Sudan University of Sciences and Technology

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Study of Short Circuit Faults-Case study Sudanese National Grid

دراسة أعطال دائرة القصر- دراسة حالة الشبكة القومية السودانية

A Project Submitted In Partial Fulfillment for the Requirements of the Degree of B.Sc. (Honor) In Electrical Engineering

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الآية الكريمة

قال تعالى:

"أَمَّن جَعَلَ الْأَرْضَ قَرَارًا وَجَعَلَ خِلَالَهَا أَنْهَارًا وَجَعَلَ لَهَا رَوَاسِيَ وَجَعَلَ بَيْنَ الْبَحْرَيْنِ
حَاجِزًا أَإِلَٰهٌ مَّعَ اللَّهِ بَلْ أَكْثَرُهُمْ لَا يَعْلَمُونَ"

النمل (٦١)

صدق الله العظيم

DEDICATION

For Human all over the world…

For all kids, those who suffer from the war…

For all student searching for the truth…

Our parents, brothers, friends and all families…

We dedicate this modest work …

ACKNOWLEDGEMENT

All gratitude to almighty of Allah for all his gifts and his guidance…

In addition, we are grateful to our mothers and fathers for their support and endurance throughout our life…

Moreover, we are thankful to all those who tough us some day.

Thanks to Dr. Mohammed Osman and thanks to everybody who helped perform this project…

We are highly grateful to school of electrical Engineering for providing all necessary support…

ABSTRACT

In the previous period, the national grid experienced many changes represented in the addition of Merawi power station and the addition of so many new stations. This extension required the calculation of short circuit levels to determine the ratings of protective devices and to ensure the safety of power system components. Short circuit levels were calculated for all buses according to IEC-60909 standard using ETAP 16.0 program. Most of the calculated fault levels were realistic and acceptable, these values were compared with the existing ratings of circuit breakers and most of the values were satisfactory except at eleven buses where the short circuit levels exceeded the ratings of the associated circuit breakers.

المستخلص

في الفترة الماضية شهدت الشبكة القومية العديد من التغيرات تمثلت في إضافة محطة توليد مروي و كوستي الحرارية واضافة العديد من المحطات. هذا التوسع تطلب إجراء دراسة حساب مستويات القصر لتحديد القيم المقننة لأجهزة الحماية والتأكد من سلامة معدات أنظمة القدرة. تم حساب مستويات القصر عند كل القضبان وفقا لمعيار اللجنة الكهروتقنية الدولية ٦٠٩٠٩ باستخدام برنامج إي تاب ١٦. كانت معظم مستويات القصر المحسوبة واقعية ومقبولة. تمت مقارنة هذه القيم مع القيم المقننة الحالية لقواطع الدائرة وكانت معظمها مرضية ما عدا 11 باسبار حيث تجاوز فيهما مستوى القصر القيمة المقننة لقواطع الدائرة.

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LIST OF ABBREVIATIONS

ETAP	Electrical Transient Analysis Program
IEC	International Electro-technical Commission.
ANSI	American National Standards Institute.
LG	Line-to-Ground fault.
LL	Line-to-Line fault.
LLG	Line-to-Line-to-Ground fault.
MVA	Short-circuit Mega Volt Ampere.
NEC	National Electricity Corporation.
AC	Alternating Current.
DC	Direct Current.
RMS	Root Mean Square
AFR	Afraa
ARO	Arooma
ATB	Atbara
BAG	Bagair
BNT	Bant
DEB	Debba
DON	Dongla
FAO	Alfao
FAR	Faroog

GAD	Giad
GAM	Gamoiea
GDF	Algadaref
GRB	Grba
GND	Gneed
HAG	AlhagAbdellah
HWT	Awata
IBA	Eid Babiker
IZB	Izbah
IZG	Izrgab
JAS	Japal Substation
KHE	Khartoum Earth
KHN	Khartoum North
KLX	Kilo 10
KSL	Kasala
KUK	Helat Kuku
LOM	Local Market
MAR	Marinjan
MAN	Managel
MHD	Mahdiea
MRK	Mrkheiat
MSH	Mshkoor

MUG	Mugran
MWP	Marwei plant
MWT	Marwei Town
OBD	Alobied
RBK	Rabak
SHG	Shagara
RNK	Alrank
ROS	Rlroseries
SNG	Sengah
SNJ	SennarJuntion
SNP	Sennar Plant
TND	Tndelti
UMR	Umrawaba
WHL	WadiHalfa
WWA	Wawa
P.U	Per Unit

LIST OF SYMBOLES

Z	Impedance, Ω
V	Voltage, Volt
R	Resistance, Ω
L	Inductance, H
X	Reactance, Ω
ω	Angular velocity, rad/sec
f	Frequency, Hz
i	Current, Ampere A
φ	Voltage phase angle, rad

CHAPTER ONE

INTRODUCTION

1.1 Overview

Over the past century, the electric power industry continues to shape and contribute to the welfare, progress, and technological advances of the human race. The growth of electric energy consumption in the world has been nothing but phenomenal this growth requires proper design of power system to enable it to perform effectively, efficiently, safely and economically.

One of the studies that must be carried out in the early design stages and at any time a significant modification is anticipated, is the short circuit study which is the analysis of a power system to determine the magnitude of the currents that flow after a fault occurs. These currents are then compared to the ratings of the electrical components which are a part of the power system. The comparison determines the suitability of the equipment for use in the analyzed power system. The specification and purchase of new electrical power equipment is dependent on selecting the equipment with the proper ratings for the application. The selection of the equipment is partially based on the magnitude of the fault currents which can flow through the equipment. The equipment selected must be designed and built so that it can successfully handle (carry and interrupt) the fault currents which flow during a short circuit.

Electric Power System is the interconnected network to generate and supply the electrical power to the customers in an economical and reliable manner. Electrical power consumption has been increased due to the technological and industrial growth which makes the power system network very complex. Power System Network is a dynamic system and it may subject to various disturbances which includes the short circuit fault that affects the reliability of the power system. The fault current level in the power system is affected by the addition of new generators, transmission lines and sub-stations.

The fault current has to be identified by performing short circuit analysis and the effect of the same on the power system components can be prevented by the proper selection of protective devices. The power system components such as generators, power cables, transformers and transmission lines should be designed to withstand the momentary short circuit current at the time of fault. The fault current can be determined by the intervening reactance of the power components such as generator, transmission line, power cable and transformer. The perspective short –circuit current (PSCC) in a system during a fault is of large interest to the design engineers, to design the electrical insulation and the protective system.

The short circuit faults in the power system can be classified into two major categories namely symmetrical and unsymmetrical faults. Three phase short circuit fault is very rare but most severe fault and it is of most concern from the transient stability point of view.[1]

1.2 Problem Statement

The national grid has been extending rapidly and new stations were added to the system. The network under study comprises the old Blue Nile grid, the old primary distribution ring at 110 KV around Khartoum, new ring at 220 KV around Khartoum, the 500 KV transmission system from Merrawi, the east network and many other new stations. This extension required carrying out short circuit analysis in order to guarantee the safe operation of the system and the safety of equipment.

1.3 Project Objectives

The objectives of this project are

1- To determine the maximum short-circuit currents at all busses .

2- To compare the values of short-circuit currents with the existing ratings of circuit breakers .

3- To gain new knowledge and experience in dealing with power system analysis programs to analyze large networks.

1.4 Methodology and Tools

This analysis was done using the ETAP 16.0 program which obeys the IEC 60909 (International Electro-technical Commission) standard.

1.5 Project Layout

Project is consists of five Parts

- **Chapter 1:** Gives an overview of the subject and the contents of the chapters in thesis .
- **Chapter 2**: This chapter covers the theoretical background needed to understand the project and at the end of the chapter a brief introduction about the IEC 60909 standard is presented .
- **Chapter 3**: This chapter gives a general description of the national grid structure, and discussed short-circuit calculations using ETAP 16 in compliance with IEC 60909-0 standard .
- **Chapter 4**: This chapter shows the simulation and results of the project and the discussion of these results, also there is a comparison between the calculated fault currents and existing ratings of circuit breakers.
- **Chapter 5**: This chapter represent conclusion and recommendations.

CHAPTER TWO

THEORITICAL BACKGROUND

2.1 Purpose of Power System Short-circuit Faults

Fault studies it is an important part of power systems analysis and the problem consists of determining bus voltage and line current during faults. Fault studies are used for proper choice of circuit breakers and protective relaying.

2.1.1 Nature and types of faults

A short-circuit fault takes place when two or more conductors come in contacts with each other when normally they operate with a potential difference between them. The contact may be a physical metallic one, or it may occur through an arc. In the metal-to-metal contact case, the voltage between the two parts is reduced to zero. On the other hand, the voltage through an arc will be of a very small value.

Short-circuit faults in three phase systems are classified as:

1. Balanced or symmetrical three-phase faults
2. Unsymmetrical faults, and these include**:**
    - i. Single line-to-ground faults.
    - ii. Line-to-line faults.
    - iii. Double line-to-ground faults.[2]

All the above faults except the three-phase type cause an imbalance between the phases, and so they are called unsymmetrical faults. [3]

Experience has shown that between 70% and 80% of transmission-line faults are single line-to-ground faults, which arise from the flashover of only one line to the tower and ground. Roughly, 5% of all faults are symmetrical three-phase faults.

A fault will cause currents of high value to flow through the network to the faulted point. The amount of current may be much greater than the designed thermal ability of the conductors in the power lines or machines feeding the fault. As a result, temperature rise may cause damage by annealing of conductors and insulation charring. In addition, the low voltage in the neighborhood of the fault will cause equipment malfunction. [2]

Another important consequence is that Power flow is severely restricted or even completely blocked, while the short circuit lasts. As a result of blockage of power flow, power system areas can lose synchronism. The longer a fault lasts the more is the possibility of loss of synchronism. [4]

Short-circuit and protection studies are an essential tool for the electric energy systems engineer. The task is to calculate the fault conditions and to provide protective equipment designed to isolate the faulted zone from the remainder of the system in the appropriate time.

2.1.2 Causes of faults

Except on mainly underground systems, the vast majority of short-circuit faults are weather related followed by equipment failure. The weather factors that usually cause short-circuit faults are: lightning strikes, accumulation of snow or ice, heavy rain, strong winds or gales, salt pollution depositing on insulators on overhead lines and in substations, floods and fires adjacent to electrical equipment, e.g. beneath overhead lines.

Lightning strikes may discharge currents in the range of a few kilo amps up to 100 or 200 kA for a duration of several microseconds. If the strike hits an overhead line or its earth wire, the voltage produced across the insulator may be so large that a back-flashover and short- circuit occurs.

This may involve one or all three phases of a three-phase electrical circuit and as a result, a transient power frequency short-circuit current flows.

Other causes of short-circuit faults are fires The hot air in the flames of a fire has a much lower insulation strength than air at ambient temperature. A flashover across an insulator to earth or from a phase conductor to a tree may occur.

Equipment failure, e.g. machines, transformers, reactors, cables, etc., cause many short-circuit faults. These may be caused by failure of internal insulation due to ageing and degradation, break down due to high switching or lightning over-voltages, by mechanical incidents or by inappropriate installation.

Short-circuit faults may also be caused by human error. A classical example is one where maintenance staffs inadvertently leave isolated equipment connected through safety earth clamps when maintenance work is completed. A three-phase to earth short-circuit fault occurs when the equipment is reenergized to return it to service. [5]

2.2 Terminology of Short-circuit Wave Form and Current Interruption

In this section we discussed the wave form and current interruption in transient balanced three-phase system during a balanced fault .

