LOAD FLOW, LARGEST MOTOR STARTING, SHORT CIRCUIT & PROTECTION RELAY COORDINATION IN GAS COMPRESSOR STATION

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RESEARCH REPORT SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF ENGINEERING (POWER SYSTEMS)

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ABSTRACT

The demand for oil and gas increases every year due to the immense development the world is currently undergoing. Oil and gas operating companies need to come up with innovative and optimistic design for the facilities to extract and deliver the oil and gas from the earth's crust, processing and delivering to the user. Thus, having a reliable and robust power system design for the compressor station is vital. The main objective of this research is to perform load flow, largest motor starting, short circuit studies and relay protection coordination for the compressor station. The studies are performed using ETAP Power Systems Software. Based on the load flow studies performed, all the equipment steady state loading and voltage deviation is within the acceptable range. The largest motor starting study is performed to investigate and to confirm should the direct on-line method is practical for starting the largest motor to the system transient performance. From the motor starting study performed, a direct online starting method is sufficient to start the largest motor and the voltage drop occurs within the standard range. The short circuit studies were able to specify the maximum short circuit current all the high voltage and low voltage equipment in the system are required to withstand during a fault prior to tripping by the protection system. The final studies is the relay discrimination studies that showing how the sequence of response by relays accordingly to the desired setting. The results of the studies performed will be useful for electrical consultants to design an optimized, reliable and robust electrical network on compressor station.

[LOAD FLOW, LARGEST MOTOR STARTING, SHORT CIRCUIT & PROTECTION RELAY COORDINATION IN GAS COMPRESSOR STATION]

ABSTRAK

Permintaan bagi minyak dan gas meningkat setiap tahun disebabkan oleh perkembangan pesat yang di alami dunia. Syarikat-syarikat minyak dan gas perlu inovatif dan optimistik dalam mereka bentuk kemudahan untuk mengeluarkan, memproses dan menghantar minyak dan gas dari kerak bumi. Oleh itu, mempunyai reka bentuk sistem kuasa yang boleh dipercayai dan mantap untuk platform miyak dan gas luar pesisir pantai adalah sangat penting. Objektif utama kajian ini adalah untuk melaksanakan analisa aliran kuasa, analisa permulaan motor terbesar, analisa litar pintas dan analisa koordinasi geganti untuk sebuah stesen gas pemampat. Kajian dilakukan menggunakan ETAP Power Systems Software. Berdasarkan analisa aliran kuasa dilaksanakan, semua peralatan elektrik dan voltan sisihan terletak dalam julat yang boleh diterima. Kajian permulaan motor terbesar dilakukan untuk menyiasat dan memastikan kaedah sambungan secara terus adalah praktikal untuk memulakan motor terbesar kepada sistem kuasa tersebut. Dari permulaan motor terbesar yang dilakukan, kaedah sambungan secara langsung sudah mencukupi untuk memulakan motor terbesar dan voltan jatuh di dalam ruangan piawai. Kajian litar pintas dapat menentukan litar pintas maksimum semua peralatan elektrik voltan tinggi dan voltan rendah dalam sistem dikehendaki menahan semasa litar pintas berlaku sebelum “tripping” oleh sistem perlindungan. Akhir sekali, analisa koordinasi geganti yang menunjukan urutan tindak balas oleh geganti menuruti penetapan yang di kehendaki. Keputusan kajian yang dilakukan akan berguna untuk perunding elektrik untuk mereka bentuk rangkaian elektrik yang optimum, dipercayai dan mantap di stesen gas pemampat.

ACKNOWLEDGEMENTS

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LIST OF SYMBOLS AND ABBREVIATIONS

kVA	:	Kilo-volt Ampere
kW	:	Kilo-Watt
kVar	:	Kilo-volt Ampere Reactive
kA	:	Kilo-Ampere
kV	:	Kilo-Volt
V	:	Volt
A	:	Ampere

CHAPTER 1: INTRODUCTION

1.1 Background

Fuel gas is one of the ordinary sources of energy in a physical gaseous form. Fuel gas is composed from hydrocarbons. The demand on this source energy is huge and rapidly because its selling price is economy compare to fuel oil. Figure 1 shows the statistics the prime energy consumption as reported by International Energy Agency 2014 claimed Malaysia has 43% usage on the natural gas (another type of fuel gas) for generating the electricity for local commercial and local residential facilities.

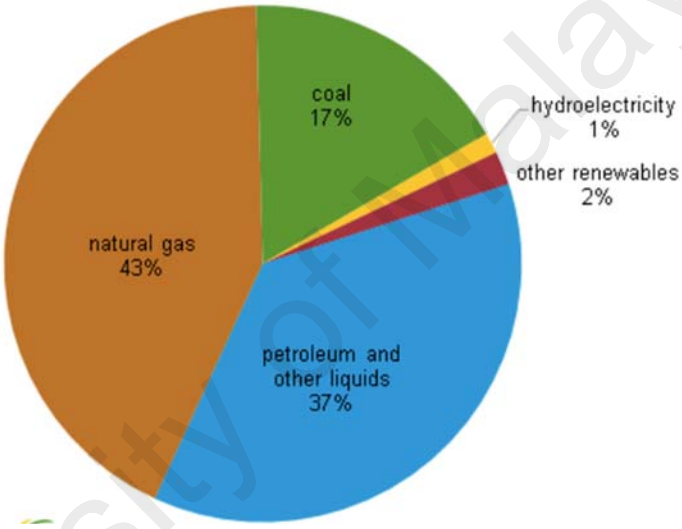

Figure 1.1: Malaysia primary energy consumption

As shown in figure 2, fuel gas can be readily transmitted and distributed through pipes from the point of origin directly to the place of distribution. Primarily, the fuel gas in the natural gas form, and secondary in chemically process stages it can be separated to Hydrogen, propane, methane, coal gas, water gas, blast furnace gas, coke oven gas and compressed natural gas.

