outages in many countries. Faults are mainly due to conductor to ground short circuit at mid-span or phase-to-phase short circuit depending on line configuration and voltage level. To reduce these outages to a minimum, the clearance of existing lines must be increased in forests. Clearing and vegetation on the line right of way in such areas is also a consideration. Another problem arising from burning is the contamination of the insulators due to the accumulation of particles (soot, dust) on its surfaces. In this case, the line insulation requirements should be determined in such a way that the outages under fire could be reduced to a minimum [3]. Other causes of faults on overhead lines are trees, birds, aircraft, fog, ice, snow loading, punctured or broken insulators, open-circuit conductors and abnormal loading.

2.3 Type of Faults:

There are two types of faults which can occur on any transmission lines; balanced faults and unbalanced faults also known as symmetrical and asymmetrical faults respectively. Most of the faults that occur on power systems are not the balanced three-phase faults, but the unbalances faults. In addition, faults can be categorized as the shunt faults, series faults and simultaneous faults [5]. In the analysis of power system under fault conditions, it is necessary to make a distinction between the types of fault to ensure the best results possible in the analysis. However, for this project only shunt faults are to be analyzed.

2.3.1 Series Faults:

Series faults represent open conductor and take place when unbalanced series impedance conditions of the lines are present. Two examples of series fault are when the system holds one or two broken lines, or impedance inserted in one or two lines. In the real world a series faults takes place, for example, when circuit breakers controls the lines and do not open all three phases, in this case, one or two phases of the line may be open while the other/s is closed [5]. Series faults are characterized by increase of voltage and frequency and fall in current in the faulted phases.

2.3.2 Shunt Faults:

The shunt faults are the most common type of fault taking place in the field. They involve power conductors or conductor-to-ground or short circuits between conductors. One of the most important characteristics of shunt faults is the increment the current suffers and fall in voltage and frequency. Shunt faults cab be classified into four categories [7].

1. Line-to-ground fault: this type of fault exists when one phase of any transmission lines establishes a connection with the ground either by ice, wind, falling tree or any other incident. 70% of all transmission lines faults are classified under this category [4].

2. Line-to-line fault: as a result of high winds, one phase could touch anther phase & line-to-line fault takes place. 15% of all transmission lines faults are considered line-to-line faults [4].

3. Double line-to-ground: falling tree where two phases become in contact with the ground could lead to this type of fault. In addition, two phases will be involved instead of one at the line-to-ground faults scenarios. 10% of all transmission lines faults are under this type of faults [4].

4. Three phase fault: in this case, falling tower, failure of equipment or even a line breaking and touching the remaining phases can cause three phase faults. In reality, this type of fault not often exists which can be seen from its share of 5% of all transmission lines faults [4].

The first three of these faults are known as asymmetrical faults.

2.4 Power System Protection:

Power system protections are one of the electrical powers engineering that in the matter of electrical power systems from faults through the isolation of the faulted system from the health of the electrical network. To be said, it is very important system to protect humans or any components from gain any damage. System protections are used to detect and isolates the faulty system automatically [3].

Some abnormal conditions are often occurring in an interconnected system. For this reason, the damage of the equipment and the interruption of the supply connected to the power system could be happen [3].

2.5 Protection System Components:

Generally, protection system consists of three main components which are protection devices (relay), instrument transformers (CTs and VTs) and circuit breakers as shown in figure 2.1[10].

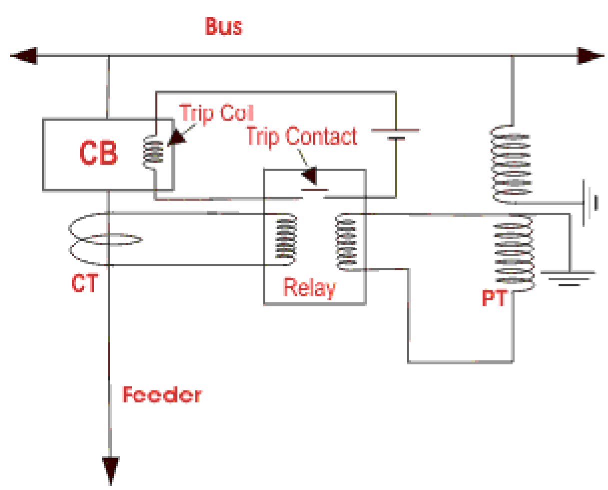

Figure 2-1: Power system protection components [10]

2.5.1 Current Transformers:

They provide a current proportional to the current flowing through the primary circuit in order to perform energy metering or to analyze this current through a protection device. The secondary is connected to low impedance (used in practically short-circuited conditions). BS 3938 specifically defines current transformers designed for protection under the heading class X.

According to the British Standard, class X is defined by the rated secondary current, the minimum knee-point voltage, the maximum resistance of the secondary winding and the maximum magnetizing current at the rated knee-point voltage.

Rated knee-point voltage (VK) at the rated frequency is the voltage value applied to the secondary terminals, which, when increased by 10%, causes a maximum increase of 50% in magnetizing current.

While the maximum resistance of the secondary winding (Rct) is the maximum resistance of this winding, corrected at 75°C or at the maximum operating temperature if this is greater.

The maximum magnetizing current (I_m) is the value of the magnetizing current at the rated knee-point voltage, or at a specified percentage of this current as shown in figure 2.2 [11].

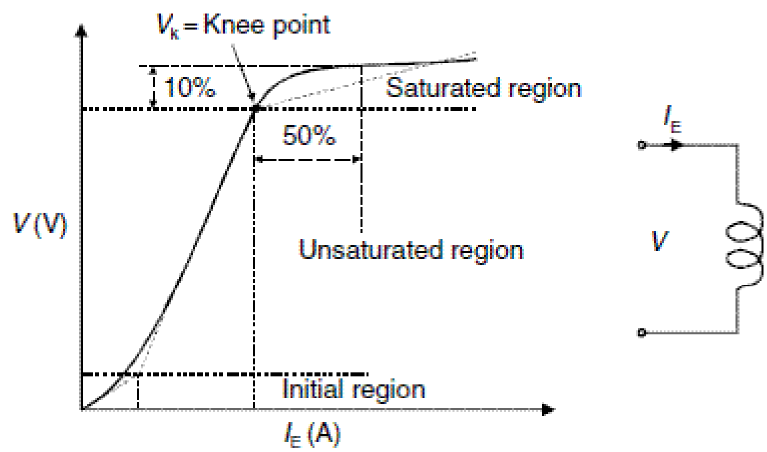

Figure 2-2: Knee-point voltage and magnetizing current of a CT according to BS [11]

2.5.2 Voltage Transformers:

A voltage transformer is designed to give the secondary a voltage proportional to that applied to the primary. For a VT, the primary voltage/secondary voltage ratio is constant, the main tow type are electromagnetic voltage transformer and capacitive voltage transformer which refer to internal constriction. Voltage transformers used for protection in compliance with IEC 60044-2 The IEC accuracy classes are 3P and 6P. In practice, only class 3P is used, The accuracy class is guaranteed for the following values, voltages between 5% of the primary voltage and the maximum value of this voltage which is the product of the primary voltage and the rated voltage factor ($kT \times Vn$) and for a secondary load between 25% and 100% of the accuracy power with an inductive power factor of 0.8 [11].

2.5.3 Protection Devices (Relays):

One of the important equipment in the protection of power system are protective relays. IEEE defined relay as “an electric device that designed to interpret input conditions in a prescribed manner, and after specified conditions are met to respond to cause contact operation or similar abrupt changes in associated electric control circuits [14]”. Thus, the main function of protective relays is to separate a faulty area by controlling the circuit breaker with the least interruption to give service. The relay is automatic devices to detect and to measure abnormal conditions of electrical circuit, and closes its contact with the system.

There are many types of relay can be used in protect transmission lines systems according to their characteristic, logic, actuating parameter and operation mechanism such as magnitude relay, instantaneous relay, differential relay, directional relay, and distance schemes [11].

2.5.4 Circuit Breaker:

The International Electro Technical Commission (IEC) Standard IEC 60947-2 defines a circuit breaker as “a mechanical switching device, capable of making, carrying and breaking currents under normal circuit conditions and also making, carrying for a specified time and breaking currents under specified abnormal circuit conditions such as those of short-circuit.

The protective relay detects and evaluates the fault and determines when the circuit should be opened. The circuit breaker functions under control of the relay, to open the circuit when required. A closed-circuit breaker has sufficient energy to open its contacts stored in one form or another (generally a charged spring). When a protective relay signals to open the circuit, the store energy is released causing the circuit breaker to open. Except in special cases where the protective relays are mounted on the breaker, the connection between the relay and circuit breaker is by hard wiring. The important characteristics from a protection point of view are:

i) The speed with which the main current is opened after a tripping impulse received.

ii) The capacity of the circuit that the main contacts are capable of interrupting. The first characteristic is referred to as the ‘tripping time’ and is expressed in cycles. Modern high-speed circuit breakers have tripping times between three and eight cycles.

The tripping or total clearing or break time is made up as follows:

i) Opening time: The time between instant of application of tripping power to the instant of separation of the main contacts.

ii) Arcing time: The time between the instant of separation of the main circuit breaker contacts to the instant of arc extinction of short-circuit current. Total break or clearing time: The sum of the above [11].

Figure 2.3 shows the simplified circuit diagram of trip circuit of a circuit breaker [11].

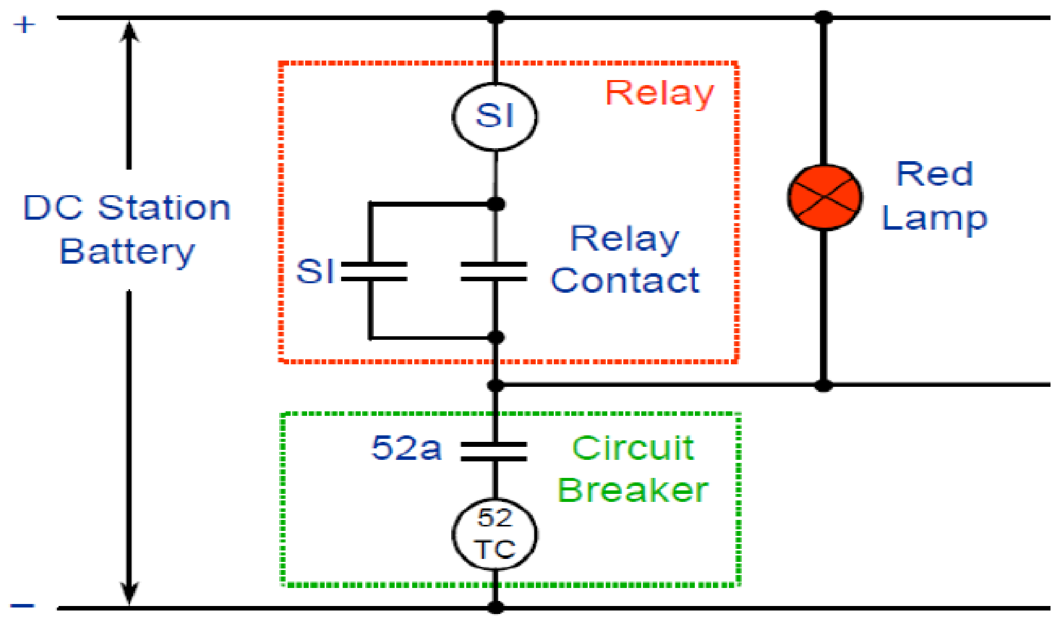

Figure 2-3: The trip circuit of a circuit breaker [11]

2.5.6 Tripping Batteries:

The operation of monitoring devices like relays and the tripping mechanisms of breakers require independent power source, which does not vary with the main source being monitored. Batteries provide this power and hence they form an important role in protection circuits. The relay/circuit breaker combination depends entirely on the tripping battery for successful operation. Without this, relays and breakers will not operate, becoming ‘solid’, making their capital investment very useless and the performance of the whole network unacceptable. It is therefore necessary to ensure that batteries and chargers are regularly inspected and maintained at the highest possible level of efficiency at all times to enable correct operation of relays at the correct time [11].