2.2.1 Transients in a sample balanced three-phase system during a balanced fault

In order to approach the problem of calculating the initial current when a system is short circuited, consider figure 2.1 which shows a simple balanced three-phase electric circuit where L and R are the circuit inductance and resistance for each phase, and L_e and R_e are the earth return path inductance and resistance, respectively.

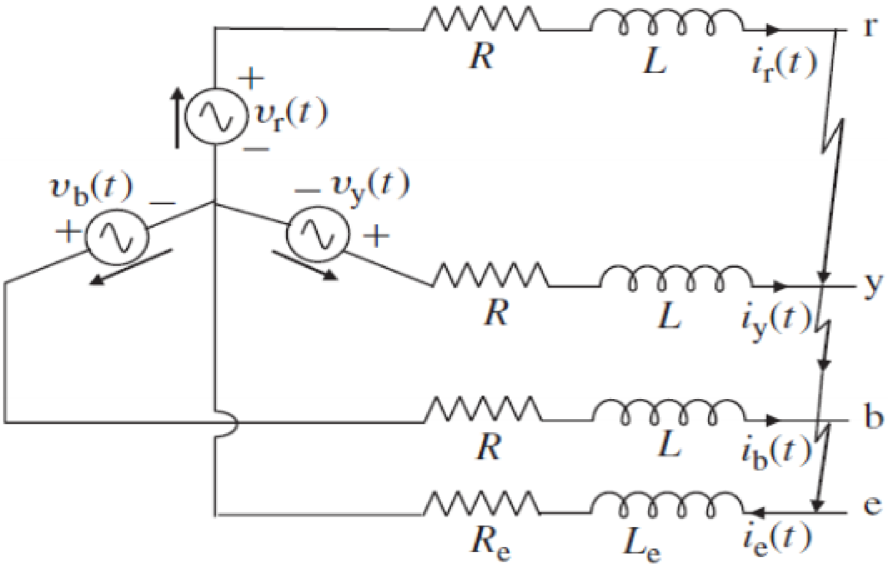


Figure 2.1 Basic balanced three-phase circuit with earth return**.**

The balanced three-phase circuit voltage sources are given by:

$$v_i(t) = \sqrt{2}\,V_{rms}\ \sin(\omega t + \varphi_i) \qquad i = r, y, b \tag{2.1}$$

Where (V_{rms}) is rms voltage magnitude, $\omega = 2\pi f$ in rad/s, (f) is power frequency in Hz and (φ) is voltage phase angle in rad. If a solid three-phase to earth short-circuit fault occurs between phases r, y, b and earth e at t =0, the following relation is valid:

$$L\frac{di_i(t)}{dt} + R_i(t) + L_e\frac{di_e(t)}{dt} + R_e i_e(t) = v_i(t) \qquad i = r, y, b \tag{2.2}$$

Substituting i = r,y,b in equation (2.2) and adding the resulting three equations one can obtain:

$$L\frac{d[i_r(t)+i_y(t)+i_b(t)]}{dt} + R[i_r(t) + i_y(t) + i_b(t)] + 3L_e\frac{di_e(t)}{dt} + 3R_e i_e(t) = v_r(t) + v_y(t) + v_b(t) \tag{2.3}$$

Since the three-phase voltage sources are balanced, then:

$$v_r(t) + v_y(t) + v_b(t) = 0 \qquad (2.4)$$

And from figure 2.1

$$i_r(t) + i_y(t) + i_b(t) = i_e(t) \qquad (2.5)$$

Therefore, substituting equations (2.4) and (2.5) in equation (2.3) yields:

$$(L + 3L_e)\frac{di_e}{dt} + (R + 3R_e)i_e(t) \qquad (2.6)$$

: The solution to equation (2.6) is given by

$$i_e(t) = k \times e^{\left(\frac{-t}{L+3L_e/_{R+3R_e}}\right)} \qquad (2.7)$$

Where (K) is a constant that satisfies the initial condition . Since the three-phase system is symmetrical and balanced, $i_e(t=0)=0$. Thus, Eq. (2.7) gives (K=0) and $i_e(t=0)=0$. That is, following a three-phase short circuit , no current will flow in the earth return connection and the three fault current $i_i(t)$ will flow independently as in single-phase circuit . Therefore, with $i_e(t)=0$, the solution of Equation (2.2) is given by :

$$i_i(t) = \sqrt{2}\ I_{rms}\left[\sin\left(\omega t + \varphi_i - \tan^{-1}\left(\frac{\omega L}{R}\right)\right) - \sin\left(\varphi_i - \tan^{-1}\left(\frac{\omega L}{R}\right)\right) \times e^{\left(\frac{-t}{L/_R}\right)}\right] \qquad (2.8)$$

Where

$$I_{rms} = \frac{V_{rms}}{\sqrt{R^2+(\omega L)^2}} \qquad (2.9)$$

Equation (2.8) can be written as the sum of an ac component and a unidirectional dc component as follows:

$$i_i(t) = i_{i(ac)}(t) + i_{i(dc)}(t) \qquad i = r, y, b \qquad (2.10)$$

$i_i(t)$ is called the asymmetrical short-circuit current.

Where

$$i_{i(ac)}(t) = \sqrt{2}\, I_{rms} \left[\sin\left(\omega t + \varphi_i - \tan^{-1}\left(\frac{\omega L}{R}\right)\right)\right] \tag{2.11}$$

And

$$i_{i(dc)}(t) = -\sqrt{2}\ I_{rms} \left[\sin\left(\varphi_i - \tan^{-1}\left(\frac{\omega L}{R}\right)\right) \times e^{\left(\frac{\omega L}{L/R}\right)}\right] \tag{2.12}$$

In this analysis, the magnitude of the ac current component is constant because it is assumed that the source inductance L is constant or time independent. This assumption is only generally valid if the location of short-circuit fault is electrically remote from electrical machines feeding short-circuit current into the fault. The initial magnitude of the dc current component in any phase depends on the instant on the voltage waveform when the short-circuit occurs, i.e. on ϕ_r and on the magnitude of the ac current component I_{rms}.[5]

If the value of steady-state term is not zero when t=0, the dc component appears in the solution in order to satisfy the physical condition of zero current at instant of short-circuit occurrence. Note that the dc term does not exist if the circuit is closed at a point on the voltage wave such that variation,

$\varphi_i - \tan^{-1}\left(\frac{\omega L}{R}\right) = 0$ or $\varphi_i - \tan^{-1}\left(\frac{\omega L}{R}\right) = \pi$. Figure 2.2 (a) shows the variation of current with time according to Eq. (2.10) when $\varphi_i - \tan^{-1}\left(\frac{\omega L}{R}\right) = 0$. If the short-circuit occurs at a point on the voltage wave such that $\varphi_i - \tan^{-1}\left(\frac{\omega L}{R}\right) = \pm\, {}^{\pi}/_{2}$ the dc component has its maximum initial value, which is equal to the maximum value of the sinusoidal component. Figure 2.2 (b) shows current versus time when $\varphi_i - \tan^{-1}\left(\frac{\omega L}{R}\right) = \pm\, {}^{\pi}/_{2}$.

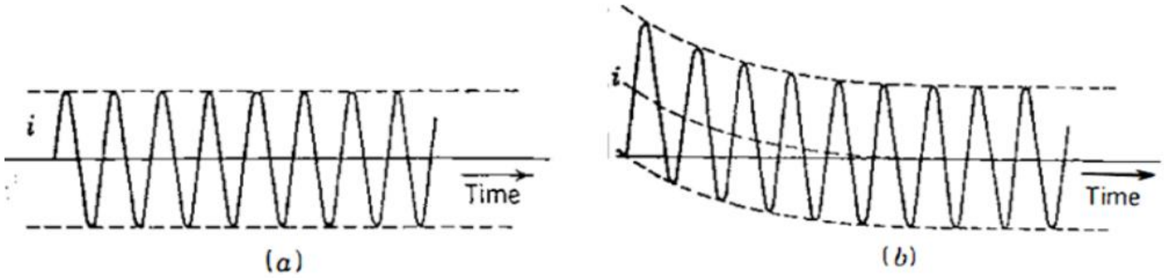


Figure 2.2 Current as a function of time in an RL circuit for: (a) $\varphi_i - \tan^{-1}\left(\frac{\omega L}{R}\right) = 0$; (b) $\varphi_i - \tan^{-1}\left(\frac{\omega L}{R}\right) = \pm {}^{\pi}/_{2}$

The dc component may have any value from (0 to I_{max}), depending on the instantaneous value of the voltage when short circuit occurred and on the power factor of the circuit. At the instant of applying the voltage the dc and steady-state components always have the same magnitude but are opposite in sign in order to express the zero value of current then existing.[3]

The rate of decay of the dc current component in the three phases depends on the circuit time constant L/R or circuit X/R ratio where X/R=ωL/R. Again, the assumption of a constant L results in a time-independent X/R ratio or constant rate of decay. [5]

Short-circuit currents are detected by protection relays which initiate the interruption of these currents by circuit-breakers. Figure 2.3 shows a general asymmetrical short-circuit current waveform and the terminology used to describe the various current components as well as the short circuit current interruption.

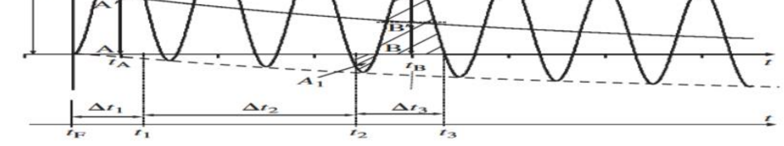


Figure 2.3 Asymmetrical short-circuit current waveform and current interruption

t_f ≡ Instant of short-circuit fault.

Δt_1 ≡ Protection relay time.

t_A ≡ Instant of ‘initial peak’ of short-circuit current.

t_1 ≡ Instant of energisation of circuit-breaker trip circuit.

Δt_2 ≡ Circuit-breaker opening time.

t_2 ≡ Instant of circuit-breaker contact separation = instant of arc initiation.

Δt_3 ≡ Circuit-breaker current arcing time.

t_3 ≡ Instant of final arc extinction = instant of short-circuit current interruption.

t_B ≡ Instant of peak of major current loop just before current interruption.

$2\sqrt{2}\, I_k^{''} = 2.828\, I_k^{''} =$ Theoretical current at the instant of short-circuit fault t_F.

Where $I_k^{''}$ is the rms short-circuit current at t =t_F.[5]

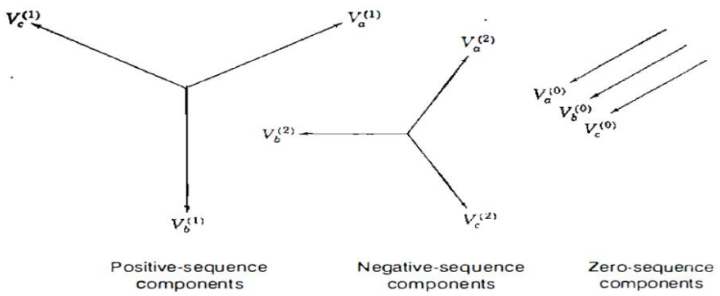
2.3 Short-circuit Calculations

In this section the method of symmetrical components has been discussed.

2.3.1 The method of symmetrical components

The method symmetrical components was introduced by C. L. Fortescue in 1918. It is one of the most powerful tools for dealing with unbalanced poly phase circuits. Fortescue’s work proves that an unbalanced system of (n) related phasors can be resolved into n systems of balanced phasors called the symmetrical components of the original phasors. The (n) phasors of each set of components are equal in length, and the angles between adjacent phasors of the set are equal.