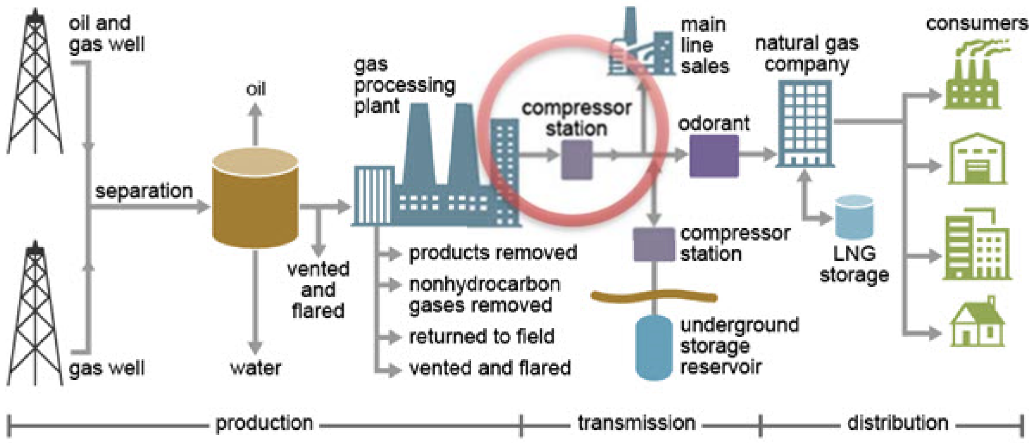

Figure 1.2: Natural gas production and distribution

A compressor station is a requirement facility to transport the process natural gas in the long distance from one location to another location. The transport gas that is natural gas will be transported through gas pipeline need to be constantly pressurized at interval 65 kilometers to 160 kilometers. The requirement to have a compressor gas station is not just on the to achieve the constant pressurized but its also depends on the factor of frequent elevation changes will also require more compressor gas station.

In ensuring the effective operation in pumping the receiving natural gas that entering the compressor gas station, a motor running compressor is selected as its prime because of its robustness as compare to mechanical rotating gas turbine and steam turbine.

As to design a reliable electrical system, an optimum power system studies such as short circuit analysis, load flow analysis, largest motor starting analysis and protection coordination studies are required to be performed. The power system studies must be conducted since every facility will be having its on maximum demand and load characteristics especially in dynamic load such as asynchronous motor with compressor pump application.

The required type of power system studies depends on the size scale and scope of the project requirement. Typically for the compressor gas station that handled only 2000 MMSCFD will only need these following four (4) power system studies:

- Load Flow Studies
- Largest Motor Starting Studies
- Short Circuit Studies
- Protection Coordination Studies

1.2 Problem Statement

This compressor gas station is design to handle an output of 2000 MMSCFD fuel gas during operation. This fuel gas will be compressed and transmitted to any desired location through gas pipeline. Therefore, the compressor station will ensure the gas delivery pressure and supply requirements can be satisfied.

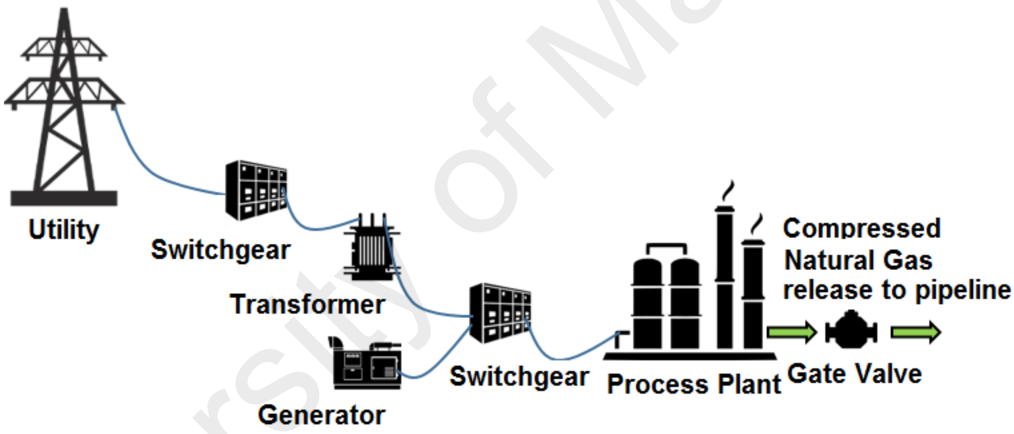

Figure 1.3: Electrical and process system arrangement

To achieve the design requirements the electrical and process facility arrangement should be as in Figure 1.3, there would be one (1) gas compressor trains assembled (within process plant). The gas compressor train consists of typical auxiliary load and the largest load connected to Low Voltage switchboard.