2.6 Short Circuit Analysis:

Short circuit analysis is used to calculate the phase and sequence currents and voltages “seen” by protective relays for simulated faults at various locations internal and external to the relay’s desired zone of protection. These voltage and current quantities are used to determine the relay’s sensitivity and expected operating characteristics for faults at various locations and with various power system configuration contingencies.

Lumped series impedance parameters are used for short circuit analysis. Shunt impedance parameters are generally ignored, first of all to simplify the short circuit calculations, and secondly because the effect of shunt impedance parameters is generally negligible under the reduced voltage and high current conditions during a fault.

Short circuit calculations are generally made using sequence component analysis to simplify the calculation of unbalanced three-phase systems into balanced single-sequence networks. Positive-, negative-, and zero-sequence impedances are required to perform the complete array of three-phase, phase-to-phase, phase-to-phase-to-ground, and phase-to-ground fault analysis. Sequence quantities are computed, then used directly, or converted to phase quantities for protective relay analysis and settings.

2.7 Type of Short Circuits:

IEC 60909 and the associated standards classify short circuit currents according to their magnitudes (maximum and minimum) and fault distances from the generator (far and near). Maximum short circuit currents determine equipment ratings, while minimum currents dictate protective device settings. Near-to generator and far-from generator classifications determine whether or not to model the AC component decay in the calculation, respectively. [18]

2.7.1 Near-to-Generator Short Circuit:

This is a short circuit condition to which at least one synchronous machine contributes a prospective initial short circuit current which is more than twice the generator s rated current, or a short circuit condition to which synchronous and asynchronous motors contribute more than 5% of the initial symmetrical short circuit current I_k". [18]

Figure 2-4 shows near-to-generator short circuits current

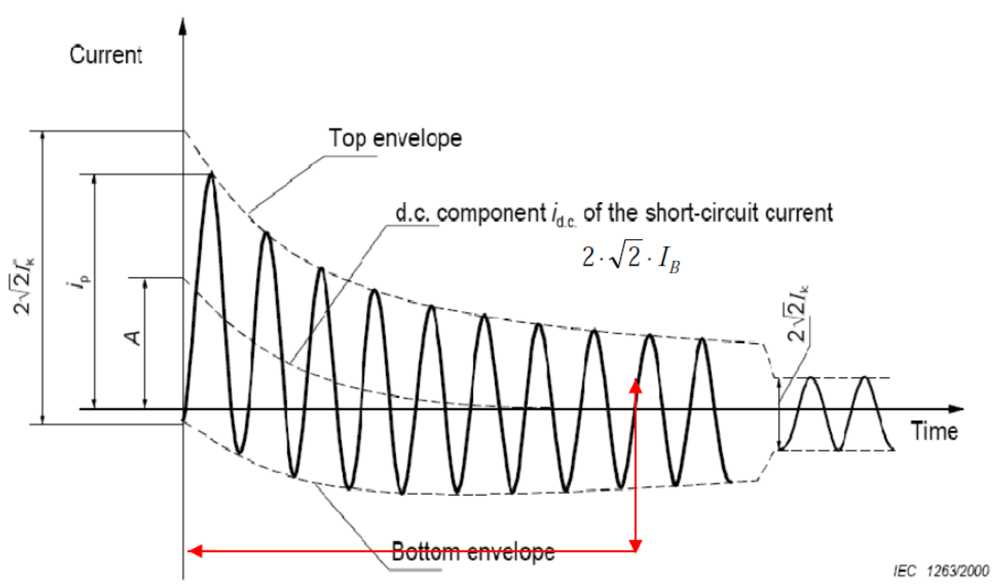

Figure 2-4: Near –to- generator short circuits

Where:

I_k'' ≡ Initial symmetrical short-circuit current

i_P≡ Peak short-circuit current

I_k≡ Steady-state short-circuit current

A≡ Initial value of the d.c component

I_B ≡ Symmetrical short-circuit breaking current

2.7.2 Far-From-Generator Short Circuit:

This is the short circuit condition during which the magnitude of symmetrical ac component of available short circuit current remains essentially constant. Figure 2-5 shows far-from-generator short circuits

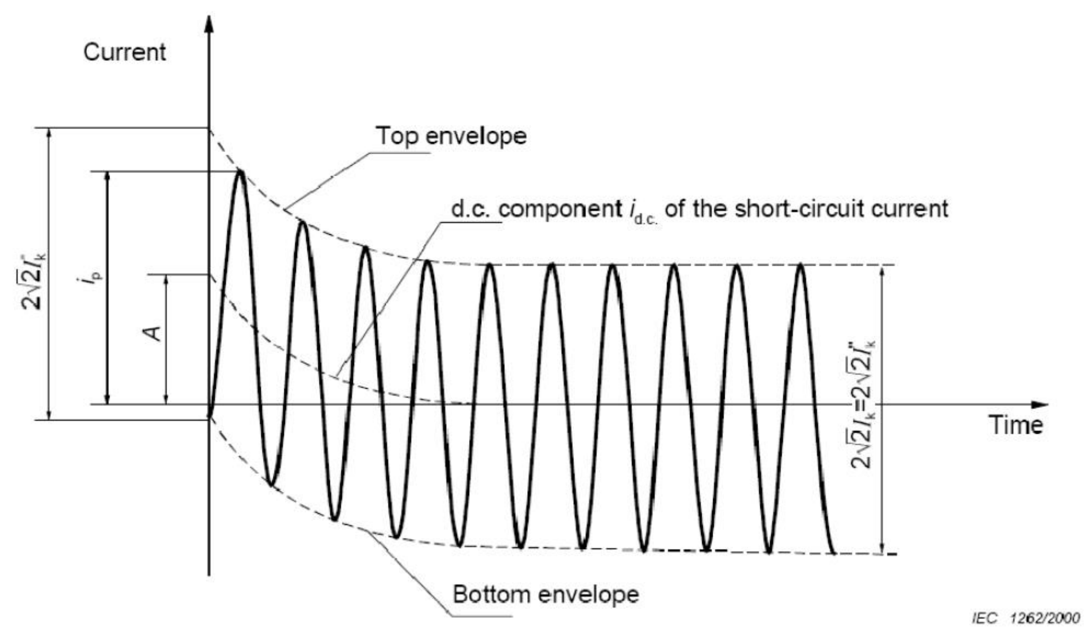

Figure 2-5: Far-from-generator short circuits

Where:

I_k'' ≡ Initial symmetrical short-circuit current

$i_P \equiv$ Peak short-circuit current

$I_k \equiv$ Steady-state short-circuit current

$A \equiv$ Initial value of the d.c component

2.8 General Information About IEC 60 909:

IEC 60 909 includes a standard procedure for the calculation of short circuit currents in low and high voltage networks up to 380 KV at 50 Hz or 60 Hz. The purpose of this procedure is to find a brief, general and easy to handle calculation procedure, which is intended to lead with sufficient accuracy to results on the safe side. for this purpose, we calculate with an equivalent voltage source at the position of the short circuit. It is also possible to use the superposition method here [8].

A complete calculation of the time behavior for far-from-generator and near-to-generator short circuit is not required here. In most cases, it is sufficient to calculate the three-pole and the single-pole short circuit currents, assuming that for the duration of the short circuit no change takes place in the type of short circuit, the step switch of the variable-ratio transformers is set to the principal tapping and arc resistances can be neglected [8].

The short circuit currents and short circuit impedances can always be determined by the following methods:

- Calculation by hand.
- Calculation using a PC.
- Using field test.

- Measurements on network models.

The short circuit currents and short circuits impedances can be measured in low voltage network with measuring instruments directly at the assumed position of the short circuit.

For the dimensioning and the choice of operational equipment and overcurrent protective equipment, the calculation of short circuit currents in three-phase networks is of great importance, since the electrical system must be designed not only for the normal operating state but also to withstand fault situations [8].

IEC 60 909 describes the basis for calculation, which consists of three parts:

1. Main part I: networks with circuit currents without decaying AC periodic component) far-from-generator short circuit).
2. Main part II: networks with circuit currents with decaying AC periodic component) near-from-generator short circuit).
3. Main part III: double ground connection, transferred short circuit currents via ground.

2.9 Short Circuit Definitions According to IEC 60909:

1. Initial symmetrical short-circuits current I_k":

R.M.S value of the A.C symmetrical component of a prospective (available) short-circuit current, applicable at the instant of short circuit if the impedance remains at zero-time value.

2. Steady-state short-circuit current I_k:

R.M.S value of the short-circuit current which remains after the decay of the transient phenomena

3. Symmetrical short-circuit breaking current I_b:

R.M.S value of an integral cycle of the symmetrical a.c. component of the prospective short-circuit current at the instant of contact separation of the first pole to open of a switching device

4. Decaying (a periodic) component Id.c. of short-circuit current:

Mean value between the top and bottom envelope of a short circuit current decaying from an initial value to zero.

5. Peak short-circuit current i_p:

Maximum possible instantaneous value of the prospective (available) short circuit current

NOTE: The magnitude of the peak short-circuits current varies in accordance with the moment at which the short circuit occurs. [19]

2.10 Purpose of Short-Circuits Calculation:

Summarizes the objectives of determining short circuit currents in power systems in table2.1

Table 2-1: Purpose of Short-Circuit Values

ITEMS	Design Criterion	Physical Effect	Relevant short circuit current
1	Breaking capacity of circuit breakers	Thermal stress to arcing chamber; arc extinction	Symmetrical short-circuit breaking current I_b
2	Mechanical stress to	Forces to electrical	Peak short-circuit current

	equipment	devices (e.g. bus bars, cables…)	i_p
3	Thermal stress to equipment	Temperature rise of electrical devices (e.g. cables)	Initial symmetrical short circuit current I_k" Fault duration
4	Protection setting	Selective detection of partial short-circuit currents	Minimum symmetrical short-circuit current I_k
5	Earthing, Interference, EMC	Potential rise Magnetic fields	Maximum initial symmetrical short-circuit current I_k"

2.11 About ETAP:

ETAP is Electromagnetic Transient Analysis Program. This software provides engineers, operators, and managers a platform for continuous functionality from modeling to operation. ETAP‟s model-driven architecture enables „Faster than Real-Time‟ operations - where data and analytics meet to provide predictive behavior, preemptive action, and situational intelligence to the owner-operator. ETAP offers a suite of fully integrated electrical engineering software solutions including arc flash, load flow, short circuit, transient stability, relay coordination, cable capacity, optimal power flow, and more. Its modular functionality can be customized to fit the needs of any company, from small to large power systems.