According to Fortescue’s theorem, three unbalanced phasors of a three-phase system can be resolved into three balanced systems of phasors, these three sets are shown in figure 2.4



Positive-sequence components

Negative-sequence components

Zero-sequence components

Figure 2.4 Three sets of balanced phasors which are the symmetrical components of three phase unbalanced phasors.

The balanced sets of components are:

1. Positive-sequence components consisting of three phasors equal in magnitude, displaced from each other by 120° in phase and having the same phase sequence as the original phasors.
2. Negative-sequence components consisting of three phasors equal in magnitude, displaced from each other by 120° in phase, and having the phase sequence opposite to that of the original phasors.
3. Zero-sequence components consisting of three phasors equal in magnitude and with zero phase displacement from each other

If the original phasors are designated V_a, V_b and V_c with the sequence abc, hence the positive-sequence is (abc) and the negative-sequence is (cba). Subscript (1) is given to positive-sequence, (2) to negative-sequence and (0) to zero-sequence.

Since each of the original unbalanced phasors is the sum of its components, original phasors expressed in terms of their components are

$$V_a = V_a^0 + V_a^1 + V_a^2 \qquad I_a = I_a^0 + I_a^1 + I_a^2 \tag{2.13}$$

$$V_b = V_b^0 + V_b^1 + V_b^2 \qquad I_b = I_b^0 + I_b^1 + I_b^2 \tag{2.14}$$

$$V_c = V_c^0 + V_c^1 + V_c^2 \qquad I_c = I_c^0 + I_c^1 + I_c^2 \tag{2.15}$$

The synthesis of a set of three unbalanced phasors from the three sets of symmetrical components of fig. 2.4 is shown in fig. 2.5

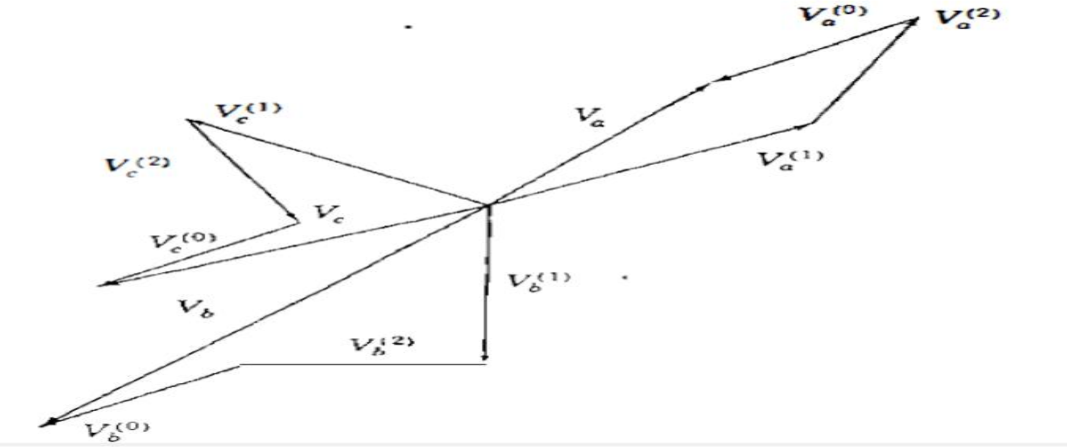


Figure 2.5 Graphical addition of components of figure 2.4 to obtain three unbalanced phasors.

From figure 2.4 vector analysis gives:

$$V_a^0 = V_b^0 \qquad V_c^0 = V_a^0$$

$$V_b^1 = a^2 V_a^1 \qquad V_c^1 = aV_a^1 \tag{2.16}$$

$$V_b^2 = aV_a^2 \qquad V_c^2 = a^2 V_a^2$$

Where $a = e^{120j}$.

Repeating Eq. (2.13) and substituting Eqs. (2.16) in Eqs (2.14) and (2.15) yields:

$$V_a = V_a^0 + V_a^1 \quad + V_a^2 \qquad I_a = I_a^0 + I_a^1 \quad + I_a^2 \tag{2.17}$$

$$V_b = V_b^0 + a^2 V_b^1 + aV_b^2 \qquad I_b = I_b^0 + a^2 I_b^1 + aI_b^2 \tag{2.18}$$

$$V_c = V_a^0 + aV_a^1 + a^2 V_a^2 \qquad I_c = I_c^0 + aI_c^1 + a^2 I_c^2 \tag{2.19}$$

Or in matrix form

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \begin{bmatrix} V_a^0 \\ V_a^1 \\ V_a^2 \end{bmatrix} = A \begin{bmatrix} V_a^0 \\ V_a^1 \\ V_a^2 \end{bmatrix} \tag{2.20}$$

Where

$$A = \begin{bmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{bmatrix} \tag{2.21}$$

And it can be proved that the inverse of matrix A given by:

$$A^{-1} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \tag{2.22}$$

And multiplying both sides of Eq.(2.20) by A^{-1}yields

$$\begin{bmatrix} V_a^0 \\ V_a^1 \\ V_a^2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{2.23}$$

Once symmetrical components of phase (a) has been found, the other two phases can be found from Eqs. (2.18) and (2.19).

These relations of symmetrical components are also applicable to current, and by changing variable V to variable I symmetrical components of current can be found. [3]

2.3.2 Calculation of unbalanced faults

The calculations of unbalanced faults has been obtained for each type of unbalanced faults in this section.

2.3.2.1 Single line to ground fault

The single line-to-ground fault, the most common type, is caused by lightning or by conductors making contact with grounded structures. Assuming that the fault occurs on phase (a) through impedance Z_f .

Also assuming that the generator is initially on no-load and the boundary condition at the fault point and from figure 2.6 :

$$I_b = 0 \tag{2.24}$$

$$I_c = 0 \tag{2.25}$$

$$V_a = Z_f I_a \tag{2.26}$$

The symmetrical components of the fault currents are:

$$\begin{bmatrix} I_{a1} \\ I_{a2} \\ I_{a0} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & a & a^2 \\ 1 & a^2 & a \\ 1 & 1 & 1 \end{bmatrix}\begin{bmatrix} I_a \\ 0 \\ 0 \end{bmatrix} \tag{2.27}$$

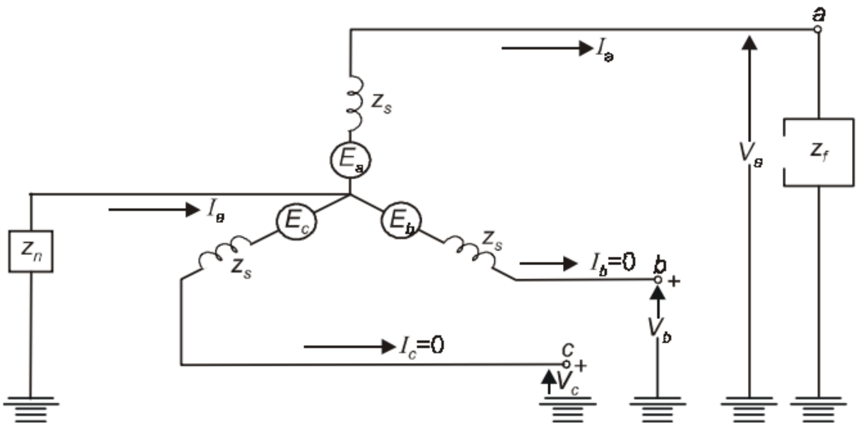


Figure 2.6 L-G fault on phase (a)

From the symmetrical components we find

$$I_{a1} = I_{a2} = I_{a0} = \frac{1}{3} I_a \tag{2.28}$$

$$V_{a1} + V_{a2} + V_{a0} = Z_f . I_a = 3\, Z_f I_{a1} \tag{2.29}$$

From Equations (2.28) , (2.29), positive, negative and zero sequence currents are equal and the sum of sequence voltages equals ($3Z_f\ I_{a1}$). These equations suggest a series connection of sequence networks through an impedance (3 Z_f). Figure 2.7 shows the sequence network connection for L-G fault .[6]

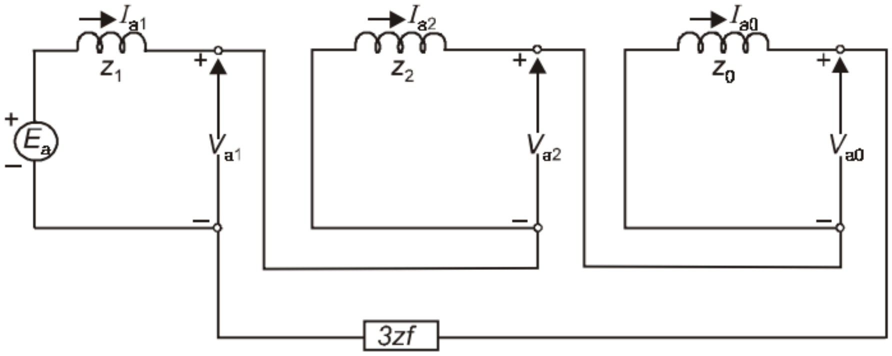


Figure 2.7 Sequence network connection for L-G fault

Thus for L-G faults, the Thivenin impedance to the point of fault is obtained for each sequence network. From figure 2.7, we can write

$$I_{a1} = \frac{E_a}{(Z_1+Z_2+Z_0)+3Z_f} \quad (2.30)$$

Fault currents I_a is given by

$$I_a = 3I_{a1} = \frac{3E_a}{(Z_1+Z_2+Z_0)+3Z_f} \quad (2.31)$$

Under L-G fault condition , the voltage of line b to ground is

$$V_b = a^2 V_{a1} + a\,V_{a2} + V_{a0} \quad (2.32)$$

$$\text{Or} \quad V_b = a^2\left(E_a - Z_1.\frac{I_a}{3}\right) + a\left(-Z_2.\frac{I_a}{3}\right) + \left(-Z_0.\frac{I_a}{3}\right) \quad (2.33)$$

Using equation (2.31) and (2.33) we get

$$V_b = E_a\,\frac{\left[3a^2 Z_f + Z_2(a^2-a) + Z_0(a^2-1)\right]}{(Z_1+Z_2+Z_0)+3Z_f} \quad (2.34)$$

Similarly

$$V_c = a\,V_{a1} + a^2 V_{a2} + V_{a0} \tag{2.35}$$

$$V_c = a\left(E_a - Z_1.\frac{I_a}{3}\right) + a^2\left(-Z_2.\frac{I_a}{3}\right) + \left(-Z_0.\frac{I_a}{3}\right) \tag{2.36}$$

Using equation (2.31) and (2.36), we get

$$V_c = E_a\,\frac{\left[3a\,Z_f + Z_2(a-a^2) + Z_0(a-1)\right]}{(Z_1+Z_2+Z_0)+3Z_f} \tag{2.37}$$

2.3.2.2 Line-to-line faults

The boundary conditions at the fault point are

$$V_b - V_c = Z_f.I_b \tag{2.38}$$

$$I_b + I_c = 0 \tag{2.39}$$

$$I_a = 0 \tag{2.40}$$

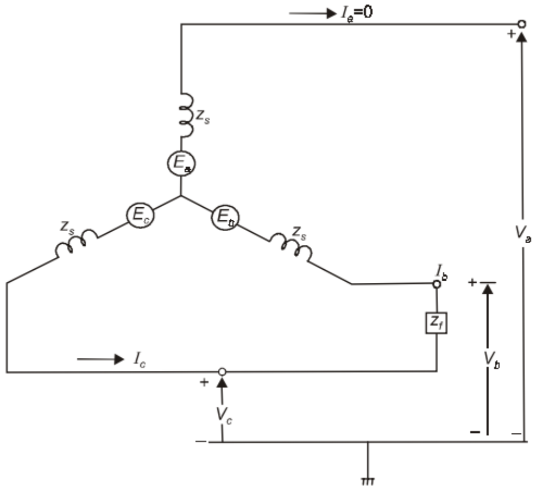


Figure 2.8 line-to-line fault between phase (b) and (c)