Within this study, the gas compressor station will be powered by incoming utility 11kV fed to switchgear and further stepped down from 11kV to 0.433kV to supply various loads. There is one (1) 415V low voltage switchboards and it will be having its own gas engine driven emergency generator.

The electrical system studies such as load flow studies, largest motor starting studies, short circuit studies and protection coordination studies are fundamental requisite to be performed for it to be able to provide input to the electrical designers. Load flow studies are required to identify system performance with regards to voltage profile, equipment capacity and power factor at steady state. The largest motor starting study is required to select the starting method of the largest motor and as well to examine the electrical system behavior and to determine voltage dip on busbars/motor terminals during starting of largest motor. Short circuit studies are required to examine the maximum short circuit current at various switchboards during fault condition and also to identify the adequacy of the equipment under worst-case operation when subjected to onerous conditions. Protection relay studies are required to carry out protection relay coordination study for overcurrent (OC)/ earthfault (EF) relays by plotting the Time Current Curves (TCC).

1.3 Objectives

The objectives of this project are:

1. To perform load flow study, motor starting study and short circuit study and analyse the electrical network performance based on ETAP simulation results
2. To conduct protection relay coordination and propose optimum relay settings

1.4 Scope of research

The scope of this research will be focusing in load flow studies, largest motor starting studies, short circuit studies and protection coordination relay studies for the gas compressor station. The equipment sizing such as generator, transformer, switchboard and uninterruptible power supply (UPS) will be sizing based on certain basis and assumption, it will not be covered within this research project. Recommendation for power system improvements based on the simulations will be provided as an outcome of this research.

1.5 Research project outline

This report is divided into five (5) chapters as per following:

Chapter 1: Introduction – Within this chapter, the background of the research is discussed and the research objectives and scope are described.

Chapter 2: Literature Review - Within this chapter, related research materials and power system studies would be summarized and discussed.

Chapter 3 – Methodology - Within this chapter, the technique of simulation being modeled in ETAP software is explained. Standard generic equipment parameter required for the simulation will be shown and the scenarios of the simulations performed for each study will be explained.

Chapter 4: Results & Discussions – Within this chapter, the results obtained from the load flow studies, largest motor studies, short circuit studies and protection coordination studies will be discussed.

Chapter 5: Conclusion – Within this chapter, the overall research will be concluded.

CHAPTER 2: LITERATURE REVIEW

2.1 Electrical system for gas compressor station

Compressor gas station is a platform for a gas transit to normalize its pressure accordingly. Due to long distance gas travel through uneven terrain and outdoor environmentally expose to the ambient temperature, the travel gas will have pressure drop and increase of the temperature. The need to have gas compressor station is compulsory. To have this gas be reset to its desires temperature and pressure, the main system is to have a compressor and it's auxiliary such as gas cooler to ensure the reliability of the system to be running without any downtime, an electrical system with reliable design is deemed. The electrical system should include diesel generator as back-up power in case loss of utility supply, switchgear for distribution of power, transformer for change the nominal voltage based on equipment voltage rating and cable for conducting the current.

2.2 Load flow studies

In power engineering, the power-flow study, or load-flow study, is a numerical analysis of the flow of electric power in an interconnected system. A power-flow study usually uses simplified notation such as an one-line diagram and per-unit system, and focuses on various aspects of AC power parameters, such as voltages, voltage angles, real power and reactive power. It analyzes the power systems in normal steady-state operation.

Power-flow or load-flow studies are important for planning future expansion of power systems as well as in determining the best operation of existing systems. The principal information obtained from the power-flow study is the magnitude and phase angle of the voltage at each bus, and the real and reactive power flowing in each line.

As based on Malaysia oil and gas industries standards, the acceptable steady state voltage range of the system shall be maintained at +/- 5% of the nominal voltage and the steady state frequency deviation should be maintained at +/- 2% (IEC 60038).

The load flow studies will also analyze to determine the real and reactive power flow in the system, transformer tap settings and also generator excitation set points. Generally the load flow study will analyze the system performance for a given load and generating capacity during steady state stage.

2.2.1 Newthon Raphson Method Load Flow Algorithm

$$V_k e^{-j\theta_k} \sum_{m=1}^{N} (G_{km} + jB_{km}) V_m e^{j\theta_m} = P_{\mathrm{NET}k} - jQ_{\mathrm{NET}k}, \qquad k = 1, \cdots, N$$

where

V_k	voltage magnitude at node k
θ_k	voltage angle at node k
$G_{km} + jB_{km}$	element of nodal admittance matrix
$P_{\mathrm{NET}k}$, $Q_{\mathrm{NET}k}$	net real and reactive power entering node k.

Equation 2.1: Newthon Raphson Method Load Flow Algorithm

As refer to Equation 2.1, it represents the network in the optimal power equation that is used in load flow studies. It can be seen there are four (4) variables, which are P_{NETk}, Q_{NET}, V_k and θ_k. The bus in load flow study can be categorized into three (3) types as per following:

a. Slack Bus: Which also known as reference bus. Known parameters are voltage magnitude V_k and voltage angle θ_k and the unknown are reactive power Q and active power P that need to be solved.
b. PQ Bus: Which also known as load bus. It's vice versa from the Slack Bus which, known parameters are reactive power Q and active power P and the unknown are voltage magnitude V_k and voltage angle θ_k that need to be solved.
c. PV Bus: Which also known as generator bus. Known parameters are voltage magnitude V_k and active power P and the unknown are reactive power Q and voltage angle θ_k that need to be solved.