Chapter Three

THE MATHEMATICAL MODEL

3.1 Introduction:

In IEC short-circuit calculations; an equivalent voltage source at the fault location replaces all voltage sources. A voltage factor c is applied to adjust the value of the equivalent voltage source for minimum and maximum current calculations. All machines are represented by their internal impedances. Transformer taps can be set at either the nominal position or at an operating position, and different schemes are available to correct transformer impedance and system voltages if off-nominal tap setting exists. System impedances are assumed to be balanced 3-phase, and the method of symmetrical components is used for unbalanced fault calculations. Zero sequence capacitances of transmission lines, cables and shunt admittances can be considered for unbalanced fault calculations (LG and LLG) if the option in the study case is selected to include branch Y and static load. This means that the capacitances of static loads and branches are considered based on IEC 60909-0 2001. Calculations consider electrical distance from the fault location to synchronous generators. For a far-from-generator fault, calculations assume that the steady-state value of the short-circuit current is equal to the initial symmetrical short-circuit current and only the DC component decays to zero. However, for a near-to-generator fault, calculations count for decaying in both AC and DC components. The equivalent R/X ratios determine the rates of decay of both components, and different values are taken for generators and loads near the fault.

3.2 Fault Analysis in Power Systems:

In general, a fault is any event, unbalanced situation or any asymmetrical situation that interferes with the normal current flow in a power system and forces voltages and currents to differ from each other.

It is important to distinguish between series and shunt faults in order to make an accurate fault analysis of an asymmetrical three-phase system. When the fault is caused by an unbalance in the line impedance and does not involve a ground, or any type of inter-connection between phase conductors it is known as a series fault. On the other hand, when the fault occurs and there is an inter-connection between phase-conductors or between conductor(s) and ground and/or neutral it is known as a shunt fault. [12]

Statistically, series faults do not occur as often as shunt faults does. Because of this fact only the shunt faults are explained here in detail since the emphasis in this project is on analysis of a power system under shunt faults.

3.2.1 Three-Phase Fault:

By definition a three-phase fault is a symmetrical fault. Even though it is the least frequent fault, it is the most dangerous. Some of the characteristics of a three-phase fault are a very large fault current and usually a voltage level equals to zero at the site where the fault takes place. [12]

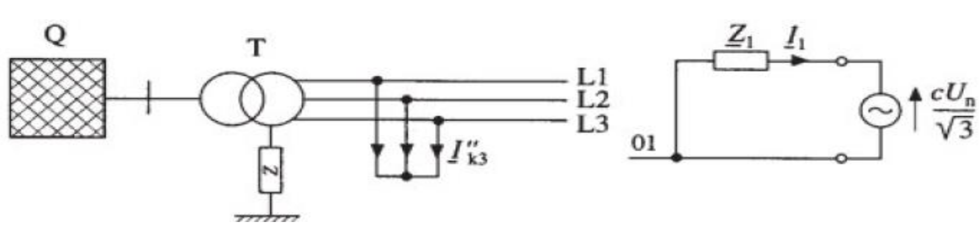

Figure 3-1: Equivalent circuit for a three-phase short circuit with equivalent voltage source at position of fault

For the dimensioning of electrical systems, it is necessary to consider three- pole short circuits in order to guarantee the mechanical and thermal of the systems and the rated making and breaking capabilities of the overcurrent protection equipment.

- The requirements for calculating the largest three- pole short circuit are:
- The network circuitry is mostly responsible for this current.
- The network feeder delivers the maximum short circuit power.
- The voltage factor is chosen in accordance with IEC 60 909.

The following fault conditions apply for the equivalent circuit shown in Figure 3-1:

$$U_R = U_S = U_T = 0, \tag{3.1}$$

$$I_R + I_S + I_T = 0, \tag{3.2}$$

It then follows that:

$$\begin{bmatrix} U0 \\ U1 \\ U2 \end{bmatrix} = \frac{1}{3} . \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a2 \\ 1 & a2 & a \end{bmatrix} . \begin{bmatrix} UR \\ US \\ UT \end{bmatrix} , \tag{3.3}$$

$$U_0 = U_1 = U_2 = 0 \tag{3.4}$$

$$\begin{bmatrix} I0 \\ I1 \\ I2 \end{bmatrix} = \frac{1}{3} . \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a2 \\ 1 & a2 & a \end{bmatrix} . \begin{bmatrix} IR \\ IS \\ IT \end{bmatrix} \tag{3.5}$$

For three-pole short circuits:

$$I''_{k3} = \frac{c.Un}{\sqrt{3}.Z1} \tag{3.6}$$

Where by for Z_1:

$$Z_1 = \sqrt{(R_{1Q} + R_{1T} + R_{1L})^2 + (X_{1Q} + X_{1T} + X_{1L})^2}, \tag{3.7}$$

Or with the impedances of the individual operational equipment:

$$Z_1 = Z_{1Q} + Z_{1T} + Z_{1L}. \tag{3.8}$$

3.2.2 Double Line-to-Ground Fault:

A double line-to-ground fault represents a serious event that causes a significant asymmetry in a three-phase symmetrical system and it may spread into a three-phase fault when not clear in appropriate time. [12]

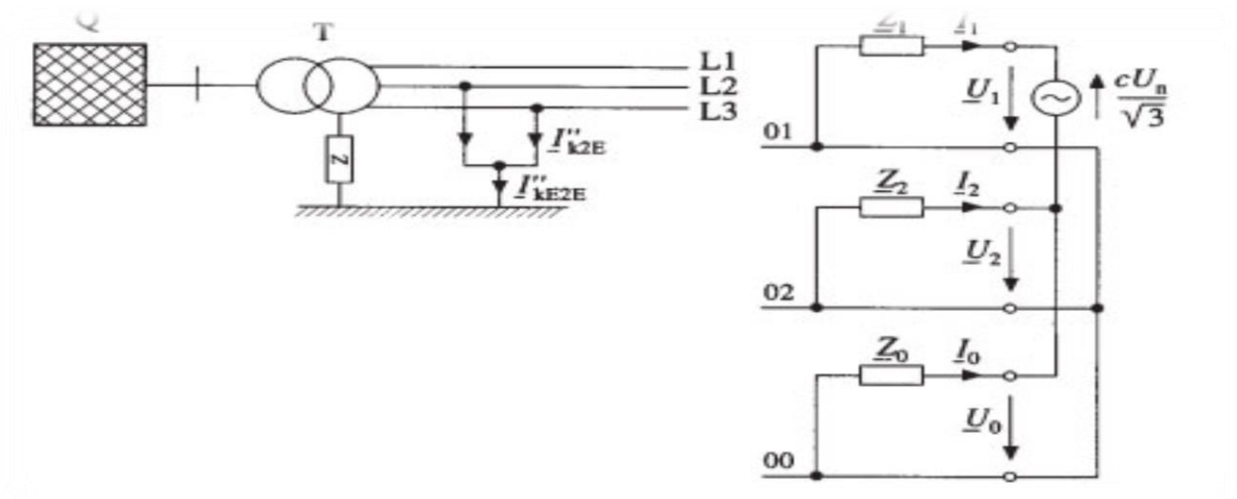

Figure 3-2: Equivalent circuit for a two-phase short circuit with contact to ground

This represents the general case of a two-pole short circuit. As can be seen from Figure 3-2, for the two-pole short circuit the following boundary conditions apply:

$I_R = 0$, $I_S = I_T$, $I_{KE2E} = I_S + I_T$, $U_S = U_T = 0$.

$$I_k''_{E2E} = \frac{\sqrt{3}.c.Un}{Z1.2Z0} \tag{3.9}$$

3.2.3 Line-to-Line Fault:

A line-to-line fault may take place either on an overhead and/or underground transmission system and occurs when two conductors are short-circuited. One of the characteristic of this type of fault is that its fault impedance magnitude could vary over a wide range making very hard to predict its upper and lower limits. It is when the fault impedance is zero that the highest asymmetry at the line-to-line fault occurs [12].

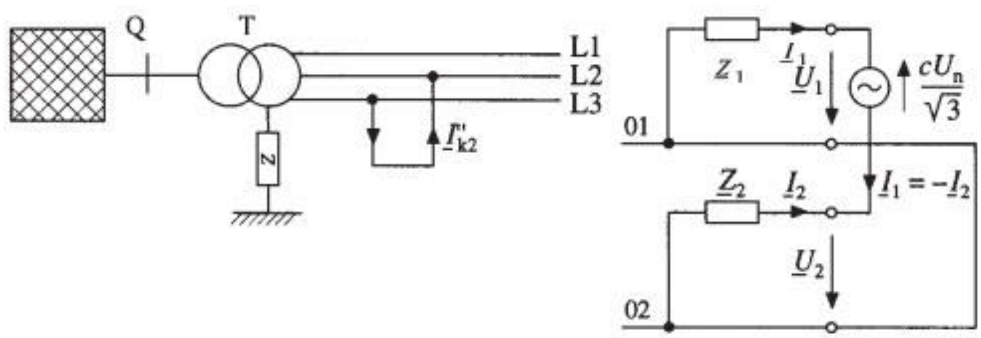

Figure 3-3: Equivalent circuit for a two-phase short circuit without contact to ground

According to Figure 3-3, a two-pole fault without contact to ground should occur between the two conductors.

For the equations giving the currents:

$I_S = - I_T$. $I_R = 0$

The zero-sequence system current is zero, because no current flows through ground, i.e. $I_0 = 0$, $U_0 = 0$.

For a two-pole short circuit current, this results in:

$$I_k''_2 = \frac{c.Un}{Z1+Z2} \tag{3.10}$$

$$I_k''_2 = \frac{\sqrt{3}}{2} Ik''3 \tag{3.11}$$

The voltage system for two-pole short circuit shifts in such a way that the voltage on the third, fault-free conductor, in this case U_R, remains unchanged.

Two-pole short circuit currents without contact to ground can be larger with powerful asynchronous motors than for three-pole short circuits.

3.2.4 Single Line-to-Ground Fault:

The single line-to-ground fault is usually referred as "short circuit" fault and occurs when one conductor falls to ground or makes contact with the neutral wire.

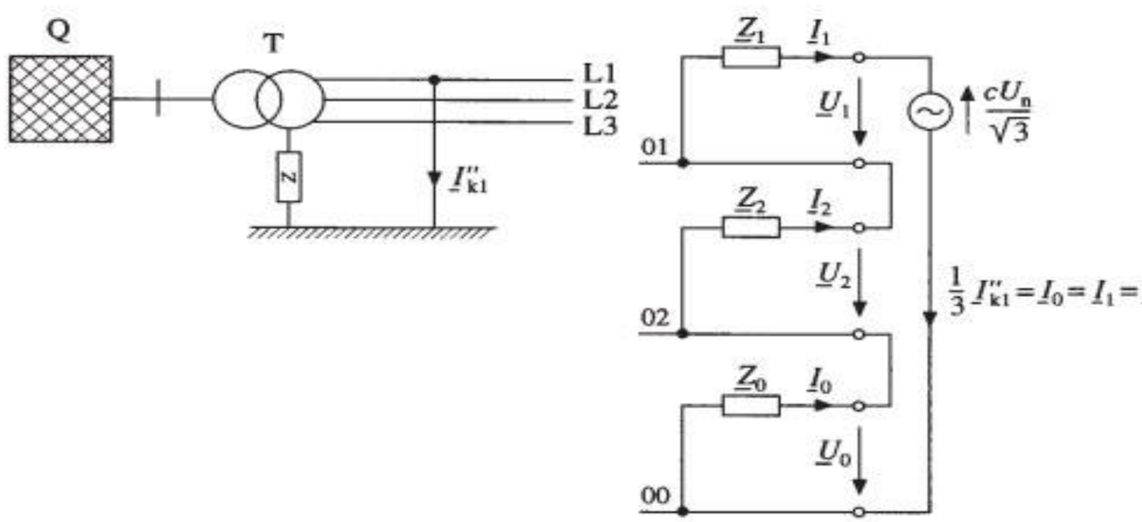

Figure 3-4: Equivalent circuit of single-phase short circuit to ground

The single-pole short circuit current occurs frequently in electrical networks. Its calculation is necessary in order to ensure

- The maximum conductor lengths
- Protection against indirect contact
- Protection against thermal stress

Calculation the smallest short circuit current required that:

- The voltage factor used is taken from IEC 60 909
- Motors can be neglected
- In low voltage networks the temperature of the conductors is set to 80° C
- Setting up the network so that the smallest I''_{K1min} flows.