The symmetrical components of the fault currents are:

$$\begin{bmatrix} I_{a1} \\ I_{a2} \\ I_{a0} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & a & a^2 \\ 1 & a^2 & a \\ 1 & 1 & 1 \end{bmatrix}\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \tag{2.41}$$

Substituting $I_a = 0\,, I_c = -I_b$

$$\begin{bmatrix} I_{a1} \\ I_{a2} \\ I_{a0} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & a & a^2 \\ 1 & a^2 & a \\ 1 & 1 & 1 \end{bmatrix}\begin{bmatrix} 0 \\ I_b \\ -I_b \end{bmatrix} \tag{2.42}$$

From which we get

$$I_{a2} = -I_{a1} \tag{2.43}$$

$$I_{a0} = 0 \tag{2.44}$$

The symmetrical components of voltages under fault are

$$\begin{bmatrix} V_{a1} \\ V_{a2} \\ V_{a0} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & a & a^2 \\ 1 & a^2 & a \\ 1 & 1 & 1 \end{bmatrix}\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \tag{2.45}$$

Substituting $V_c = V_b - Z_f.I_b$, we get

$$\begin{bmatrix} V_{a1} \\ V_{a2} \\ V_{a0} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & a & a^2 \\ 1 & a^2 & a \\ 1 & 1 & 1 \end{bmatrix}\begin{bmatrix} V_a \\ V_b \\ V_b - Z_f.I_b \end{bmatrix} \tag{2.46}$$

From equation(2.46)

$$3\,V_{a1} = V_a + (a + a^2)V_b - a^2 Z_f.I_b \tag{2.47}$$

$$3\,V_{a2} = V_a + (a + a^2)V_b - a.Z_f.I_b \tag{2.48}$$

Subtracting equation (2.47) from equation (2.48), we get

$$3(V_{a1} - V_{a2}) = (a - a^2)Z_f.I_b \tag{2.49}$$

$$3(V_{a1} - V_{a2}) = j\sqrt{3}\,Z_f.I_b \tag{2.50}$$

Now

$$I_b = (a^2 - a)I_{a1} \tag{2.51}$$

$$I_b = -j\sqrt{3}\,I_{a1} \tag{2.52}$$

Using equation (2.50) and (2.52) , we get

$$V_{a1} - V_{a2} = Z_f . I_{a1} \qquad (2.53)$$

Equation (2.53) and (2.43) can be represented by connecting the positive and negative sequence networks in opposition and the equivalent circuit.[6]

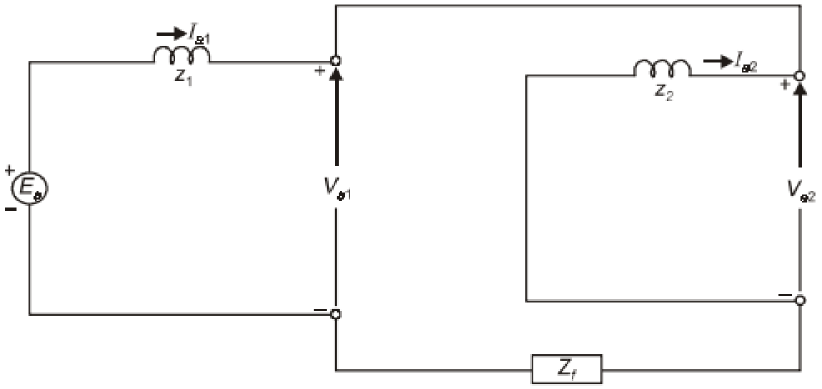


Figure 2.9 Sequence network for L-L fault.

From Figure 2.9

$$I_{a1} = \frac{E_a}{(Z_1 + Z_2 + Z_f)} \qquad (2.54)$$

Also

$$I_b = -I_c = \frac{-j\sqrt{3}\, E_a}{(Z_1 + Z_2 + Z_f)} \qquad (2.55)$$

2.3.2.3 Double line-to-ground faults

Figure 2.10 shows a double Line-to-Ground fault

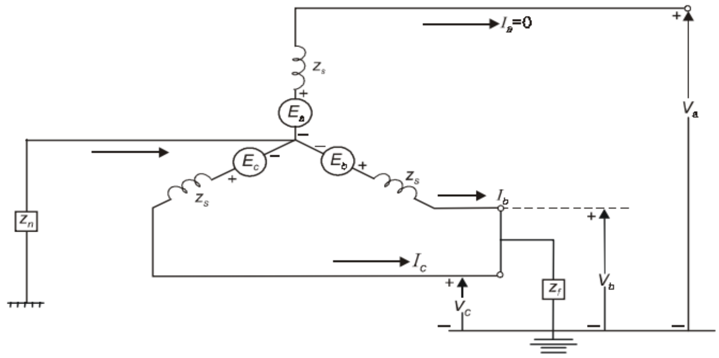


Figure 2.10 L-L-G Fault.

The boundary conditions at the fault point are:

$$I_a = 0 \tag{2.56}$$

$$I_{a1} + I_{a2} + I_{a0} = 0 \tag{2.57}$$

$$V_b = V_c = (I_b + I_c)Z_f = 3Z_f I_{a0} \tag{2.58}$$

The symmetrical components of voltages are given by

$$\begin{bmatrix} V_{a1} \\ V_{a2} \\ V_{a0} \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & a & a^2 \\ 1 & a^2 & a \\ 1 & 1 & 1 \end{bmatrix}\begin{bmatrix} V_a \\ V_b \\ V_c = V_b \end{bmatrix} \tag{2.59}$$

From equation(2.59), we get

$$V_{a1} = V_{a2} = \frac{1}{3}[V_a + (a + a^2)V_b] \tag{2.60}$$

$$V_{a0} = \frac{1}{3}(V_a + 2V_b) \tag{2.61}$$

Using equation (2.60) and (2.61), we get

$$V_{a0} - V_{a1} = \frac{1}{3}(2 - a - a^2)V_b = 3\ Z_f . I_{a0} \tag{2.62}$$

$$V_{a0} = V_{a1} + 3\ Z_f . I_{a0} \tag{2.63}$$

From equations (2.57), (2.60) and (2.63) we can draw the connection of sequence network as shown in Figure 2.11.[6]

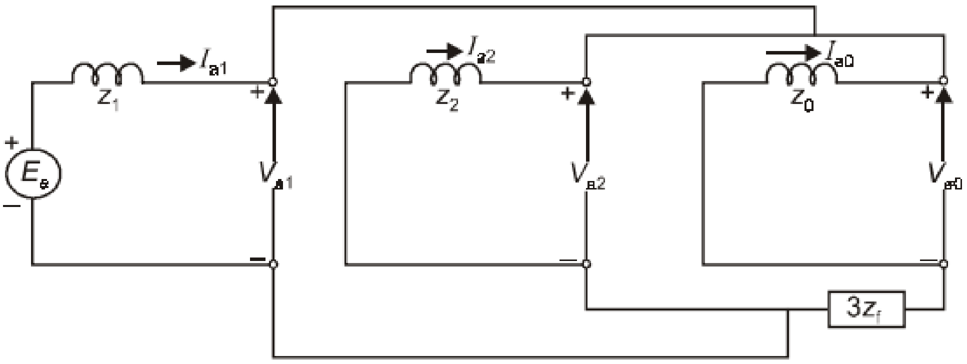


Figure 2.11 Sequence network connection for Double-Line-to-Ground fault

From Figure 2.11 we can write

$$I_{a1} = \frac{E_a}{Z_1 + \frac{Z_2\left(Z_0+3Z_f\right)}{\left(Z_2+Z_0+3Z_f\right)}} \qquad (2.64)$$

Also

$$I_{a2} = \frac{-(E_a - Z_1.I_{a1})}{Z_2} \qquad (2.65)$$

And

$$I_{a0} = \frac{-(E_a - Z_1.I_{a1})}{\left(Z_0+3Z_f\right)} \qquad (2.66)$$

2.4 International Standards for Short-circuit Analysis in AC Power Systems

Guidelines and standards for short-circuit analysis have been developed in some countries. These standards generally aim at producing consistency and repeatability of conservative results or results that are sufficiently accurate for their intended purpose. Three very popular and widely used approaches are the International Electro-technical Commission (IEC) 60909-0:2001 Standard ,the American Institute for Electrical and Electronics Engineers (IEEE) C37.010:1999 Standard also known as American National Standard Institute (ANSI) and the UK Engineering Recommendation ER G7/4 procedure. The IEC standard is the one used in the project, so it will have the attention in this brief introduction.

2.4.1 ANSI Standard (C37)

The short circuit current calculations based on the ANSI standard has been performed in three different networks namely $\left(\frac{1}{2}\right)$ cycle, $\left(1\,\frac{1}{2}\right)$ to 4 cycle and 30 cycle.

- In $\left(\frac{1}{2}\right)$ cycle network, the sub-transient reactance of the network components is used to calculate the fault current and the corresponding network is called as sub-transient network. Here, the momentary short circuit current is calculated after $\left(\frac{1}{2}\right)$ cycle of the fault occurrence.
- In $\left(1\frac{1}{2}\right)$ to 4 cycle network, the transient reactance of the network components is used to calculate the fault current and the corresponding network is called as transient network. In this network, the interrupting short circuit current is calculated after 4 cycles of the fault occurrence.
- In 30 cycle network, the steady state reactance of the network components is used to calculate the fault current and it is used to calculate the steady state short circuit current.[1]

2.4.2 International Electro-Technical Commission 60909-0 Standard

In 1988, the International Electro-technical Commission published IEC Standard IEC 60909 entitled 'Short-Circuit Current Calculation in Three-Phase AC Systems'. This was derived from the German Verband Deutscher Electrotechniker (VDE) 0102 Standard. The IEC Standard was subsequently updated in 2001 and is the only international standard recommending methods for calculating short circuit currents in three-phase ac power systems. Its aim, when conceived, was to present a practical and concise procedure, which, if necessary, can be used to carry out hand calculations and which leads to conservative results with sufficient accuracy. However, non-conservative results were subsequently identified in particular applications and this objective was revised in the 2001 update to 'leading to results which are generally of acceptable accuracy'.

The Standard is applicable in low voltage and high voltage systems up to 550 kV nominal voltages and a nominal frequency of 50 or 60 Hz. The Standard deals with the calculation of maximum and minimum short-circuit currents and distinguishes between short circuits with and without ac current component decay corresponding to short circuits that are near to and far from generators.[5]

CHAPTER THREE

SHORT CIRCUIT FAULTS CALCULATIONS

The aim is to calculate short- circuit currents for all types of faults at (500 KV) buses, (220 KV) buses and (110 KV) buses in addition to are the tertiary windings of all 3 winding transformers connected to these buses. And also to calculate short-circuit MVA. These currents are calculated in order to determine the appropriate ratings of circuit breakers, or in other words, to size circuit breakers.