Method of solving the unknown parameters can be achieved with the Equation 2.1 by partial derivatives using Jacobian Matrix. This Newton Raphson Method will be repeated until the value of unknown has converged and achieved.

2.3 Motor starting studies

When large motor needed and installed in the industrial and large commercial systems, the system will be having unwanted consequences on the performance and surrounding equipment.

The inrush starting current or locked rotor current to start the motor is several times which is 6-7 times higher of it full rated load current. The consequences neglecting this study can result in:

a. Nuisance tripping of protection breakers.
b. Excessive running currents.
c. Voltage drop at Motor terminal and at its dedicated tie in switchgear.
d. Triggering voltage relays.
e. Low starting torques resulting in a failure to start.
f. Stalling of other running motors connected to the power system.
g. Equipment damage of heaters, power supplies and other electrical gear.
h. Computer and control systems rebooting as their low voltage detectors trigger.

A need to perform this study whenever the motor power rating is exceeds 30% of the transformer base kVA rating that supply connected directly from the utility or when the motor power rating exceeds 10% of the generator kVA rating that connected as a prime independent generation supply to the system. Once need to aware that the voltage drop at the terminal should not more than 80% of the nominal voltage as to make sure adequate starting torque (IEEE, 1980).

Table 2.1 indicates the required voltage percentage at the system during motor starting to have a robust system.

Table 2.1: Minimum required voltage at various location in the system during motor starting (IEEE, 1980)

Location	Minimum required voltage
Starting motor terminal	80%
Accelerating motor terminal	71%
AC contactor pick up	85%
DC contactor pick up	80%
Average contactor hold in	60-70%

As refer to cost constraint, the motor is started with direct on-line (DOL) but if the voltage drop in the system is higher, it is recommended to install a starter to reduce the locked rotor current during starting of the motor. As shown in Table 2.1, there are minimum required voltage at each stage/location in the system.

There are a few type of motor starter that can be used for example, such as per following:

a. Star delta starter
b. Soft starter
c. Autotransformer
d. Variable speed drive (VSD)

There are some factor on starter selection, which are as following:

a. Footprint area
b. Capital expenditure (Capex) and Operation expenditure (Opex)
c. Special Function (speed variables)

If the area of the starter to be installed is limited, autotransformer will not be suitable for the selection due to its bulky size as compare to others starter and if the selection is not just to reduce the locked rotor current but at the same time to control the speed of the motor, so the best starter for this criteria is variable speed drive. Frequently, most designer will choose star delta starter and soft starter because of its simplicity in installation and inexpensive on its Capex and Opex.

Within this research, only DOL will be used for the largest motor starting studies because the locked rotor current is 6-7 times of the motor rating current and this will contributes on the worst case scenario on the voltage impact during largest motor starting.

2.3.1 Direct on-line (DOL) starter

Direct on-line starter is the most common starter to be used in the industry due to its construction simplicity and inexpensive initial cost. Eventhough the motor can achieve its high starting torque but the severe voltage drop will occurs in the system (Patil & Porate, 2009). But sometimes, the direct on-line starter is not always can fit with all kind of loads because some of the loads are keen to have its rotor shaft to be gradually increase in speed to avoid any mechanical damage.

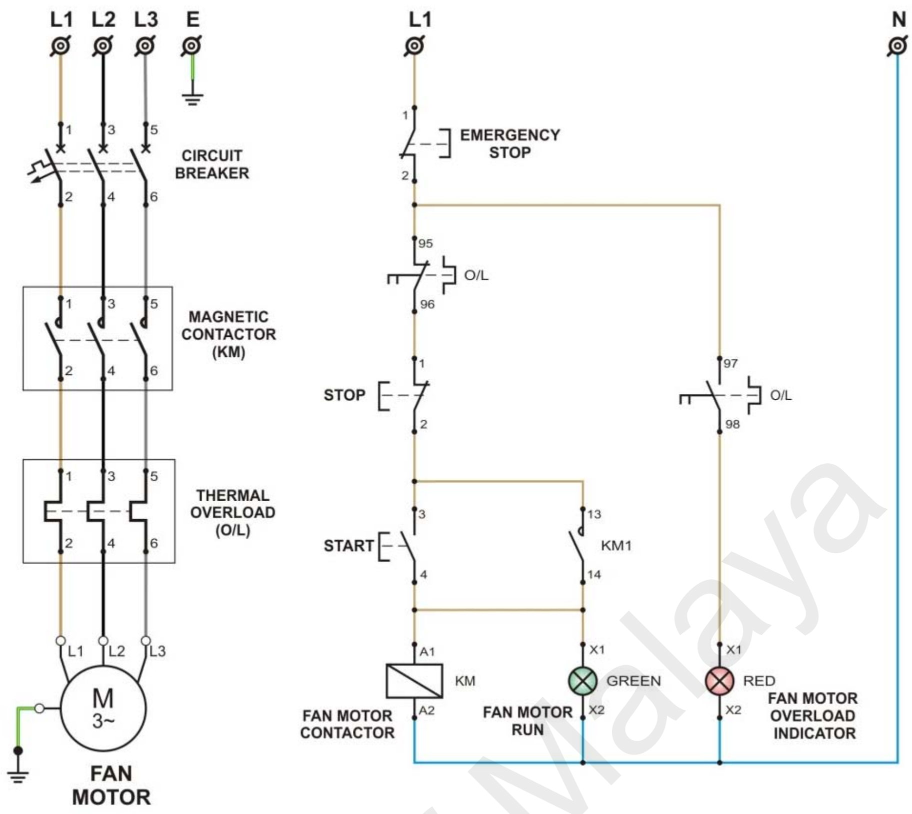

Figure 2.1: Schematic direct on-line 3 phase motor starter

Figure 2.1 shows the typical schematics of the direct on-line motor starter.