For the component systems shown in Figure 3-4, we can then use the values:

$I_S = I_T = 0$, $I''_{K1} = I_R.U_R = 0$.

Since the currents in the positive-sequence, negative-sequence and zero-sequence systems are identical; this means that the three systems must be connected in series. For the current, then:

$$3.\ I_0 = I_R + I_S + I_T \quad (3.12)$$

$$I_{1R} = I_{2R} = I_0 \quad (3.13)$$

$$I_R = I_{1R} + I_{2R} + I_{0R} = 3.I_{IR} \quad (3.14)$$

$$I_{1R} = \frac{E''}{Z1+Z2+Z0} \quad (3.15)$$

$$I_R = \frac{3.E''}{Z1+Z2+Z0} \quad (3.16)$$

Using the relationship

$$E'' = \frac{3.Un}{\sqrt{3}} \quad (3.17)$$

It follows for a single-pole short circuit under the condition $Z_1 = Z_2$ that

$$I_k''_{1min} = \sqrt{3}\,\frac{.cmin.Un}{2Z1+Z0} \quad (3.18)$$

For the loop impedance of short circuit:

$$I_k''_{1min} = \frac{cmin.Un}{\sqrt{3}.zs} \quad (3.19)$$

Equating the right sides of equations 3.18 and 3.19 yields:

$$Z_S = \frac{2z1+z0}{3} \quad (3.20)$$

According to IEC 60 909,

$$I''_{k1min} = \frac{\sqrt{3}\cdot c_{min}\cdot U_n}{\sqrt{(2R_{1Q}+2R_{1T}+2R_{1L}+R_{0T}+R_{0L})^2+(2X_{1Q}+2X_{1T}+2X_{1L}+X_{0T}+X_{0L})^2}} \quad (3.21)$$

Equations 3.18, 3.19 and 3.21 are identical and give the same result for the calculation of $I_k''_{1min}$.

For asymmetrical short circuits, the largest short circuit current can be determined with the aid of Figure 3-5 and depends on the network design. The double ground fault I''_{KEE} is not included in the figure, because it leads to smaller short circuits than the two-pole short circuit. The ranges of the different types of short circuits according to the neutral point treatment are indicated in this diagram. The phase angles of the impedances Z_1, Z2 and Z_0 in this figure must not differ by more than 15°.

The symbols in Figure 3-5 have the meanings:

k_2 Two-pole short circuit current

k_3 Three-pole short circuit current

k_{2E} Two-pole short circuit current without contact to ground

k_1 Single-pole ground fault current

δ Ground fault factor

$$a = \frac{short\ circuit\ current\ for\ asymmetrical\ short\ circuit}{short\ circuit\ current\ for\ three{-}pole\ \ short\ circuit}$$

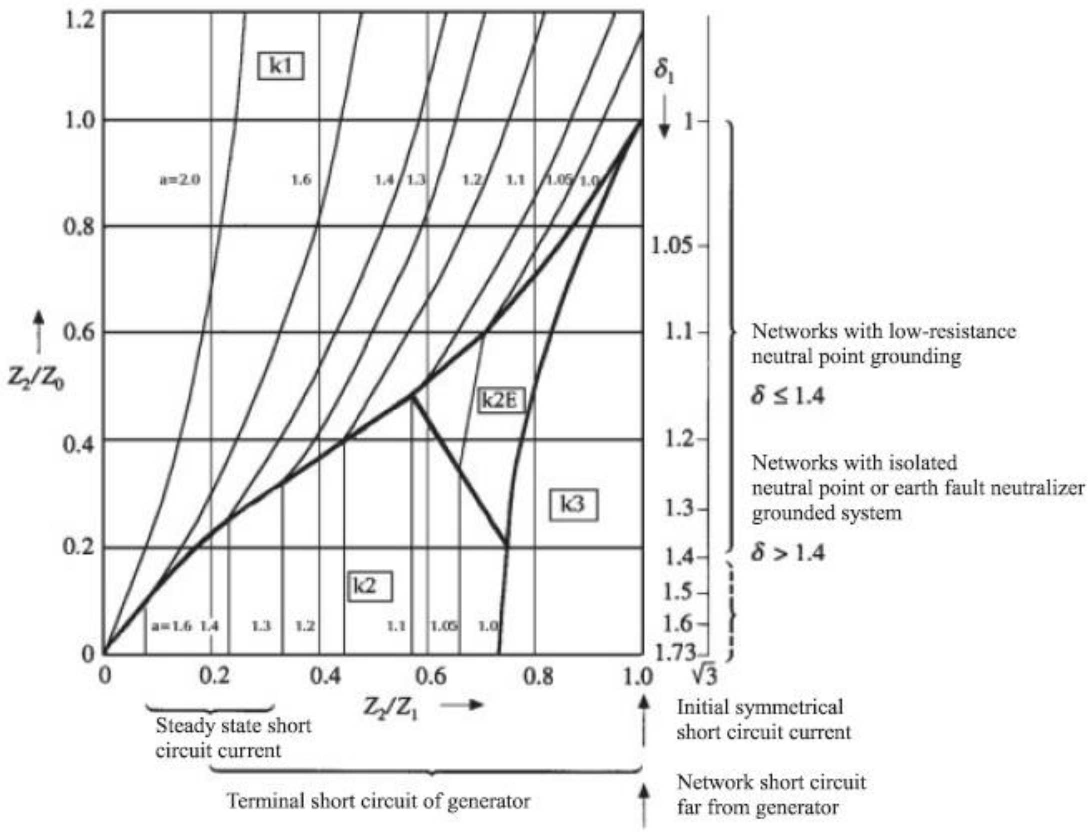

Figure 3-5: Largest short circuit currents for asymmetrical circuits

3.3 Short Circuit Currents:

In IEC 60 909 the different types of short circuits are clearly defined. This chapter deals with the short circuit currents and sets up the equations required to determine these currents. For the calculation RST components are used instead of L1-L2-L3, for reasons of simplification.

3.3.1 Peak short circuit current i_p:

The initial short circuit current I_k'' and the withstand ratio k determine the peak short circuit current i_p. The factor k depends on the ratio R/X of short circuit path and takes account of the decay of the DC aperiodic component in the short circuit. The peak value i_p occurs during the period immediately following the occurrence of the short circuit (transient period). If the ratio R/X is known, the factor k can be read from the curves in figure 3-6.

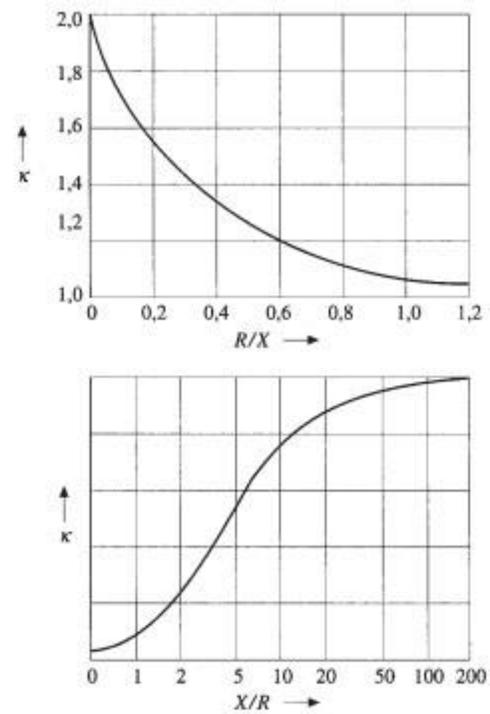

Figure 3-6: Factor k for calculating the peak short circuit current i_p

The peak short circuit current calculated determines the dynamic loading of electrical systems.

The peak short circuit current can be calculated in unmeshed networks from the equation:

$i_p = k.\sqrt{2}\, Ik''$ (3.22)

Standard values:

K < 1.4: in public networks

K ≤ 1.8 … 2.04: immediately downstream from transformer feeder

K can also be calculated from the following equation:

$$K = 1.02 + 0.98.\, e^{-3\frac{R}{X}} \quad (3.23)$$

The peak short circuit current i_p can be calculated in all networks using the basic equation $i_p = k.\sqrt{2}\, Ik''$ with the three following procedures it is possible to determine the factor k in meshed networks.

- Procedure A ($k=k_a$):

  K is determined from the smallest R/X ratio of all branches in the network. In low voltage networks, k ≤ 1.8.

- Procedure B (k=1.15kb):

  K is determined from the smallest R/X ratio of short circuit impedance at the position F of the short circuit and multiplied by a safety factor of 1.15 in order to take account of different R/X ratios in parallel branches.

1. For low voltage networks: k ≤ 1.8.
2. For medium and high voltage networks: k ≤ 2.0

- Procedure C ($k=k_c$):

  With procedure C, k is determined with an equivalent frequency, as below:

  1. Calculation of reactance for all network branches i for the equivalent frequency f_c in the positive-sequence system:

$X_{ic} = \frac{fc}{f} X_i$

f: nominal frequency – 50 Hz, 60 Hz

f: equivalent frequency – 20 Hz, 24 Hz

2. Calculation of equivalent impedance at the position of the short circuit from the resistances R_i and the reactance X_i of the network branches in the positive-sequence system:

   $Z_c = R_c + j\,X_c$.

3. Determination of the factor k_c from the ratio:

   $\frac{R}{X} = \frac{fc}{f} \frac{RC}{XC}$

3.3.2 Symmetrical breaking current i_a:

The symmetrical breaking current is the effective value of short circuit current $I''_k(t)$, which flows through the switch at the time of the first contact separation and is used for near-to-generator short circuit feeder. For far-from-generator short circuit, the breaking currents are identical with the initial short circuit currents:

$$I_a = \mu \,.\, I''k. \quad (3.24)$$

Synchronous machines

$$I_a = \mu \,.\, I''kG. \quad (3.25)$$

I_a depends on the duration of the short circuit and the innstallation position of the switchgear at the position of the short circuit. μ charachterizes the decay behavior of short circuit current and is a function of the variables $I''kG/I''rG$ and t_{min} (Figure 3-7).