3.1 Structure of the National Grid

The network comprises 49 stations distributed over a wide area of Sudan, some of them contain only one bus and the others contain two buses of two voltage levels (500 KV to 220 KV, or 220 KV to 110 KV) in addition to a third and maybe fourth auxiliary bus of 33 KV or 11 KV. Among these 49 stations there are 5 generation stations summarized in table 3.1

Table 3.1 Generation in the National Grid

Station	Number of generators	Maximum output (MW)
Merawi-Hydro	10	1270.3
Garri	14	566
Roseires	7	280
Khartoum-north	7	417
Sinnar	2	15

- Total number of buses is eighty two buses, of these eighty two buses there are four 500 KV buses, forty five 220 KV buses, thirty two 110 KV buses.
- Total number of transmission lines is eighty one lines some of them are single circuit and the others are double circuit.
- For transformers, there are thirty three 3-winding transformers, of these thirty three there are nine step-up transformers connecting generators to buses, and rest are connected between buses. Number of 2-winding transformers is fifteen and all of them step-up from generation level to transmission level.

3.2 Methodology and Tools

In order to accommodate with the international standards and to insure accurate results, the project was implemented using ETAP 16.0 program.

The ETAP Short-Circuit Analysis program analyzes the effect of 3-phase, line-to-ground, line-to line, and line-to-line-to-ground faults on power systems.

The program calculates the total short circuit currents as well as the contributions of individual motors, generators, and utility ties in the system. Fault duties are in compliance with the latest editions of the ANSI/IEEE Standards (C37 series) and IEC Standards (IEC 60909 and others). [5]

The project is implemented in compliance with the IEC 60909 standard since it is the one used by the NEC (or recently the Sudanese electricity transmission company).

3.2.1 General description of calculation methodology

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. Maximum short circuit currents determine equipment ratings, while minimum currents dictate protective device settings. Protective device settings are beyond the scope of the project, so, only maximum short circuit currents is are given attention .

All machines are represented by their internal impedances. Transformer taps can be set at either the nominal position or at the tapped 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. 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. [7]

3.2.2 Definition of terms

IEC standards use the following definitions, which are relevant in the calculations and outputs of ETAP.

Initial Symmetrical Short circuit current (I_k'')

This is the rms value of the AC symmetrical component of an available short circuit current applicable at the instant of short circuit if the impedance remains at zero time value.

Peak Short Circuit Current (i_K)

This is the maximum possible instantaneous value of the available short circuit current.

Symmetrical Short Circuit Breaking Current (I_b)

This is the rms value of an integral cycle of the symmetrical AC component of the available short circuit current at the instant of contact separation of the first pole of a switching device.

Steady-State Short Circuit Current (I_k)

This is the rms value of the short circuit current, which remains after the decay of the transient phenomena.

Subtransient Voltage (E'') of a Synchronous Machine

This is the rms value of the symmetrical internal voltage of a synchronous machine which is active behind the subtransient reactance $\left(X_d''\right)$ at the moment of short circuit.

Far-From-Generator Short Circuit

This is a short circuit condition during which the magnitude of the symmetrical AC component of available short circuit current remains essentially constant.

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 rated current, or a short circuit condition to which synchronous and asynchronous motors contribute more than 5% of the initial symmetrical short circuit current $\left(I_k^{''}\right)$ without motors.

Subtransient Reactance $\left(X_d^{''}\right)$ of a Synchronous Machine

This is the effective reactance at the moment of short circuit. For the calculation of short circuit currents, the saturated value of $\left(\mathrm{X}_\mathrm{d}^{''}\right)$ is taken.

Voltage Factor c

This is the factor used to adjust the value of the equivalent voltage source for minimum and maximum current calculations according to table 3.2

Table 3.2: Values of voltage factor c.

Nominal Voltage (Un)	Voltage Factor c	
	For Maximum Short circuit current (c_{max})	For minimum short circuit current (c_{min})
Others < 1001 V	1.1	0.95
Medium voltage: > 1 kV to 35 kV	1.10	1.00
High voltage: > 35 kV to 230 kV	1.10	1.00

ETAP enables the user to set a User-Define c Factor. The user-defined values must be in the range between the values given in the c_{max} and c_{min} columns. [7]

3.2.3 IEC 60909 based calculation methods

Initial Symmetrical Short Circuit Current Calculation

Initial symmetrical short-circuit current$\left(I_k^{''}\right)$ is calculated using the following formula:

$$I_k^{''} = \frac{c\,U_n}{\sqrt{3}\ Z_k} \tag{3.1}$$

Where Z_k is the equivalent impedance at the fault location.

Peak Short Circuit Current Calculation

Peak short-circuit current$\left(i_p\right)$ is calculated using the following formula:

$$i_p = \sqrt{2}\, k\, I_k^{''} \tag{3.2}$$

Where k is a function of the system R/X ratio at the fault location.

IEC Standards provide three methods for calculating the k factor:

- **Method A:** Uniform ratio R/X. The value of the k factor is determined from taking the smallest ratio of R/X of all the branches of the network. Only branches that contain a total of 80 percent of the current at the nominal voltage corresponding to the short circuit location are included. Branches may be a series combination of several elements.
- **Method B:** R/X ratio at the short circuit location. The value of the k factor is determined by multiplying the k factor by a safety factor of 1.15, which covers inaccuracies caused after obtaining the R/X ratio from a network reduction with complex impedances.
- **Method C:** Equivalent frequency. The value of the k factor is calculated using a frequency altered R/X. R/X is calculated at a lower frequency and then multiplied by a frequency dependent multiplying factor.

Symmetrical Short Circuit Breaking Current Calculation

For a far-from-generator fault, the symmetrical short circuit breaking current (I_b) is equal to the initial symmetrical short circuit current.

$$I_b = I_k^{''} \tag{3.3}$$

For a near-to-generator fault, I_b is obtained by combining contributions from each individual machine. I_b for different types of machines is calculated using the following formula:

$$I_b = \begin{cases} \mu\, I_k'' \; for\ synchronous\ machines \\ \mu\, q\, I_k'' \; for\ asynchronous\ machines \end{cases} \tag{3.4}$$

Where µ and q are factors that account for AC decay. They are functions of the ratio of the minimum time delay and the ratio of the machine initial short circuit current to its rated current, as well as real power per pair of poles of asynchronous machines.

IEC Standards allow the user to include or exclude AC decay effect from asynchronous machines in the calculation.

DC Component of Short Circuit Current Calculation

The DC component of the short circuit current for the minimum delay time of a protective device is calculated based on initial symmetrical short circuit current and system X/R ratio:

$$I_{dc} = I_k''\sqrt{2}\, e^{\left(\frac{2\pi f t_{min}}{{}^{x}/_{R}}\right)} \tag{3.5}$$

Where f is the system frequency, t_{min} is the minimum delay time of the protective device under concern, and X/R is the system value at the faulted bus.

Asymmetrical Short Circuit Breaking Current Calculation

The asymmetrical short circuit breaking current for comparison with circuit breaker rating is calculated as the rms value of symmetrical and DC components of the short circuit current.

This current is the one that is relied on when determining the circuit breaker rating.

Steady-State Short circuit current Calculation

Steady-state short circuit current (I_k) is a combination of contributions from synchronous generators and power grid. (I_k) for each synchronous generator is calculated using the following formula:

$$I_{kmax} = \lambda_{max} I_{rG} \tag{3.6}$$

Where λ is a function of a generator excitation voltage, ratio between its initial symmetrical short circuit current and rated current, other generator parameters, and I_{rG} is the generator rated current.

The steady-state short circuit current calculated is dependent on the option selected for Short circuit current in the study case. If the Max and User-Defined c Factor is selected, the maximum steady-state short circuit current is reported. If the Min option is selected, the minimum steady-state short circuit current is reported.

This maximum steady-state short circuit current is used to determine minimum device ratings. The minimum steady-state short circuit value is used for relay coordination purposes in preventing the occurrence of nuisance trips and loading deviations. [7]

CHAPTER FOUR

SIMULATION AND RESULTS

4.1 System Description

The network which has been studied is Sudanese electrical power system network. It contains of 81 transmission lines, 15 2-winding transformers. Total number of buses is eighty two buses, of these eighty two buses there are four 500 KV buses, forty five 220 KV buses, thirty two 110 KV buses.

4.2 Procedure

In this section the procedures of this project has been discussed.

4.2.1 Data collection

Data was collection phase began by obtaining the single line diagram which showed the distribution of buses geographically and their KV ratings. This one line diagram was supplied by Eng. Esraa and it is shown in appendix (A) . Then the rest of the data was supplied by the Sudanese electricity transmission company (Load dispatch centre), the system data shown in appendix (B) and these data included:

1. Transmission lines data (lengths in Kilometers and impedance per Kilometer).
2. Transformers data.
    - i. Names of stations containing the transformers.
    - ii. MVA rating for all windings.
    - iii. KV rating for all windings.
    - iv. X/R ratio (the value 5 was assumed as a typical value).

3. Generator data
    1. Generators names which are named after stations
    2. Nominal KV rating.
    3. MVA rating.
    4. Power factor.
    5. Direct axis reactance.
    6. Direct axis subtransient reactance (considered to be the positive-sequence reactance).
    7. Negative-sequence reactance.
    8. Zero-sequence reactance.

4.2.2 Data entering

Here, a detailed description of how data was entered to the program is presented.

4.2.2.1 One line diagram

The one line diagram was constructed on the ETAP work space element by element, and all components symbols were chosen according to the IEC standard. Figure 4.1 shows part of the one line diagram.

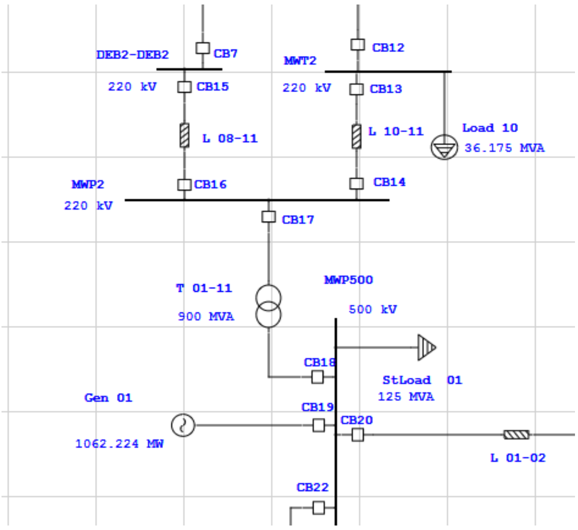


Figure 4.1 Part of the one line diagram as drawn on ETAP work space

4.2.2.2 Busses

The program asks the user to insert bus name and nominal KV. Figure 4.2 shows the bus editor window.