2.4 Short circuit studies

A short circuit is an electrical circuit that allows a current to travel along an unintended path from one phase to another different phase with each other or to the ground itself. A short circuit also dangerous to the equipment if the system could not isolate the fault within the shortest time possible. Following are the effects of short circuit current in a system (IEEE, 1980).

- Damaging excessive current flow in the system that can cause system and equipment failure.
- Result on voltage dip at faulted area could effect on other equipment operation.
- Result on transient and/on sustained overvoltage in the system.
- Result to hazardous to people at the vicinity.

In the short circuit studies, the minimum and maximum fault current value need to be determined in the system. With the maximum fault current value in the system, the selection of appropriate equipment which can withstand the amount of fault current before isolation and for protection coordination can be determined. With the minimum fault current value in the system, the satisfy grading margin and the stability of the protection coordination during the fault can be ensured (Parise & Member, 1993).

The following are the 4 (four) types fault in a system:

- Three phase fault.
- Single line to ground fault.
- Line to line fault.
- Double line to ground fault.

For this research, it is a common practice in the industry to simulate all type of fault to determine the highest value of fault current that may occur in the system.

Figure 2.2 shows the short circuit current parameters based on IEC 60909.

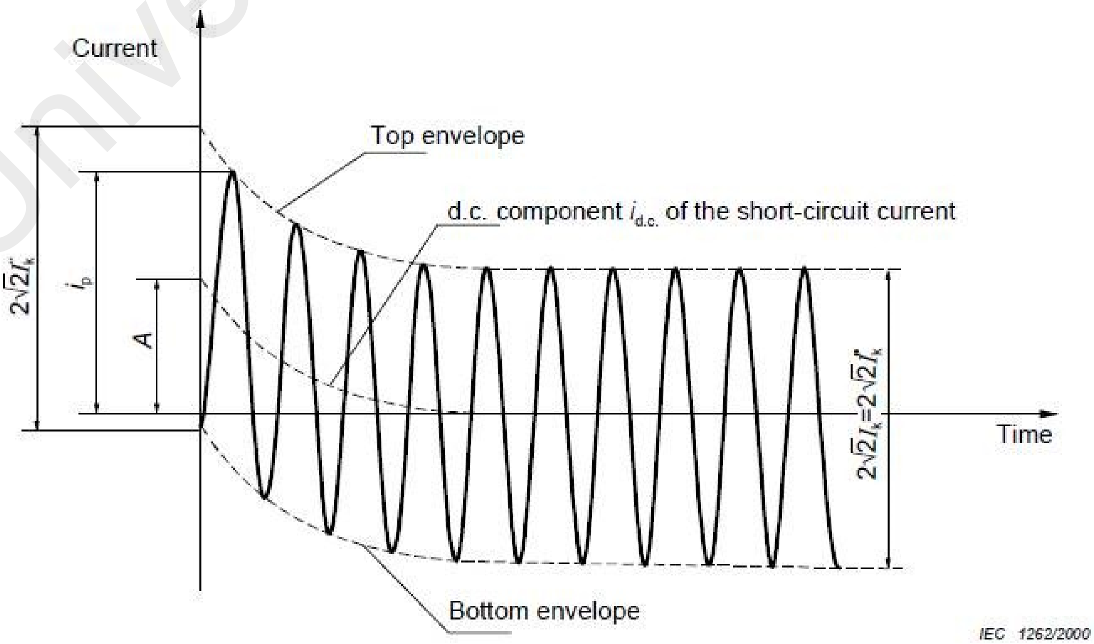

Figure 2.2: Short circuit current parameters based on IEC 60909

Following are the description of the parameters based on Figure 2.2:

a. **Initial symmetrical short circuit current, I_k"** is the instantaneous rms value of the symmetrical AC component of the fault current. This value of short circuit current is defined at the instant of the fault happening as the AC component of the fault decays especially for fault near to generators.

b. **Peak short circuit current, I_{peak}** is the maximum possible instantaneous fault current that will happen in the system based on system impedances (X/R) and the phase angles during the fault.

c. **Steady state short circuit current, I_k** is steady state short circuit current based on the system steady state impedances after the decay of the transient short circuit components.

d. **DC component of short circuit current, $i_{d.c}$** is the mean value between the upper and lower envelope curve of the short circuit current decaying from **initial value of the DC component, *A*** to zero.

Table 2.2 shows the voltage factor (c) as per IEC 60909, which will be considered in the calculation. The reason of including the voltage factor c is due to the following factors in an electrical power system studies:

a. System voltage variations at different locations.

b. Changing in taps of transformers.

c. Capacitance in the system being neglected in the short circuit current calculations.

d. Sub-transient action of generators and motors.