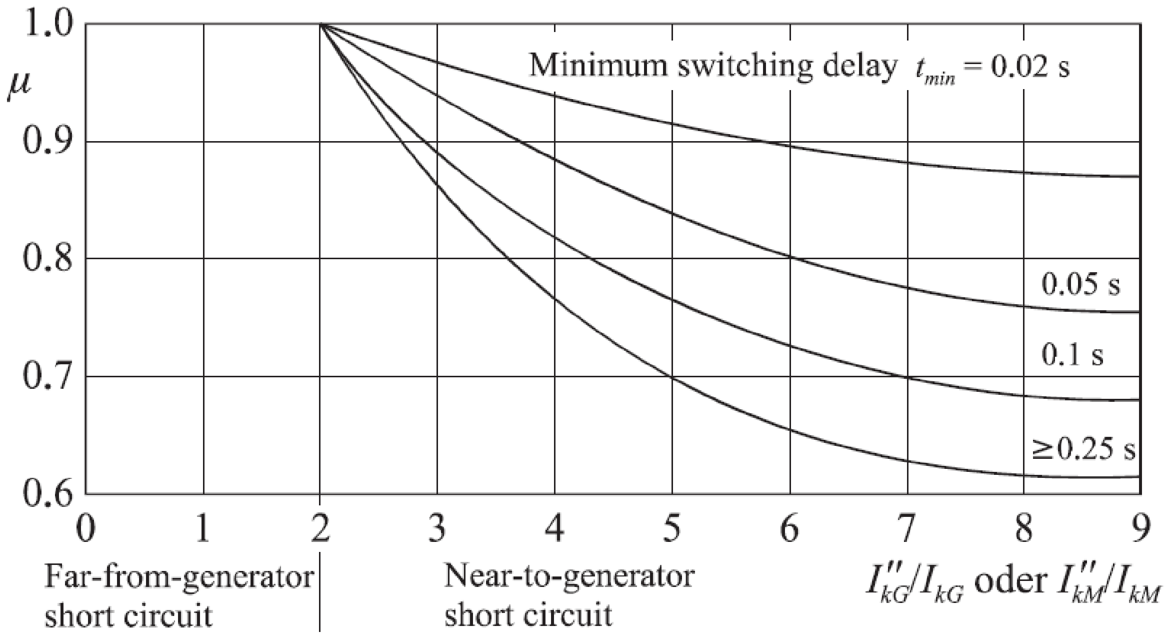

Figure 3-7: Factor μ for calculating the symmetrical breaking current I_a

The factor μ can be taken from figure 3.7 or from the following equations:

$\mu = 0.84 + 0.26\, e^{-0.26 I''kG/IrG}$ for $t_{min} = 0.02$ s

$\mu = 0.71 + 0.51\, e^{-0.30 I''kG/IrG}$ for $t_{min} = 0.05$ s

$\mu = 0.62 + 0.72\, e^{-0.32 I''kG/IrG}$ for $t_{min} = 0.10$ s

$\mu = 0.56 + 0.94\, e^{-0.38 I''kG/IrG}$ for $t_{min} = 0.25$ s

$\mu_{max} = 1$

when $I_a = I''k$, then μ = 1, i.e. a far-from-generator short circuit is present, if for each synchoronous machine the following condition is satisfied:

$$\frac{I''k3}{IrG} \leq 2. \qquad (3.26)$$

For $I_a < I_K''$ i.e. a near-to-generator short circuit:

$$\frac{I''k3}{IrG} \geq 2. \qquad (3.27)$$

In practice:

The minimum switching delay is 0.1 s.

Asynchronous machines

$$I_a = \mu . q . I''_{KM}. \tag{3.28}$$

The factor q depends on the power per pole pair.

$$I_{aQ} = I''_{kQ} \tag{3.29}$$

More exact procedure for calculation of symmetrical breaking current in meshed networks

$$\underline{I}_a = \underline{I}''_k - \sum_i \frac{\Delta \underline{U}''_{Gi}}{\frac{c \cdot U_n}{\sqrt{3}}} (1 - \mu_i) \cdot \underline{I}''_{kGi} - \sum_i \frac{\Delta \underline{U}''_{Mj}}{\frac{c \cdot U_n}{\sqrt{3}}} (1 - \mu_j \cdot q_j) \cdot \underline{I}''_{kMj} \tag{3.30}$$

With:

$$\Delta \underline{U}''_{Gi} = jX''_{di} \cdot \underline{I}''_{kGi} \tag{3.31}$$

$$\Delta \underline{U}''_{Mj} = jX''_{Mj} \cdot \underline{I}''_{kMj} \tag{3.32}$$

Figure 3-8 shows the dependence of the factor q on the effective power per pole pair of the motor and the minimum switching delay t_{min} for the equations used in calculating q, see IEC 60 909.

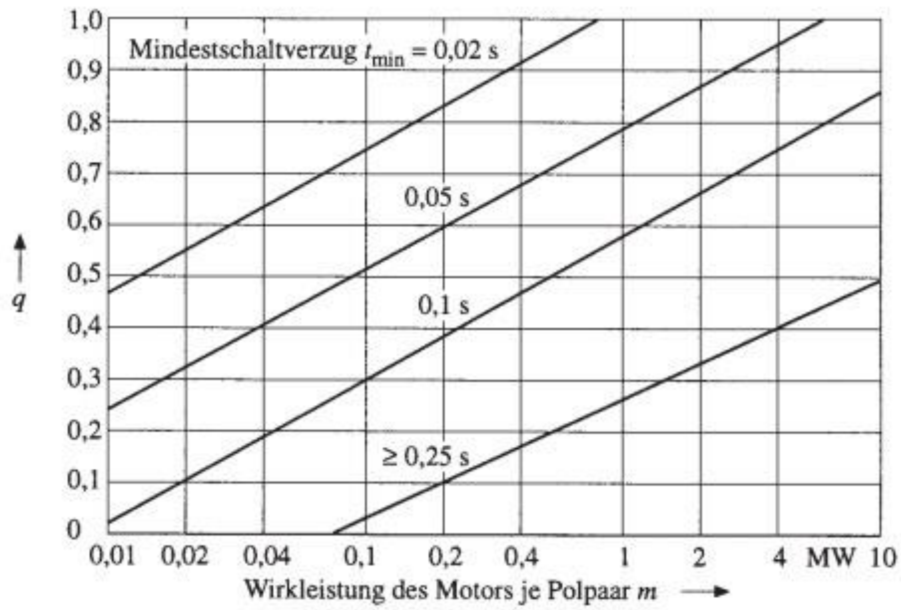

Figure 3.8: Factor q for calculating of the symmetrical breaking current for asynchronous machines

The factor q applies to induction motors and takes account of the rapid decay of the motor short circuit owing to the absence of an excitation field. It can be taken from Figure. 3.8 or from the following equations.

$q = 1.03 + 0.12 \ln m$ for $t_{min} = 0.02$ s

$q = 0.79 + 0.12 \ln m$ for $t_{min} = 0.05$ s

$q = 0.57 + 0.12 \ln m$ for $t_{min} = 0.10$ s

$q = 0.26 + 0.12 \ln m$ for $t_{min} = 0.25$ s

$q_{max} = 1$

The meanings of the symbols are:

i Generator

j Motor

$\Delta U''_{Gi}$ Initial voltage difference at connection to synchronous machine i

$\Delta U''_{Mj}$ Initial voltage difference at connection to synchronous machine j

$\frac{c\,Un}{\sqrt{3}}$ Equivalent voltage source at position of short circuit

I_a I''_k Symmetrical breaking current, initial symmetrical short circuit current considering all network inputs, synchronous machines and asynchronous machines

I''_{kGi} Initial symmetrical short circuit current of synchronous machine

I''_{kMj} Initial symmetrical short circuit current of asynchronous machine

μ_j Factor j for asynchronous machines

μ_i Factor i for synchronous machines

q_i Factor j for asynchronous machines

3.3.3 Steady state short circuit current I_k:

The steady state short circuit current is the effective value of short circuit current I''_k remaining after the decay of all transient processes. It depends strongly on the excitation current, excitation system and saturation of the synchronous machine:

For near-to-generator short circuits: $I_k < I''_k$

For far-from-generator short circuits: $I_k = I''_k = I_a$.

The following relationships show a dependence on fault position:

$$I_k = \lambda I_{rG}, \tag{3.33}$$

$I_k = I''_{k2}$,

$$I_k = \lambda \cdot \sqrt{3} \cdot I_{rG}, \qquad (3.34)$$

The factor λ depends on $I''kG/IrG$, the excitation and the type of synchronous machine.

For the steady state short circuit current, we distinguish between:

- $I_{kmax} = \lambda_{max} \cdot I_{rG}$ (maximum excitation) and
- $I_{kmin} = \lambda_{min} \cdot I_{rG}$ (constant unregulated excitation).

The upper and lower limits of λ can be taken from Figure 3.9. it should also be pointed out that the λ curves depend on the ratio of the maximum excitation voltage to the excitation voltage under normal load conditions (series 1 and 2).

The following statements can be made for series 1 and 2:

Series 1: the largest possible excitation voltage is 1.3 times the rated excitation voltage for the rated apparent power factor for turbo-generators or 1.6 times the rated excitation voltage for salient pole generators.

Series 2: the largest possible excitation voltage is 1.6 times the rated excitation voltage for the rated apparent power factor for turbo-generators or 1.3 times the rated excitation voltage for salient pole generators.

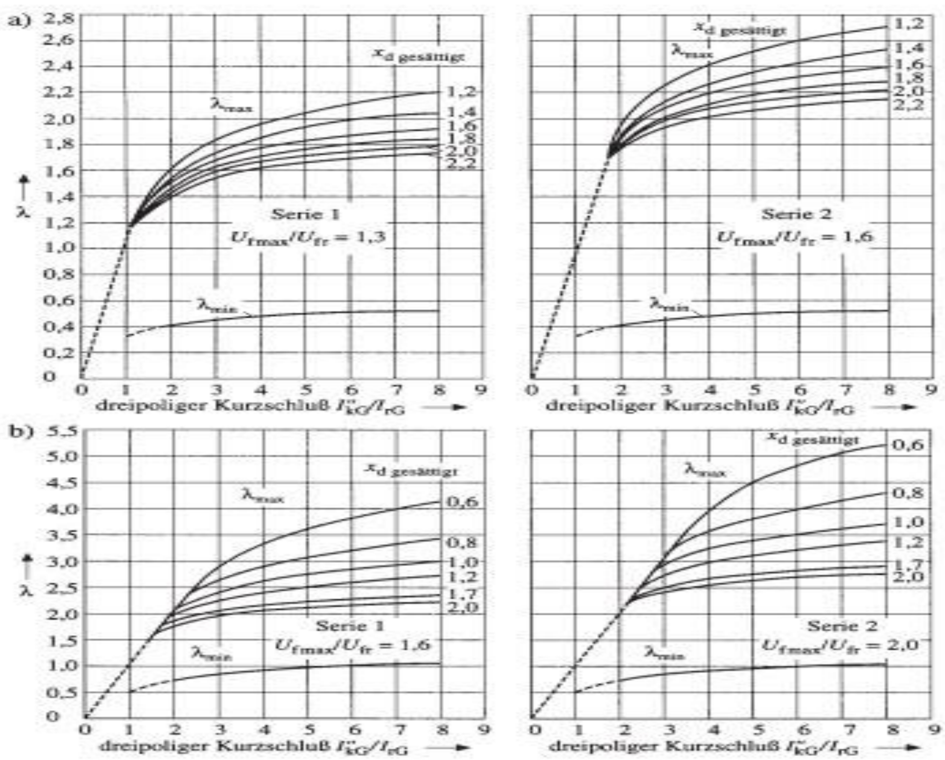

Figure 3-9: Factors λ_{min} and λ_{max} for calculating the steady state short circuit current

Chapter Four

RESULTS AND DISCUSSIONS

4.1 Khartoum National Grid:

The grid of the dissertation is a part of Sudanese national grid high voltage substations (110KV), All parameters and dimensions of transmission lines and high voltage cables are taken from network analysis department of Sudanese Electrical Transmission Company which consists of 28 bus bars, twelve transformers, twenty-eight loads and six generators, and the grid supplies power to the 220KV at buses (MAHADIYA 220, JABAL 220, GAMOIYA 220, Eid BABIKER 220 and KILOX 220). The network of the project is shown in Figure 4-1.