500 kV 0 Amps Peak 0 kA

ID: MW P500

Nominal kV: 500

Revision Data: Base

	% V	kV	Angle
Initial	100	500	0
Operating	0	0	0

Service: ● In ○ Out

State: New

Tag #:

Name:

Description:

Priority: Critical

Connection: ● 3 Phase ○ 1 Phase 2W ○ 1 Phase 3W

Load Diversity Factor: Min. 80 % Max. 125 %

Zone: 1

Area: 1

Region: 1

Voltage Limit: Min. 90 %

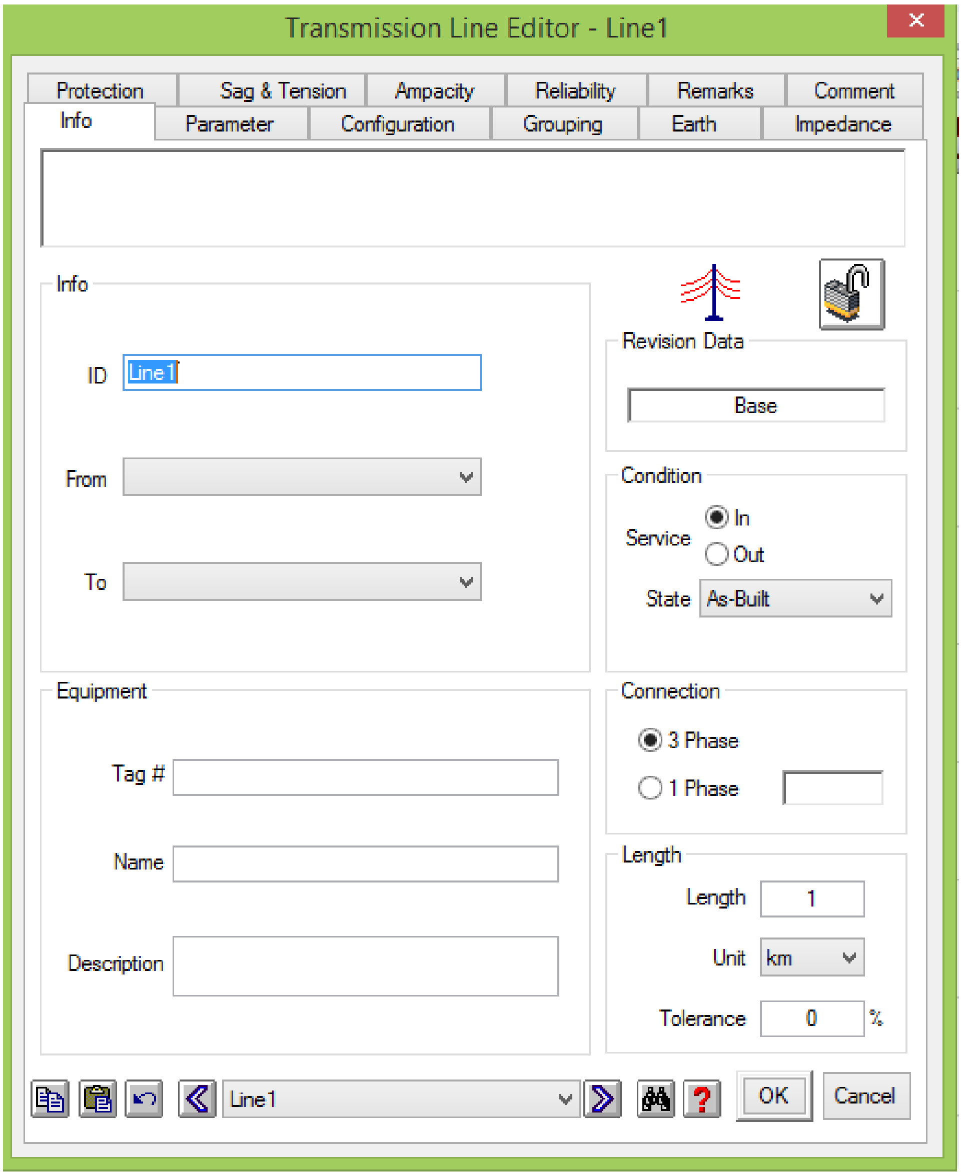
Duration: 0 Cycle

MWP500

Figure 4.2 Bus editor window.

4.2.2.3 Transmission lines

The length in kilometers and reactance in ohm per kilometer were specified for each transmission line. There is an assumption of ignoring the resistance, but the program mandates that the user must specify the resistance value, so, a small value of 0.00001 was given to the resistance. Figure 4.3 shows the transmission line editor window.



ID: Line1

Revision Data: Base

Service: ● In ○ Out

State: As-Built

Connection: ● 3 Phase ○ 1 Phase

Length: 1

Unit: km

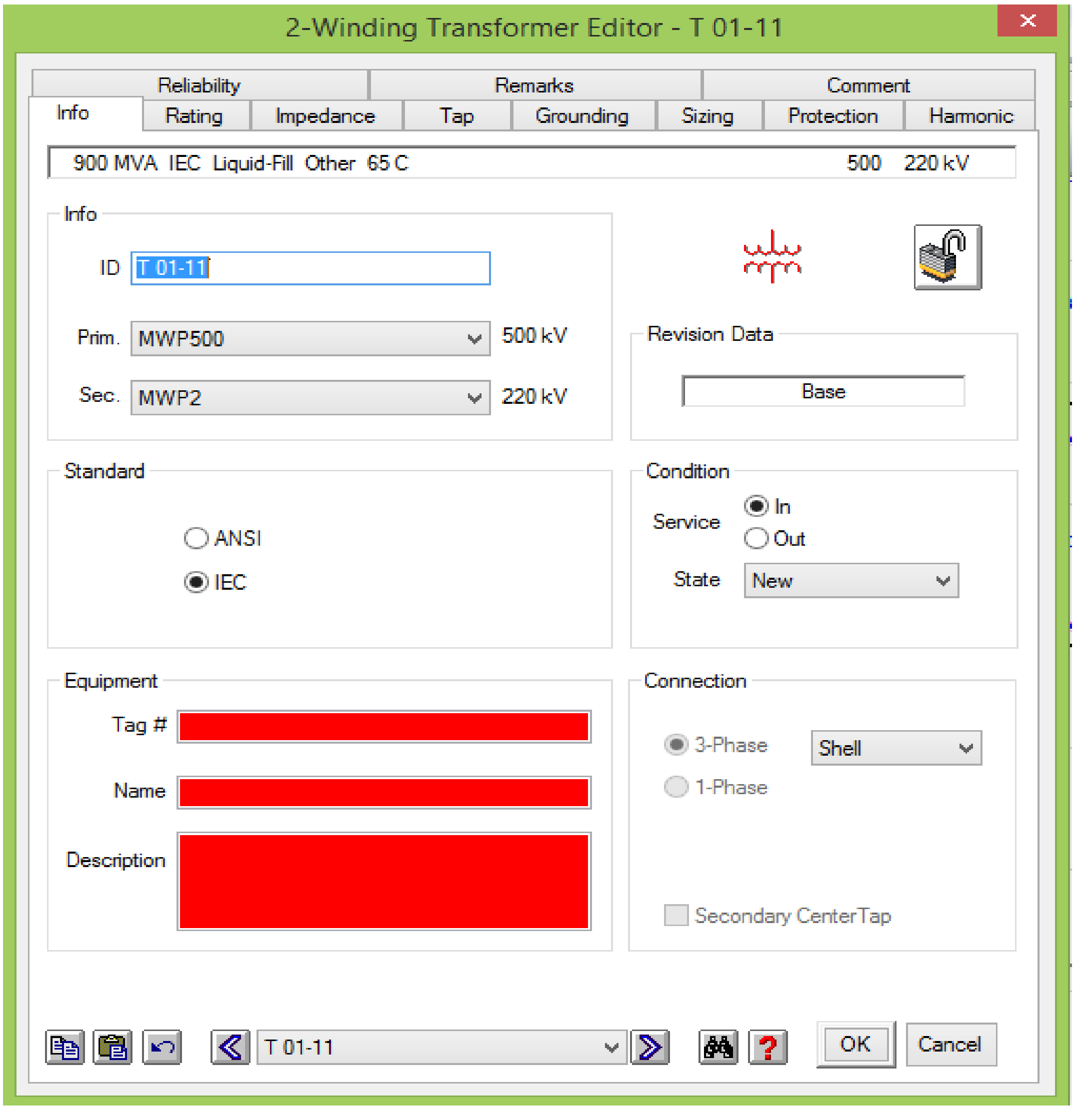
Tolerance: 0 %

Line1

Figure 4.3 Transmission line editor window.

4.2.2.4 Transformers

Every transformer was given a unique name, and the program automatically names all transformer sides according to names of buses connected to them and also sets the rated KV accordingly. The rated MVA of each side must be specified by the user, as well as the impedance as a percentage in the form of PS, PT, ST and also the X/R ratio which was given the value of 5 as a typical value. The program automatically sets the transformer base MVA as the MVA of the primary side. Figure 4.4 shows the transformer editor window.



900 MVA IEC Liquid-Fill Other 65 C 500 220 kV

Info

ID T 01-11

Prim. MWP500 500 kV

Sec. MWP2 220 kV

Revision Data: Base

Standard: ○ ANSI ● IEC

Condition

Service: ● In ○ Out

State: New

Equipment

Tag #

Name

Description

Connection: ● 3-Phase ○ 1-Phase Shell

☐ Secondary CenterTap

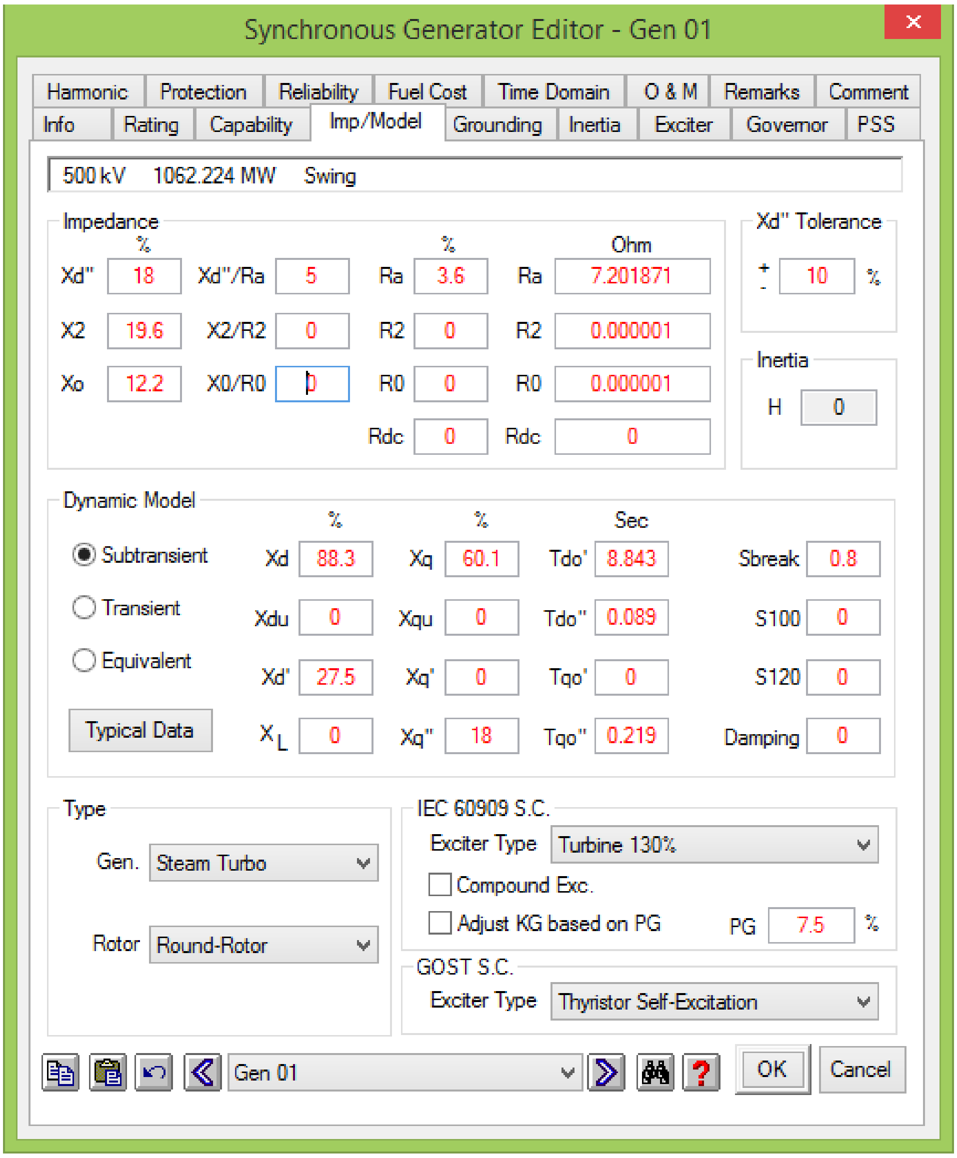
T 01-11

Figure 4.4 Transformer editor window

4.2.2.5 Generators

Every generator was given a unique name. The MVA rating, KV rating and power factor were specified.