Table 2.2: Voltage factor, c based on IEC 60909

System Voltage	Voltage factor c for maximum short circuit current	Voltage factor c for minimum short circuit current
Low Voltage (100V to 1000V)	1.05 (for LV system with tolerance +6%) 1.1 (for LV system with tolerance +10%)	0.95
Medium Voltage (1000V to 35000V)	1.1	1.0
High Voltage (more than 35000V)		

2.5 Protection coordination relay studies

In power system, the operating should be at safe manner at all times, no matter how well the designed, the faults (short circuit) cannot be avoided. These faults will present risks to personnel (life), environment, assets and reputation. The arc is highly destructive at the point of fault. Even away from the point of fault, heavy fault current flowing from upstream conductors could cause damages if they continue for more than two seconds. As such protection is used to detect and disconnect elements of power system during fault.

In this research, the focus will be on protection system, which the abnormal condition such as overcurrent protection and earth fault protection.

In many cases, it is not feasible to protect against all hazards with a relay that response to a single power system quantity. An arrangement using several quantities is required.

In such cases, either configuration can be used:

- Several relays, each responding to single quantity
- A single relay containing several elements, each responding independently to different quantity

The operating characteristics of relay depends on the energizing quantities fed to it:

- Current
- Voltage
- Combination of current and voltage

From the current and voltage information, various types of relays have been developed. For example:

- Over current relay – current
- Over/Under voltage relay – voltage
- Directional relay - phase angle between voltage and current
- Distance relay – impedance computation from voltage and current

Figure 2.3 shows examples of the zones of protection. To facilitate the removal of disturbances, the power system is divided into 'protection zones' and relays are used to monitor the system parameters (current & voltage). If fault occurs inside the protection zone, the relay will operate to isolate the zone from the rest of the power system.

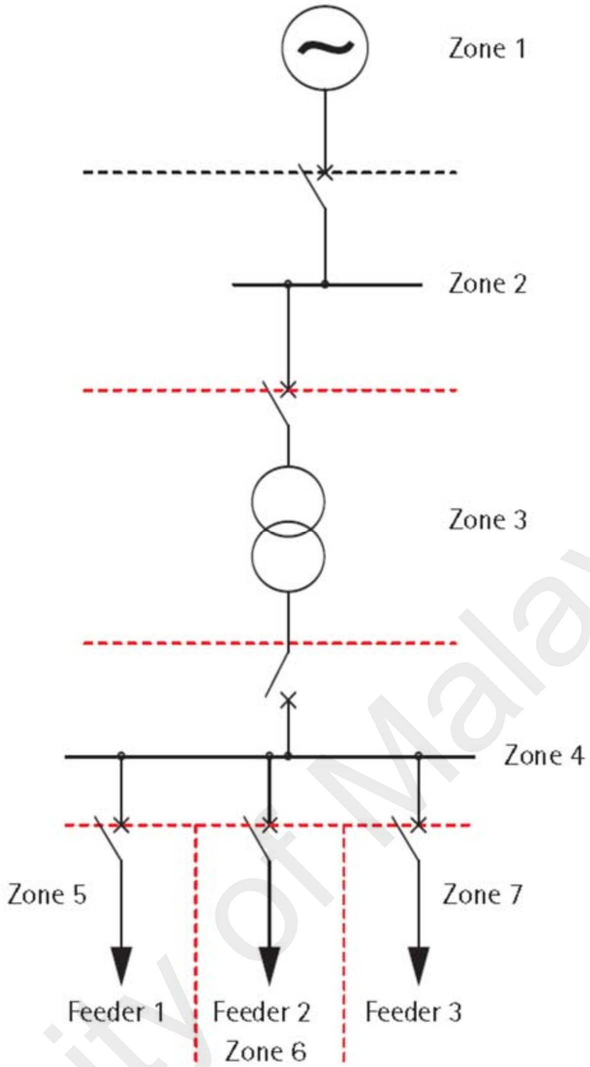

Figure 2.3: Zones of protection

Figure 2.4 shows how to achieve a correct design; both overlapping zones must cover the circuit breaker.