The interconnected system has been developed by using ETAP software. By using this software, the values of short circuit currents (I_k'', i_p, I_b, and I_k) were determined at the particular buses 110KV.

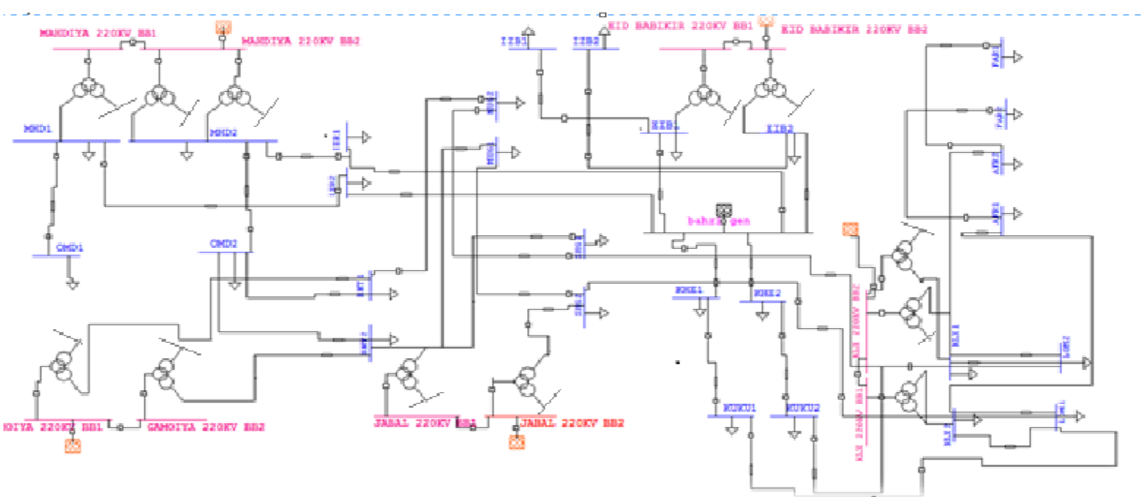

Figure 4-1: Khartoum National Grid 110KV

4.2 Simulation Result of Faults at Various Buses:

The simulation result of short circuit currents for 110 KV bus bars are: -

4.2.1 Khartoum Substations:

Khartoum consist of seven substations at high voltage (110 KV), the short circuit currents of the bus bars are:

4.2.1.1 Faults at Substation AFR at Bus 1 And Bus 2 For Two Transformers

The short circuit currents under different scenarios for faults at AFRA substation are given in Table 4.1

Table 4.1: Fault Current at Bus 1&2 at substation AFR

FAULT	3 – Phase	L – G	L – L	L – L – G
Initial Symmetrical Current (kA, rms)	11.258	12.942	9.726	12.390
Peak Current (kA),	26.937	30.965	23.270	29.646
Breaking Current (kA, rms, symm)	-	12.942	9.726	12.390
Steady State Current (kA, rms)	11.258	12.942	9.726	12.390

4.2.1.2 Faults at Substation FAR at Bus 1 And Bus 2 For Two Transformers

The short circuit currents under different scenarios for faults at FAROUG substation are given in Table 4.2

Table 4.2: Fault Current at Bus 1&2 at substation FAR

FAULT	3 – Phase	L – G	L – L	L – L – G
Initial Symmetrical Current (kA, rms)	10.328	11.217	8.924	10.883
Peak Current (kA),	24.426	26.528	21.105	25.738
Breaking Current (kA, rms, symm)	-	11.217	8.924	10.883
Steady State Current (kA, rms)	10.328	11.217	8.924	10.883

4.2.1.3 Faults at Substation KHE at Bus 1 And Bus 2 For Two Transformers

The short circuit currents under different scenarios for faults at KHARTOUM EAST substation are given in Table 4.3

Table 4.3: Fault Current at Bus 1&2 at substation KHE

FAULT	3 – Phase	L – G	L – L	L – L – G
Initial Symmetrical Current (kA, rms)	12.018	12.127	10.402	12.275
Peak Current (kA),	30.115	30.389	26.066	30.759
Breaking Current (kA, rms, symm)	-	12.127	10.402	12.275
Steady State Current (kA, rms)	12.018	12.127	10.402	12.275

4.2.1.4 Faults at Substation KLX at Bus 1 And Bus 2 For Two Transformers

The short circuit currents under different scenarios for faults at KILO X substation are given in Table 4.4

Table 4.4: Fault Current at Bus 1&2 at substation KLX

FAULT	3 – Phase	L – G	L – L	L – L – G
Initial Symmetrical Current (kA, rms)	13.893	17.393	11.995	16.811
Peak Current (kA),	34.388	43.051	29.690	41.611
Breaking Current (kA, rms, symm)	-	17.393	11.995	16.811
Steady State Current (kA, rms)	13.893	17.393	11.995	16.811

4.2.1.5 Faults at Substation LOM at Bus 1 And Bus 2 For Two Transformers

The short circuit currents under different scenarios for faults at LOCAL MARKET substation are given in Table 4.5

Table 4.5: Fault Current at Bus 1&2 at substation LOM

FAULT	3 – Phase	L – G	L – L	L – L – G
Initial Symmetrical Current (kA, rms)	12.938	14.995	11.173	14.460
Peak Current (kA),	31.628	36.657	27.312	35.348
Breaking Current (kA, rms, symm)	-	14.995	11.173	14.460
Steady State Current (kA, rms)	12.938	14.995	11.173	14.460

4.2.1.6 Faults at Substation MUG at Bus 1 And Bus 2 For Two Transformers

The short circuit currents under different scenarios for faults at MUGRAN substation are given in Table 4.6

Table 4.6: Fault Current at Bus 1&2 at substation MUG

FAULT	3 – Phase	L – G	L – L	L – L – G
Initial Symmetrical Current (kA, rms)	7.839	9.836	6.756	9.551
Peak Current (kA),	18.835	23.632	16.233	22.949
Breaking Current (kA, rms, symm)	-	9.836	6.756	9.551
Steady State Current (kA, rms)	7.839	9.836	6.756	9.551

4.2.1.7 Faults at Substation SHG at Bus 1 And Bus 2 For Two Transformers

The short circuit currents under different scenarios for faults at ELSHGARA substation are given in Table 4.7

Table 4.7: Fault Current at Bus 1&2 at substation SHG

FAULT	3 – Phase	L – G	L – L	L – L – G
Initial Symmetrical Current (kA, rms)	7.395	9.212	6.375	8.899
Peak Current (kA),	17.650	21.985	15.215	21.239
Breaking Current (kA, rms, symm)	-	9.212	6.375	8.899
Steady State Current (kA, rms)	7.395	9.212	6.375	8.899

4.2.2 Omdurman Substations:

Omdurman consist of three substations at high voltage (110 Kv), the short circuit currents of the bus bars are:

4.2.2.1Faults at Substation BNT at Bus 1 And Bus 2 For Two Transformers

The short circuit currents under different scenarios for faults at BANAT substation are given in Table 4.8

Table 4.8: Fault Current at Bus 1&2 at substation BNT

FAULT	3 – Phase	L – G	L – L	L – L – G
Initial Symmetrical Current (kA, rms)	8.032	10.056	6.921	9.774
Peak Current (kA),	19.368	24.251	16.690	23.570
Breaking Current (kA, rms, symm)	-	10.056	6.921	9.774
Steady State Current (kA, rms)	8.032	10.056	6.921	9.774

4.2.2.2 Faults at Substation MHD at Bus 1 And Bus 2 For Two Transformers

The short circuit currents under different scenarios for faults at MAHADIYA substation are given in Table 4.9

Table 4.9: Fault Current at Bus 1&2 at substation MHD

FAULT	3 – Phase	L – G	L – L	L – L – G
Initial Symmetrical Current (kA, rms)	9.237	12.394	7.970	12.450
Peak Current (kA),	22.919	30.755	19.776	30.892
Breaking Current (kA, rms, symm)	-	12.394	7.970	12.450
Steady State Current (kA, rms)	9.237	12.394	7.970	12.450

4.2.2.3 Faults at Substation OMD at Bus 1 And Bus 2 For Two Transformers

The short circuit currents under different scenarios for faults at OMDURMAN substation are given in Table 4.10

Table 4.10: Fault Current at Bus 1&2 at substation OMD

FAULT	3 – Phase	L – G	L – L	L – L – G
Initial Symmetrical Current (kA, rms)	8.08	9.694	6.921	9.358
Peak Current (kA),	19.415	23.474	16.761	22.662
Breaking Current (kA, rms, symm)	-	9.694	6.921	9.358
Steady State Current (kA, rms)	8.018	9.694	6.921	9.358

4.2.3 Bahri Substations:

Bahri consist of four substations at high voltage (110 Kv), the short circuit currents of the bus bars are:

4.2.3.1 Faults at Substation IBA at Bus 1 And Bus 2 For Two Transformers

The short circuit currents under different scenarios for faults at EIB BABIKER substation are given in Table 4.11

Table 4.11: Fault Current at Bus 1&2 at substation IBA

FAULT	3 – Phase	L – G	L – L	L – L – G
Initial Symmetrical Current (kA, rms)	15.527	18.771	13.432	18.076
Peak Current (kA),	40.163	48.555	34.746	46.757
Breaking Current (kA, rms, symm)	-	18.771	13.432	18.076
Steady State Current (kA, rms)	15.527	18.771	13.432	18.076

4.2.3.2 Faults at Substation IZB at Bus 1 And Bus 2 For Two Transformers

The short circuit currents under different scenarios for faults at IZBA substation are given in Table 4.12

Table 4.12: Fault Current at Bus 1&2 at substation IZB

FAULT	3 – Phase	L – G	L – L	L – L – G
Initial Symmetrical Current (kA, rms)	11.932	12.791	10.325	12.554
Peak Current (kA),	29.238	31.343	25.301	30.763
Breaking Current (kA, rms, symm)	-	12.791	10.325	12.554
Steady State Current (kA, rms)	11.932	12.791	10.325	12.554

4.2.3.3 Faults at Substation IZR at Bus 1 And Bus 2 For Two Transformers

The short circuit currents under different scenarios for faults at IZERGAB substation are given in Table 4.13

Table 4.13: Fault Current at Bus 1&2 at substation IZR

FAULT	3 – Phase	L – G	L – L	L – L – G
Initial Symmetrical Current (kA, rms)	11.865	11.910	10.270	12.021
Peak Current (kA),	29.196	29.307	25.270	29.580
Breaking Current (kA, rms, symm)	-	11.910	10.270	12.021
Steady State Current (kA, rms)	11.865	11.910	10.270	12.021

4.2.3.4 Faults at Substation KUK at Bus 1, Bus 2 And Bus 3 For Three Transformers

The short circuit currents under different scenarios for faults at KUKU substation are given in Table 4.14

Table 4.14: Fault Current at Bus 1&2 at substation KUK

FAULT	3 – Phase	L – G	L – L	L – L – G
Initial Symmetrical Current (kA, rms)	13.900	14.235	12.030	14.457
Peak Current (kA),	35.971	36.835	31.131	37.410
Breaking Current (kA, rms, symm)	-	14.235	12.030	14.457
Steady State Current (kA, rms)	13.900	14.235	12.030	14.457

4.3 Discussions:

4.3.1 Short-Circuit Calculations Results:

Four different types of short circuit currents are calculated for all buses. The tested different cases are set up so that each bus can have a worst-case scenario with the maximum and minimum short-circuit currents affecting each bus. The tested buses are all Khartoum state 110kV. The detailed results for all different cases are presented in Appendix C.