For the impedance, X_d'' which is the subtransient reactance was specified, also the direct axis reactance X_d, negative sequence reactance X_2 , zero-sequence reactance , and $\mathrm{X_d/R}$ ratio were all specified. Figure 4.5 shows the Generator editor window.



500 kV 1062.224 MW Swing

Impedance

	%				%		Ohm
Xd"	18	Xd"/Ra	5	Ra	3.6	Ra	7.201871
X2	19.6	X2/R2	0	R2	0	R2	0.000001
Xo	12.2	X0/R0	0	R0	0	R0	0.000001
				Rdc	0	Rdc	0

Xd" Tolerance
± 10 %

Inertia
H 0

Dynamic Model

		%		%		Sec		
● Subtransient	Xd	88.3	Xq	60.1	Tdo'	8.843	Sbreak	0.8
○ Transient	Xdu	0	Xqu	0	Tdo"	0.089	S100	0
○ Equivalent	Xd'	27.5	Xq'	0	Tqo'	0	S120	0
	X_L	0	Xq"	18	Tqo"	0.219	Damping	0

Type
Gen. Steam Turbo
Rotor Round-Rotor

IEC 60909 S.C.
Exciter Type Turbine 130%
☐ Compound Exc.
☐ Adjust KG based on PG PG 7.5 %

GOST S.C.
Exciter Type Thyristor Self-Excitation

Gen 01

Figure 4.5 Generator editor window

4.3 Case Study

The model analysis method has been successfully applied to Sudanese electrical power system network shown in Appendix (A). ETAP program is used to develop short-circuit calculation IEC-60909 Standard for :

- Three-phase symmetrical short-circuit
- unsymmetrical short-circuit which include :
    i. L-G fault
    ii. L-L fault
    iii. L-L-G fault

Then the three-phase symmetrical short-circuit current value has been compared against circuit breaker ratings .

4.4 Symmetrical Short-circuit Results

The Table below shows the symmetrical short-circuit currents obtained by the program and the calculated short-circuit MVA for buses. Buses were ordered alphabetically to ease the access to a desired value.

Table 4.1 symmetrical short-circuit measured in KA and short-circuit MVA for stations buses.

Bus name	Rated KV	3-phase fault	MVA sc
AFR1	110	24.204	4611.5
ARO2	220	3.552	1353.5
ATB2	220	9.181	3498.4
ATB5	500	4.739	4104.1
BAG1	110	10.036	1912.1
BBN2	220	1.322	503.75
BNT1	110	37.093	7067.2

DBE2	220	3.558	1355.8
DBT2	220	2.682	1022
DEB2	220	2.823	1075.7
DON2	220	3.615	1377.5
FAO1	110	2.719	518.04
FAR1	110	15.938	3036.6
FRZ2	220	15.86	6043.5
FUL2	220	1.622	618.06
GAD1	110	9.830	1872.9
GAD2	220	19.172	7305.5
GAM1	110	20.949	3991.3
GAM2	220	17.449	6649
GDF1	110	5.017	955.87
GDF2	220	6.665	2539.7
GER2	220	15.806	6022.9
GND1	110	8.988	1712.4
GRB2	220	6.339	2415.5
GRB69	66	41.33	4724.7
HAG1	110	4.924	938.15
HUD	220	15.781	6013.4
HWT2	220	7.013	2672.3
IBA1	110	35.339	6733
IBA2	220	19.113	7283
IZBI	110	21.993	4190

IZG1	110	40.474	7711.3
JAS1	110	14.612	2784
JAS2	220	20.296	7733.8
KAB2	220	16.362	6234.8
KAB5	500	6.413	5553.8
KHE1	110	40.07	7634.4
KHN1	110	52.488	10002
KLX1	110	42.668	8129.3
KLX2	220	19.003	7241
KSL2	220	4.199	1600
KUK1	110	50.91	9699.7
LOM1	110	40.793	7772.1
MAN1	110	3.06	583.01
MAR1-B1	110	11.157	2125.7
MAR2	220	9.076	3458.4
MHD1	110	37.462	7137.5
MHD2	220	13.663	5206.3
MIN1	110	2.284	435.16
MRK2	220	15.659	5966.9
MRK5	500	7.203	6238
MSH2	220	7.694	2931.8
MUG	110	36.278	6911.9
MWP2	220	10.486	3995.7
MWP500	500	12.351	10696

MWT2	220	6.337	2414.7
NHAS1	110	11.687	2226.7
NHAS2	220	10.103	3849.8
NHLF2	220	4.965	1891.9
OBD2	220	3.593	1369.1
OHAS1	110	11.323	2157.3
OMD1	110	36.104	6878.7
ORBK1	110	1.24	236.25
RBK2	220	12.087	4605.7
RNK2	220	10.492	3998
ROS2	220	19.424	7401.5
SHD2	220	3.317	1263.9
SHG1	110	37.755	7193.3
SHK2	220	6.478	2468.4
SHN2	220	9.046	3447
SNG2	220	9.197	3504.5
SNJ1	110	10.607	2020.9
SNJ2	220	8.963	3415.4
SNP1	110	19.785	3769.5
SOB1-B1	110	13.151	2505.6
SOB2	220	17.828	6793.4
TND2	220	8.435	3214.2
UMR2	220	6.066	2311.5
UTP2	220	5.492	2092.7

WHL2	220	1.433	546.05
WWA2	220	2.452	934.34
ZBD2	220	2.293	873.75

From table 4.1 the following results has been noticed

- In the 110 KV buses fault level exceeded 25 KA at 12 buses, these were BNT1 , IBA1 , IZG1 , KHE1 , KHN1 , KLX1 , KUK1 , LOM1 , MHD1 , MUG , OMD1 , SHG1 , fault levels were 37.093 KA , 35.339 KA , 40.474 KA , 40.07 KA , 52.488 KA , 42.668 KA , 50.91 KA , 40.793 KA , 37.462 KA , 36.278 KA , 36.104 KA , 37.755 KA , respectively.
- In the level of 220 KV fault levels were quite low. Fault level exceeded 15 KA at 12 Buses and the maximum was 20.296 KA recorded at JAS2.
- Fault levels at the four 500 KV busses were lower than 10 KA and the maximum was 12.351 KA recorded at Merawi.
- Highest short circuit MVA was 10696 MVA recoded at Merawi power station, this is a direct result since the highest voltage is at this bus and this value shaded with yellow.

4.5 Unsymmetrical Short-circuit Calculation

Table 4.2 Unsymmetrical Short-circuit currents measured in KA

Bus name	Rated KV	3-phase fault	LG fault	LL fault	LLG fault
AFR1	110	24.204	21.49	20.974	23.309
ARO2	220	3.552	2.91	3.097	3.352
ATB2	220	9.181	5.471	7.96	8.372

ATB5	500	4.739	5.105	4.087	5.004
BAG1	110	10.036	7.88	8.694	9.868
BBN2	220	1.322	1.12	1.145	1.258
BNT1	110	37.093	33.683	32.127	35.883
DBE2	220	3.558	2.977	3.079	3.347
DBT2	220	2.682	2.16	2.319	2.526
DEB2	220	2.823	2.599	2.443	2.757
DON2	220	3.615	2.753	3.129	3.342
FAO1	110	2.719	2.558	2.359	2.726
FAR1	110	15.938	14.273	13.808	15.38
FRZ2	220	15.86	16.33	14.275	16.448
FUL2	220	1.622	1.338	1.404	1.535
GAD1	110	9.830	7.615	8.524	9.713
GAD2	220	19.172	18.838	16.679	19.243
GAM1	110	20.949	20.72	18.143	20.943
GAM2	220	17.449	17.158	15.112	17.406
GDF1	110	5.017	5.239	4.355	5.217
GDF2	220	6.665	5.048	5.883	6.225
GER2	220	15.806	16.72	14.269	16.349
GND1	110	8.988	9.163	7.791	9.163
GRB2	220	6.339	4.649	5.560	5.92
GRB69	66	41.33	64.464	43.279	54.886
HAG1	110	4.924	4.947	4.312	4.99
HUD	220	15.781	16.043	13.668	16.09

HWT2	220	7.013	5.882	6.114	6.609
IBA1	110	35.339	33.822	30.626	35.335
IBA2	220	19.113	18.622	16.928	19.112
IZBI	110	21.993	20.705	19.051	21.732
IZG1	110	40.474	39.714	35.033	40.588
JAS1	110	14.612	14.767	12.656	14.79
JAS2	220	20.296	19.804	17.571	20.184
KAB2	220	16.362	15.808	14.521	16.254
KAB5	500	6.413	6.456	5.547	6.464
KHE1	110	40.07	39.043	34.697	44.601
KHN1	110	52.488	53.763	57.105	54.74
KLX1	110	42.668	36.603	37.00	40.84
KLX2	220	19.003	18.317	16.741	18.99
KSL2	220	4.199	3.331	3.665	3.945
KUK1	110	50.91	53.579	44.093	52.663
LOM1	110	40.793	35.265	35.36	39.067
MAN1	110	3.06	2.929	2.652	3.02
MAR1-B1	110	11.157	11.405	9.699	11.406
MAR2	220	9.076	7.747	7.901	8.582
MHD1	110	37.462	34.735	32.434	36.724
MHD2	220	13.663	13.897	11.835	13.934
MIN1	110	2.284	2.131	2.006	2.321
MRK2	220	15.659	16.067	13.562	16.078
MRK5	500	7.203	7.098	6.219	7.167

MSH2	220	7.694	7.525	6.568	7.642
MUG	110	36.278	32.704	31.423	35.018
MWP2	220	10.486	11.11	9.014	11.007
MWP500	500	12.351	13.302	10.463	12.976
MWT2	220	6.337	6.127	5.471	6.253
NHAS1	110	11.687	12.477	10.134	12.377
NHAS2	220	10.103	8.938	8.778	9.668
NHLF2	220	4.965	3.84	4.342	4.654
OBD2	220	3.593	2.931	3.104	3.392
OHAS1	110	11.323	11.916	9.818	11.838
OMD1	110	36.104	32.882	31.265	35.018
ORBK1	110	1.24	1.242	1.082	1.251
RBK2	220	12.087	11.891	11.703	11.907
RNK2	220	10.492	10.533	9.00	10.523
ROS2	220	19.424	21.525	16.502	21.345
SHD2	220	3.317	3.015	2.887	3.199
SHG1	110	37.755	33.735	32.715	36.363
SHK2	220	6.478	4.913	5.669	6.051
SHN2	220	9.046	7.591	7.915	8.658
SNG2	220	9.197	7.886	8.011	8.705
SNJ1	110	10.607	12.518	10.004	11.674
SNJ2	220	8.963	7.513	7.836	8.449
SNP1	110	19.785	33.806	22.375	26.447
SOB1-B1	110	13.151	11.969	11.391	12.73

SOB2	220	17.828	17.366	15.638	17.861
TND2	220	8.435	7.927	7.211	8.242
UMR2	220	6.066	5.474	5.214	5.854
UTP2	220	5.492	4.324	4.799	5.15
WHL2	220	1.433	1.177	1.241	1.345
WWA2	220	2.452	1.978	2.123	2.287
ZBD2	220	2.293	1.823	1.984	2.157

From table 4.2 :

- First thing to be notice here is that the highest value is 64.464 KA for line-to-ground faults.
- The second observation is that for some of these buses, the L-G and L-L-G fault currents are greater than the 3-phase fault current these fields are highlighted with yellow in the table 4.2 .