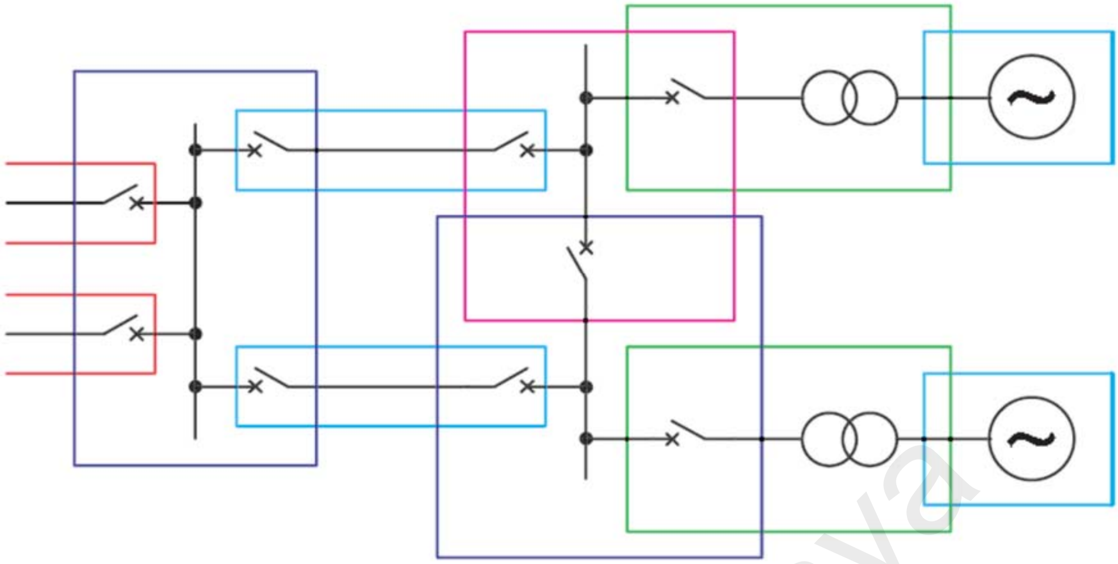

Figure 2.4: Overlapping of zones

It is important to have more than one primary protection system operating in parallel. In the event of failure or non-availability of the primary protection, some other means of fault isolation is required. This secondary system is referred to as 'back-up protection'.

In the event of fault, both the main and backup protection system will detect the fault simultaneously. However, the operation of backup protection must be delayed to ensure that the primary protection clears the fault first.

2.5.1 Overcurrent protection

Overcurrent (OC) protection is a protection against excessive current in the system or beyond the acceptable current rating of equipment. Short circuit is the type of overcurrent. There are several types of protection devices use for overcurrent protection such as fuse, molded case circuit breaker (MCCB), overcurrent relay and motor protection relay.

This research will use inverse definite minimum time (IDMT) overcurrent relay principals of grading. As refer to IEC 60255, Fig 2.5 shows the relay characteristics and Fig 2.6 shows the standard IDMT relay characteristics.

IDMT operation is define as the time of operation is inversely proportional to the fault current level and the actual characteristic is a function of both 'time' and 'current' settings. For a large variation in fault current between the two ends of the feeder, faster operating times can be achieved by the relays nearest to the source, where the fault level is the highest. The disadvantages of grading by time or current alone are overcome. The selection of overcurrent relay characteristics generally starts with selection of the correct characteristic to be used for each relay, followed by choice of the relay current settings.

Relay Characteristic	Equation (IEC 60255)
Standard Inverse (SI)	$t = TMS \times \frac{0.14}{I_r^{0.02} - 1}$
Very Inverse (VI)	$t = TMS \times \frac{13.5}{I_r - 1}$
Extremely Inverse (EI)	$t = TMS \times \frac{80}{I_r^2 - 1}$
Long time standard earth fault	$t = TMS \times \frac{120}{I_r - 1}$

Figure 2.5: Relay characteristics to IEC 60255

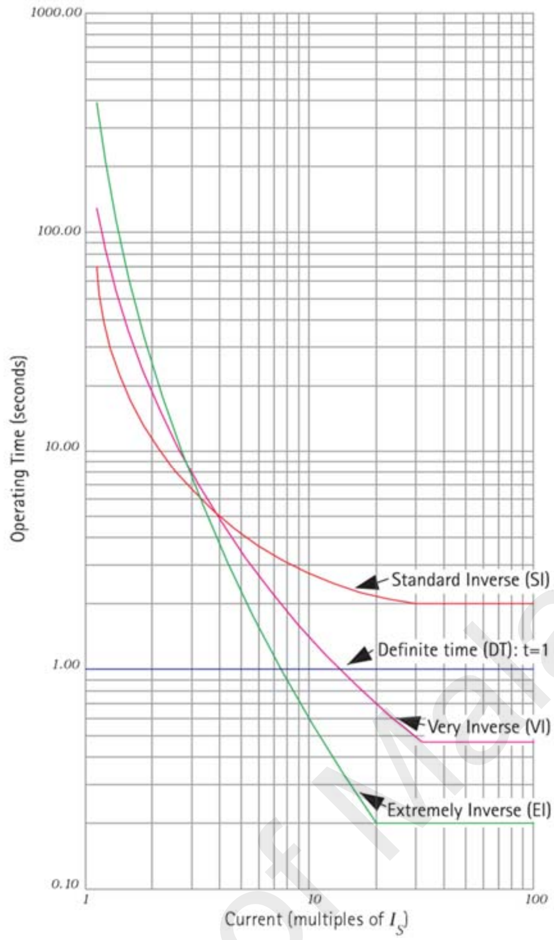

Figure 2.6: IDMT relay characteristics

The time for a relay to operate or trip depends on:

- Magnitude of fault current: How big the current is compared to the setting of plug setting multiplier (PSM).
- Plug or current setting (PS): Controls the current at which the relay starts to operate.
- Time multiplier setting (TMS): Controls the angle the moving contact needs to travel to complete the tripping process and hence the time of relay operation.

2.5.2 Earth fault protection

Under normal conditions, there is no earth fault (EF) current and the sum of the currents flowing in the phase and neutral conductors is zero. For that reason, the earth fault protection can have a very sensitive setting, independent of the load current.

During an earth fault, the fault current flows from the source, along the faulted conductors, into the fault and then returns through the earth path to the neutral of the source. For an A-phase fault, the A-phase current, $I_a = I_1 + I_2 + I_0$ and the current in the earth is $3I_0$ and the two currents are equal.

For the normal three-phase load or an unearthed three-phase fault in a three-wire system, $I_{k1} = I_a + I_b + I_c = 0$. For a two-phase fault, $I_a = 0$, $I_b = -I_c$ and $I_{k1} = 0$.