4.3.2 Maximum Fault Levels:

From figures 4-2………4-5 the highest short circuit currents for three phase faults, line to ground fault, line to line fault and line-line to ground fault in the 110KV bus burs were found in EID BABIKER (IBA), KILO10

(KLX) and KUKU (KUK) substations. They have the highest fault level because they are near to generators (source).

4.3.3 Minimum Fault Levels:

From figures 4-2…………4-5 the minimum short circuit currents for three phase faults, line to ground fault, line to line fault and line-line to ground fault in the 110KV bus burs were found in SHAGARA (SHG), MUGRAN (MUG), WAD EL BASHIR (OMD) and BANAT (BNT) substations.

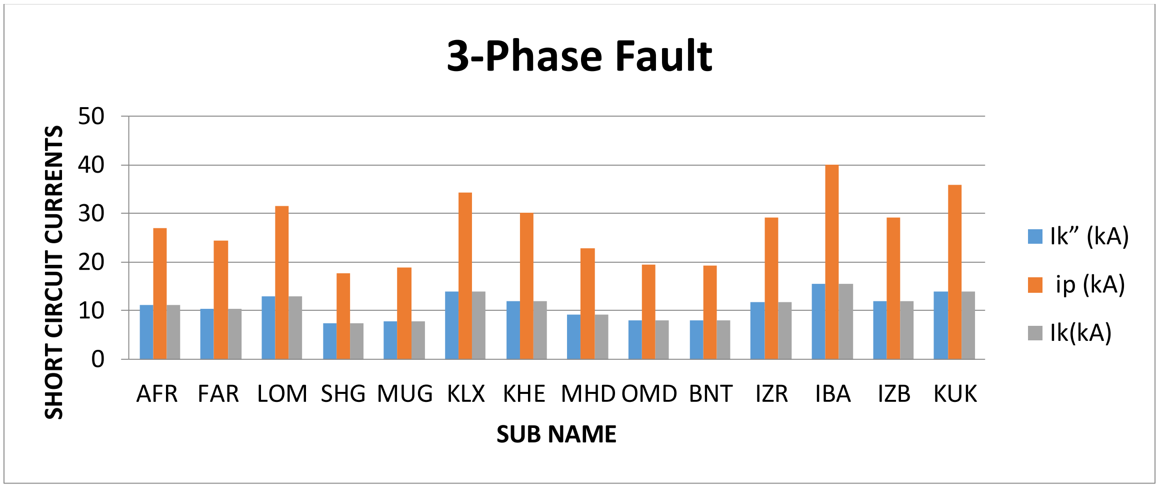

Figure 4-2: 3-Phase Fault

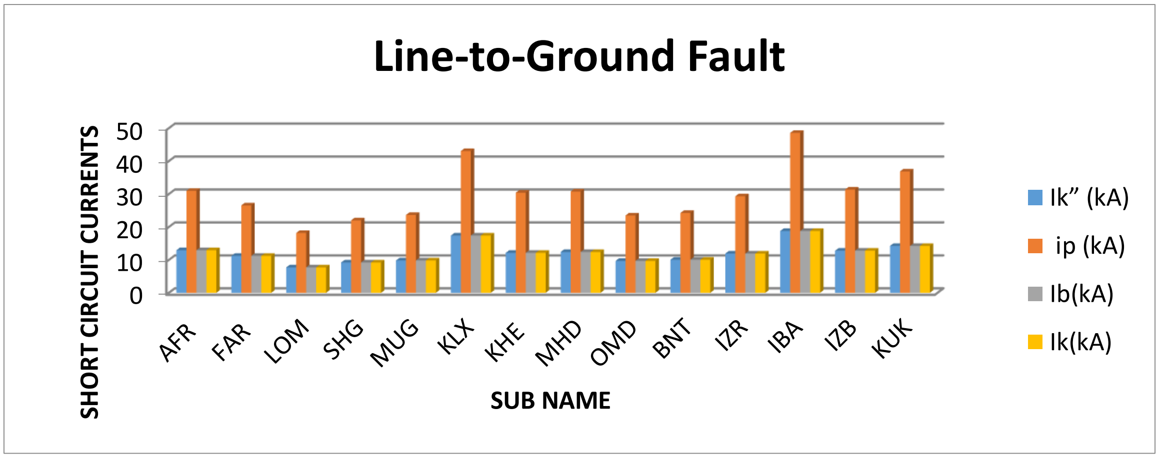

Figure 4-3: Line-to-Ground Fault

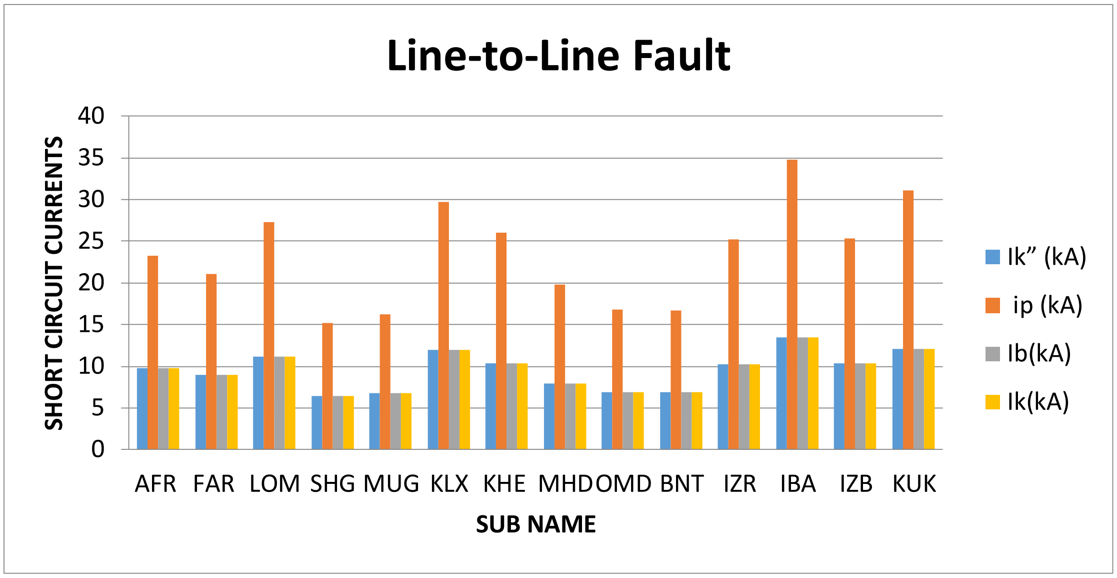

Figure 4-4: Line-to-Line Fault

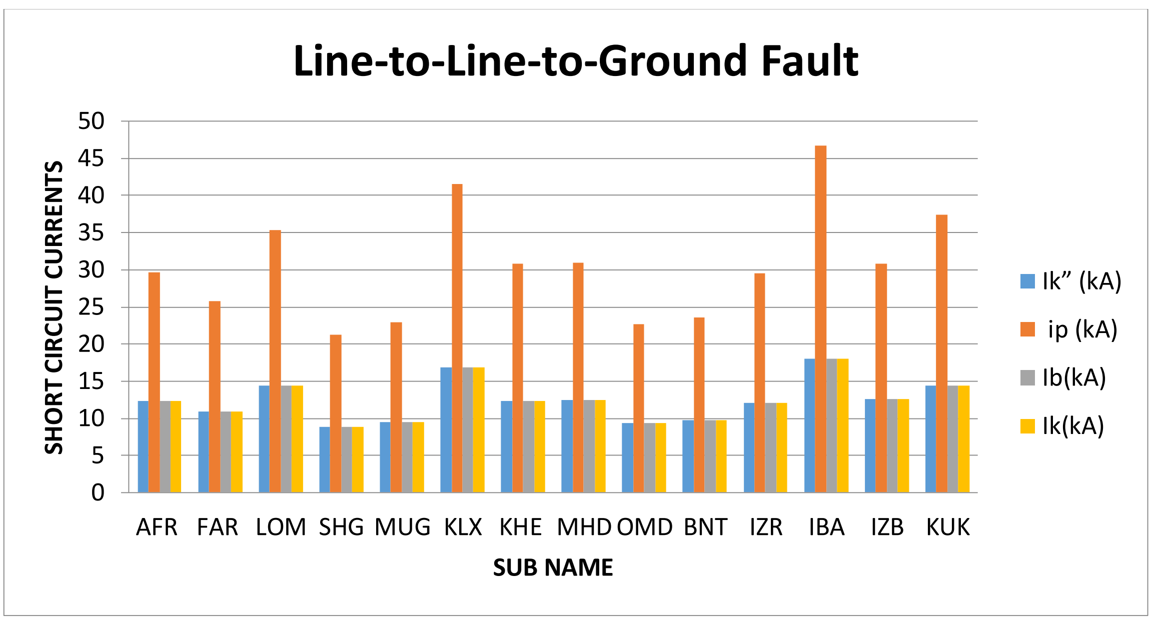

Figure 4-5: Line-to-Line-to-Ground Fault

Chapter five

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion:

In this research, IEC 60909-0 standard is used in order to calculate various types of short circuit currents in Khartoum networks. The calculations of the short circuits were carried out using ETAP program for the 110 KV levels. The maximum short circuit currents were found in EID BABIKER substation. The minimum short circuit currents were found in ELSHAGARA substation. The short circuit currents required for coordination of protective relaying were determined and the adequacies of the short circuit withstand ratings of bus bars and circuit breakers were evaluated.

5.2 Recommendations and future work:

At the end of this dissertation, the following recommendations can be given for future studies:

1. Review annually of future system fault level for all generators, EXHV, HV and MV transmission lines and transformers by transmission networks planner in SETCO Company.
2. Determination of problem areas in Khartoum 110kV networks such as EID BABIKER substation which has high values of short circuit currents. Preventive maintenance for these substations, medium voltage circuit breakers and transmission lines should be carried out.
3. Short circuit studies to be conducted on low voltage networks.

4. To reduce the value of fault level:

- Installation Current Limit Reactance in series with the item to be protected, taking into account the value of the voltage in the normal operating condition.
- Add an element of the basic power system component such as adding a transformer or increase the value of reactance in lines.