4.6 Comparison Between Results and Existing Circuit Breaker Ratings

In this section, the calculated 3-phase fault currents are compared against circuit breaker ratings as provided by the Sudanese electricity transmission company Comparison is done at table 4.3.

Table 4.3 Comparison between calculated 3-phase fault currents and circuit breaker rating

Bus name	**Rated KV**	**3-phase fault (KA)**	**Existing circuit breaker rating (KA)**
AFR1	110	24.204	31.5*
ARO1	220	3.552	31.5*

ATB2	220	9.181	40
ATB5	500	4.739	31.5
BAG1	110	10.036	31.5
BBN2	220	1.322	31.5*
BNT1	110	37.093	31.5
DBE2	220	3.558	31.5*
DBT2	220	2.682	31.5*
DEB2	220	2.823	31.5
DON2	220	3.615	40
FAO2	110	2.719	25
FAR1	110	15.938	31.5
FRZ2	220	15.86	31.5
FUL2	220	1.622	31.5*
GAD1	110	9.830	31.5
GAD2	220	19.172	40
GAM1	110	20.949	31.5
GAM2	220	17.449	31.5
GDF1	110	5.017	40
GDF2	220	6.665	40
GER2	220	15.806	31.5
GND1	110	8.988	31.5*
GRB2	220	6.339	40
GRB69	66	41.33	40
HAG1	110	4.924	31.5
HUD	220	15.781	31.5*
HWT2	220	7.013	40
IBA1	110	35.339	31.5
IBA2	220	19.113	40
IZBI	110	21.993	31.5*

IZG1	110	40.474	31.5
JAS1	110	14.612	31.5
JAS2	220	20.296	40
KAB2	220	16.362	40
KAB5	500	6.413	31.5
KHE1	110	40.07	40
KHN1	110	52.488	40
KLX1	110	42.668	40
KLX2	220	19.003	40
KSL2	220	4.199	40
KUK1	110	50.91	31.5
LOM1	110	40.793	40
MAN1	110	3.06	31.5
MAR1-B1	110	11.157	31.5
MAR2	220	9.076	40
MHD1	110	37.462	31.5
MHD2	220	13.663	31.5
MIN1	110	2.284	31.5*
MRK2	220	15.659	40
MRK5	500	7.203	31.5
MSH2	220	7.694	40
MUG	110	36.278	31.5
MWP2	220	10.486	40
MWP500	500	12.351	31.5
MWT2	220	6.337	40
NHAS1	110	11.687	31.5*
NHAS2	220	10.103	31.5*
NHLF2	220	4.965	31.5*
OBD2	220	3.593	40

OHAS1	110	11.323	31.5*
OMD1	110	36.104	31.5*
ORBK1	110	1.24	31.5*
RBK2	220	12.541	40
RNK2	220	10.492	40
ROS2	220	19.424	40
SHD2	220	3.317	40
SHG1	110	37.755	40
SHK2	220	6.478	40
SHN2	220	9.046	31.5*
SNG2	220	9.197	40
SNJ1	110	10.607	31.5
SNJ2	220	8.963	40
SNP1	110	19.785	31.5
SOB1-B1	110	13.151	31.5*
SOB2	220	17.828	31.5*
TND2	220	8.435	40
UMR2	220	6.066	40
UTP2	220	5.492	31.5*
WHL2	220	1.433	31.5*
WWA2	220	2.452	31.5*
ZBD2	220	2.293	31.5*

4.6.1 Discussion and Results

From table 4.3 :

- This table shows that for almost busses the fault level is below the circuit breaker rating except at eleven buses (highlighted in blue) in the table 4.3 .

- In some buses the fault level is close to circuit breaker rating, these breakers work properly but in case of network extension (which exactly what is happening now in the national grid) the fault level may exceed the circuit breaker rating, attention must be given to these buses. These buses are highlighted in green in table 4.3 above and they are four buses.
- There was one bus exceeded 50% of circuit-breaker rating which is highlighted in red.
- *This value is assumed because the real value couldn’t be supplied

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusions

By the end of the project, the objectives has been achieved, short-circuit levels at all buses were calculated successfully and the obtained results were reasonable and realistic. Calculated currents were compared with the excising circuit breaker ratings and all currents were lower than associated circuit breaker rating except at twelve buses that exceeded the circuit breaker ratings. Calculations were made according to the IEC 60909 standard using ETAP 16.0 program by constructing the one line diagram and entering network data.

5.2 Recommendations

Circuit breakers at KUK1 should be replaced as soon as possible by 60 KA ones or even larger to cope with extensions of the network.

Apply techniques to limit short circuit currents. These techniques are decided into two categories:

1. Limitation of short-circuit currents in power system operation. These techniques include:
    - Substation splitting and use of circuit-breaker auto closing.
    - Network splitting and reduced system parallelism
    - Decreasing short-circuit fault clearance time.
    - De-loading circuits.
2. Limitation of short-circuit currents in power design and planning. These techniques include:

- Specifying higher leakage impedance for new transformers.
- Upgrading to higher nominal system voltage levels
- Use of short-circuit fault current limiters. [4]

Each one of these methods has its merits and drawbacks, so the advantages and disadvantages of each method should be weighed against each other to achieve the optimum way to limit fault currents.

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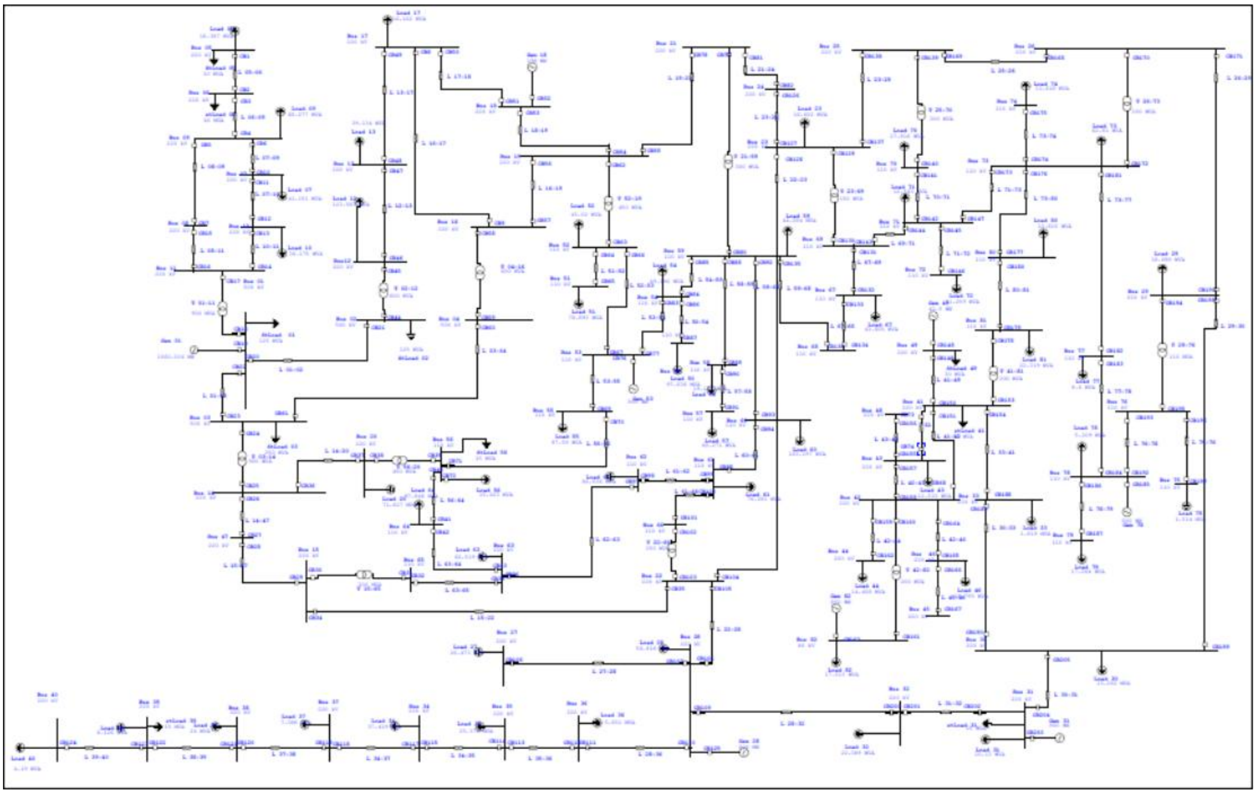
APPPENDIX(A)

Single Line Diagram of Sudanese National Grid



APPPENDIX(B)

System Data

B.1 Bus Data:

Bus No.	Bus Name	Rated KV
1	MWP500	500
2	ATB5	500
3	MRK5	500
4	KAB5	500
5	WHL2	220
6	WWA2	220
7	DEB2-B1	220
8	DEB2-B2	220
9	DON2	220
10	MWT2	220
11	MWP2	220
12	ATB2	220
13	SHN2	220
14	MRK2	220
15	GAM2	220
16	KAB2	220
17	FRZ2	220
18	GER2	220
19	IBA2	220
20	MHD2	220
21	KLX2	220
22	JAS2	220

23	GAD2	220
24	SOB2	220
25	NHAS2	220
26	MAR2	220
27	MSH2	220
28	RBK2	220
29	SNJ2	220
30	SNG2	220
31	ROS2	220
32	RNK2	220
33	HWT2	220
34	OBD2	220
35	UMR2	220
36	TND2	220
37	DBT2	220
38	ZBD2	220
39	FUL2	220
40	BBN2	220
41	GDF2	220
42	GRB2	220
43	SHK2	220
44	NHLF2	220
45	ARO2	220
46	KSL2	220
47	HUD	220
48	UTP2	220
49	SHD2	220
50	KHE1	110
51	IZB1	110

52	IBA1	110
53	KHN1	110
54	KUK1	110
55	IZG1	110
56	MHD1	110
57	FAR1	110
58	AFR1	110
59	KLX1	110
60	LOM1	110
61	SHG1	110
62	MUG	110
63	BNT1	110
64	OMD1	110
65	GAM1	110
66	JAS1	110
67	BAG1	110
68	SOB1-B2	110
69	GAD1-B2	110
70	NHAS1	110
71	OHAS1	110
72	GND1	110
73	MAR1-B1	110
74	MAN1	110
75	ORBK1	110
76	SNJ1	110
77	HAG1	110
78	SNP1	110
79	MIN1	110
80	FAO1	110

81	GDF1	110
82	GRB66	66

B.2 Transformer Data :

Name	KV Primary	KV Secondary	Rated MVA	R pu	X pu	F Hz	Tap ratio
TR NHAS	220	110	300	0	0.1534	50	0.905
TR KLX	110	220	300	0	0.1788	50	0.922
TR IBA	110	220	450	0	0.2895	50	0.905
TR ATB	220	500	600	0	0.2360	50	0905
TR KAB	220	500	600	0	0.3360	50	0.915
TR MRK	500	220	900	0	0.5040	50	0.911
TR GDF	220	110	200	0	0.2400	50	0.975
TR GRB	220	66	200	0	0.2506	50	0.905
TR MAR	220	110	200	0	0.1409	50	0.918
TR GAD	110	220	150	0	0.2010	50	0.905
TR SNJ	220	110	110	0	0.1567	50	0.945

TR MHD	110	220	450	0	0.3801	50	0.975
TR GAM	220	110	300	0	0.2574	50	0.925
TR MWP	500	220	900	0	0.2194	50	0.967
TR JAS	220	110	150	0	0.1300	50	0.913