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APPENDICES:

Appendix A: *Bus Name Abbreviations:*

AFR	Afra
BNT	Banat
FAR	Faroug
IBA	Eid Babikir
IZB	Izba
IZG	Izirgab
KHE	Khartoum East
KLX	Kilo X
KUK	Kuku
LOM	Local Market
MHD	Mahdiya
MUG	Mugran
OMD	Omdurman
SHG	Shagara

Appendix B: *Bus data:*

Bus	***Type***	***Nominal voltage (kv)***	***Pgen (MW)***	***Qgen (MVAr)***	***Pd (MW)***	***Qd (MVAr)***
MAR500	Slack	500	-	-	0.5	0.3
GER220	PV	220	280	-	0	0
KHN220	PV	110	125	-	0	0
JAS110	PV	220	127	-	0	0
MHD110	PQ	110	0	0	32.9	14.2
JAS110	PQ	110	0	0	16	7.2
SHG110	PQ	110	0	0	80	49.58
OMD110	PQ	110	0	0	89.5	51.1
MUG110	PQ	110	0	0	107	63.1
BNT110	PQ	110	0	0	74.9	42.5
IBA110	PQ	110	0	0	32	20.9
LOM110	PQ	110	0	0	50	30.99
KLX110	PQ	110	0	0	35	21.5
AFR110	PQ	110	0	0	17.05	3.927
FRG110	PQ	110	0	0	80	49.58
IZB110	PQ	110	0	0	88.4	28.8
KUK110	PQ	110	0	0	40	24.87
IZG110	PQ	110	0	0	47	42.3
GAM110	PQ	110	0	0	0	0
KHE110	PQ	110	0	0	108	42.8
IBA220	PQ	220	0	0	0	0
GAD220	PQ	220	0	0	60.3	37.37
MHD220	PQ	220	0	0	54.7	25.4
KLX220	PQ	220	0	0	0	0
GAM220	PQ	220	0	0	20.2	9.8
MRK220	PQ	220	0	0	0	0
FRZ220	PQ	220	0	0	16.8	11.1
KAB220	PQ	220	0	0	0	0
KAB500	PQ	500	0	0	0	0
MRK500	PQ	500	0	0	0	0

Appendix C: *Transmission lines data:*

No.	*From*	*To*	*Nom. (kv)*	*length (km)*	*No. of lines*	*R (Ω/km)*	*X (Ω/km)*	*C (μF/km)*
1	MHD110	IZG110	110	8	2	0.067	0.302	0.01306
2	IBA110	IZB110	110	11	2	0.067	0.302	0.01306
3	KHN110	KUK110	110	4.5	2	0.384	0.302	0.009502
4	KUK110	KHE110	110	3.2	2	0.067	0.302	0.01306
5	IBA110	KHN110	110	12	2	0.067	0.302	0.01306
6	LOM110	KLX110	110	3	2	0.067	0.302	0.01306
7	LOM110	SHG110	110	7.8	2	0.067	0.302	0.01306
8	OMD110	BNT110	110	5.9	2	0.067	0.302	0.01306
9	KLX110	AFR110	110	11	2	0.067	0.302	0.01306
16	KUK110	KLX110	110	14.6	2	0.087	0.379	0.009502
17	MUG110	SHG110	110	11	2	0.067	0.302	0.01306
18	SHG110	JAS110	110	39	2	0.067	0.302	0.01306
19	IZG 110	KHN110	110	12	2	0.067	0.302	0.01306
20	MUG110	GAM110	110	14	2	0.067	0.302	0.01306
21	MUG110	BNT 110	110	3.8	2	0.067	0.302	0.01306
22	FAR110	AFR110	110	14	2	0.067	0.302	0.01306
24	OMD110	MHD110	110	9.3	2	0.067	0.302	0.01306

Appendix D: *Transformers data:*

Name	*Vector group*	*S (MVA)*	*Vr1 (kv)*	*Vr2 (kv)*	*Vkr (%)*
AFR1	YNyn0d11	100	110	33	13.41
AFR2	YNyn0d11	100	110	33	13.41
BNT1	YNyn0d11	100	110	33	11.75
BNT2	YNyn0d11	100	110	33	11.75
FAR1	YNyn0d11	60	110	33	13.41
FAR2	YNyn0d11	60	110	33	13.41
IBA1	YNyn0d11	100	110	33	13.57
IBA2	YNyn0d11	100	110	33	13.57
IZB1	YNyn0d11	100	110	33	10.15
IZB2	YNyn0d11	100	110	33	10.15
IZG1	YNyn0d11	100	110	33	12.64
IZG2	YNyn0d11	100	110	33	12.64
KHE1	YNyn0d11	100	110	33	13.56
KHE2	YNyn0d11	100	110	33	13.56
KLX1	YNyn0d11	100	110	33	13.5
KLX2	YNyn0d11	100	110	33	13.5
KUK1	Yy0	30	110	33	9.35
KUK2	Yy0	30	110	33	9.35
KUK3	Yy0	30	110	33	9.35
LOM1	YNyn0d11	100	110	33	13.62
LOM2	YNyn0d11	100	110	33	13.62
MHD1	YNyn0d11	100	110	33	12.1
MHD2	YNyn0d11	100	110	33	12.1
MUG1	YNyn0d11	100	110	33	11.6
MUG2	YNyn0d11	100	110	33	11.6
OMD1	YNyn0d11	100	110	33	12.1
OMD2	YNyn0d11	100	110	33	12.1
SHG1	YNyn0d11	100	110	33	11.63
SHG2	YNyn0d11	100	110	33	11.63
SHG3	YNyn0d11	35	110	33	20.692

Appendix E: *Short-Circuit Summary Report in 110 k V bus burs:*

Project:	FAULT LEVEL IN 28 BUSBARS	Page:	1
Location:	KHARTOUM NATIONAL GRID	Date:	02-05-2017
Contract:	Dr.MOHAMMED OSMAN HASAN	SN:	
Engineer:	DUAA EL GASSIM ABBAS MODAWY	Revision:	Base
Filename:	Grid	Config.:	Normal

ETAP
12.6.0H

Study Case: SC

Short-Circuit Summary Report

3-Phase, LG, LL, LLG Fault Currents

Bus		3-Phase Fault			Line-to-Ground Fault				Line-to-Line Fault				*Line-to-Line-to-Ground			
ID	kV	I"k	ip	Ik	I"k	ip	Ib	Ik	I"k	ip	Ib	Ik	I"k	ip	Ib	Ik
AFR 110 BB1	110.000	11.258	26.937	11.258	12.942	30.965	12.942	12.942	9.726	23.270	9.726	9.726	12.390	29.646	12.390	12.390
AFR 110 BB2	110.000	11.258	26.937	11.258	12.942	30.965	12.942	12.942	9.726	23.270	9.726	9.726	12.390	29.646	12.390	12.390
BNT 110 BB1	110.000	8.032	19.368	8.032	10.056	24.251	10.056	10.056	6.921	16.690	6.921	6.921	9.774	23.570	9.774	9.774
BNT 110 BB2	110.000	8.032	19.368	8.032	10.056	24.251	10.056	10.056	6.921	16.690	6.921	6.921	9.774	23.570	9.774	9.774
FAR 110 BB1	110.000	10.328	24.426	10.328	11.217	26.528	11.217	11.217	8.924	21.105	8.924	8.924	10.883	25.738	10.883	10.883
FAR 110 BB2	110.000	10.328	24.426	10.328	11.217	26.528	11.217	11.217	8.924	21.105	8.924	8.924	10.883	25.738	10.883	10.883
IBA 110 BB1	110.000	15.527	40.163	15.527	18.771	48.555	18.771	18.771	13.432	34.746	13.432	13.432	18.076	46.757	18.076	18.076
IBA 110 BB2	110.000	15.527	40.163	15.527	18.771	48.555	18.771	18.771	13.432	34.746	13.432	13.432	18.076	46.757	18.076	18.076
IZB 110 BB1	110.000	11.932	29.238	11.932	12.791	31.343	12.791	12.791	10.325	25.301	10.325	10.325	12.554	30.763	12.554	12.554
IZB 110 BB2	110.000	11.932	29.238	11.932	12.791	31.343	12.791	12.791	10.325	25.301	10.325	10.325	12.554	30.763	12.554	12.554
IZR 110 BB1	110.000	11.865	29.196	11.865	11.910	29.307	11.910	11.910	10.270	25.270	10.270	10.270	12.021	29.580	12.021	12.021
IZR 110 BB2	110.000	11.865	29.196	11.865	11.910	29.307	11.910	11.910	10.270	25.270	10.270	10.270	12.021	29.580	12.021	12.021
KHE 110 BB1	110.000	12.018	30.115	12.018	12.127	30.389	12.127	12.127	10.402	26.066	10.402	10.402	12.275	30.759	12.275	12.275
KHE 110 BB2	110.000	12.018	30.115	12.018	12.127	30.389	12.127	12.127	10.402	26.066	10.402	10.402	12.275	30.759	12.275	12.275
KLX 110 BB1	110.000	13.893	34.388	13.893	17.393	43.051	17.393	17.393	11.995	29.690	11.995	11.995	16.811	41.611	16.811	16.811
KLX 110 BB2	110.000	13.893	34.388	13.893	17.393	43.051	17.393	17.393	11.995	29.690	11.995	11.995	16.811	41.611	16.811	16.811
KUK 110 BB1	110.000	13.900	35.971	13.900	14.235	36.835	14.235	14.235	12.030	31.131	12.030	12.030	14.457	37.410	14.457	14.457
KUK 110 BB2	110.000	13.900	35.971	13.900	14.235	36.835	14.235	14.235	12.030	31.131	12.030	12.030	14.457	37.410	14.457	14.457
LOM 110 BB1	110.000	6.708	15.804	6.708	7.717	18.181	7.717	7.717	5.785	13.629	5.785	5.785	7.432	17.510	7.432	7.432
LOM 110 BB2	110.000	12.938	31.628	12.938	14.995	36.657	14.995	14.995	11.173	27.312	11.173	11.173	14.460	35.348	14.460	14.460
MHD 110 BB1	110.000	9.237	22.919	9.237	12.394	30.755	12.394	12.394	7.970	19.776	7.970	7.970	12.450	30.892	12.450	12.450
MHD 110 BB2	110.000	9.237	22.919	9.237	12.394	30.755	12.394	12.394	7.970	19.776	7.970	7.970	12.450	30.892	12.450	12.450
MUG 110 BB1	110.000	7.839	18.835	7.839	9.836	23.632	9.836	9.836	6.756	16.233	6.756	6.756	9.551	22.949	9.551	9.551
MUG 110 BB2	110.000	7.839	18.835	7.839	9.836	23.632	9.836	9.836	6.756	16.233	6.756	6.756	9.551	22.949	9.551	9.551
OMD 110 BB1	110.000	8.018	19.415	8.018	9.694	23.474	9.694	9.694	6.921	16.761	6.921	6.921	9.358	22.662	9.358	9.358
OMD 110 BB2	110.000	8.018	19.415	8.018	9.694	23.474	9.694	9.694	6.921	16.761	6.921	6.921	9.358	22.662	9.358	9.358
SHG 110 BB1	110.000	7.395	17.650	7.395	9.212	21.985	9.212	9.212	6.375	15.215	6.375	6.375	8.899	21.239	8.899	8.899
SHG 110 BB2	110.000	7.395	17.650	7.395	9.212	21.985	9.212	9.212	6.375	15.215	6.375	6.375	8.899	21.239	8.899	8.899

All fault currents are in rms kA. Current ip is calculated using Method C.

* LLG fault current is the larger of the two faulted line currents.