The range of earth fault currents and the two main types of protection are as shown in Table 2.3.

Table 2.3: Protection and setting for LV and MV system

<table>
<tr><th>System</th><th>Earthing</th><th colspan="2">Typical range of earth fault current</th><th>Protection & setting</th></tr>
<tr><td rowspan="2">LV (=<1kV)</td><td rowspan="2">Solid</td><td>Shock of poor insulation</td><td><1A</td><td>Earth leakage protection 30mA – 500mA</td></tr>
<tr><td>Bolted Fault</td><td>5kA – 50kA</td><td rowspan="3">Earth fault relay 5% - 20%</td></tr>
<tr><td rowspan="2">MV (>1kV – 36kV)</td><td>Solid</td><td colspan="2">5kA – 50kA</td></tr>
<tr><td>NER</td><td colspan="2">200A – 1600A</td></tr>
</table>

2.5.3 Current transformer (CT) and CT ratio

Current transformer is used for measurement of electric currents. When current in the circuit is too high to directly apply to measuring instruments, a current transformer produces a reduced current accurately proportional to the current in the circuit, which can be conveniently connected to measuring and recording instruments. Like any other transformer, a current transformer has a primary and secondary winding. CT ratio e.g. 400/5A or 400/1A.

2.5.4 Time current curve

Time current curve is a log scale graph with time at y-axis and current at x-axis that will plot behavior as shown in figure

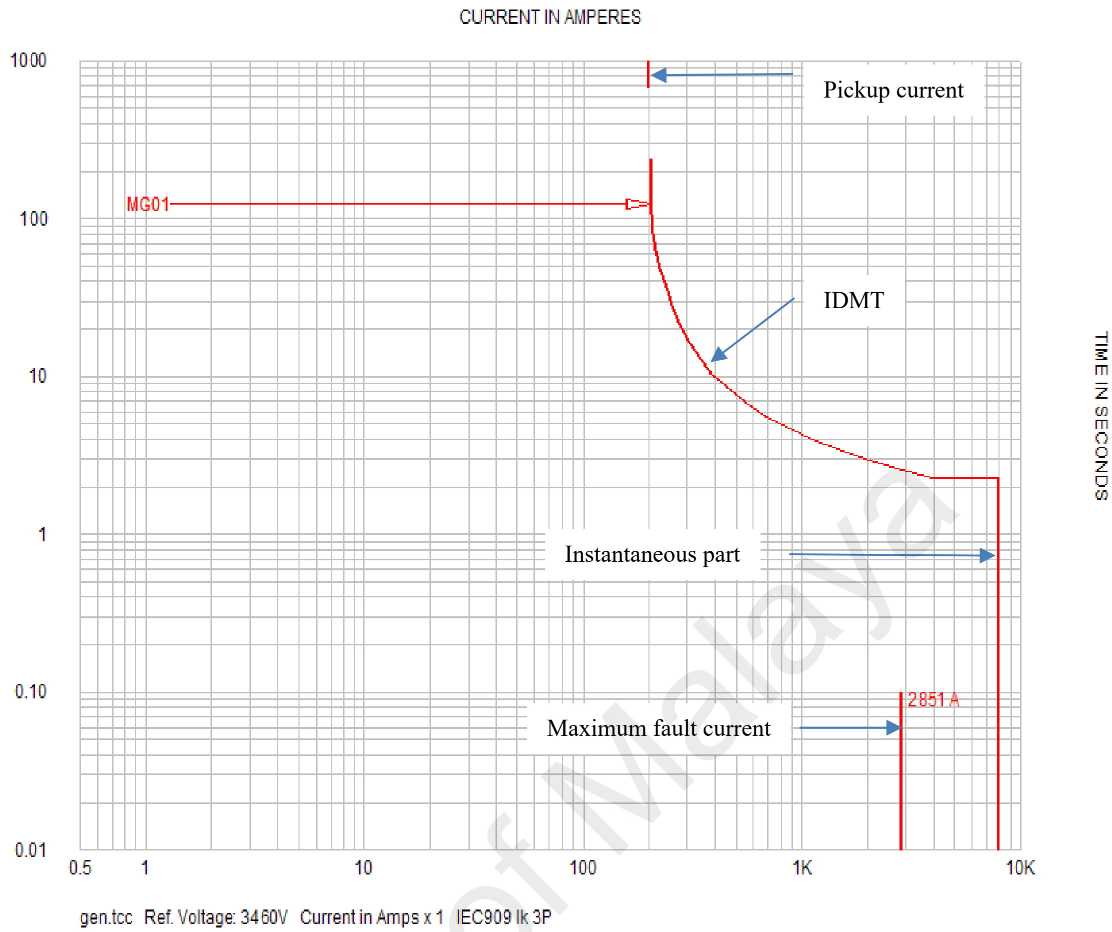

Figure 2.7: Time current curve

2.5.5 Pick up current

Pick up current function is to control minimum operating current that flow in the system.

E.g. CT ratio 400/5A

Pick up current setting is set as 0.5, therefore, pick up current = 200A at primary and 2.5A at secondary (which is pick up setting x CT ratio).

2.5.6 Time multiplier setting (TMS)

Time multiplier setting function is to control operating time where lower TMS will gives faster response.

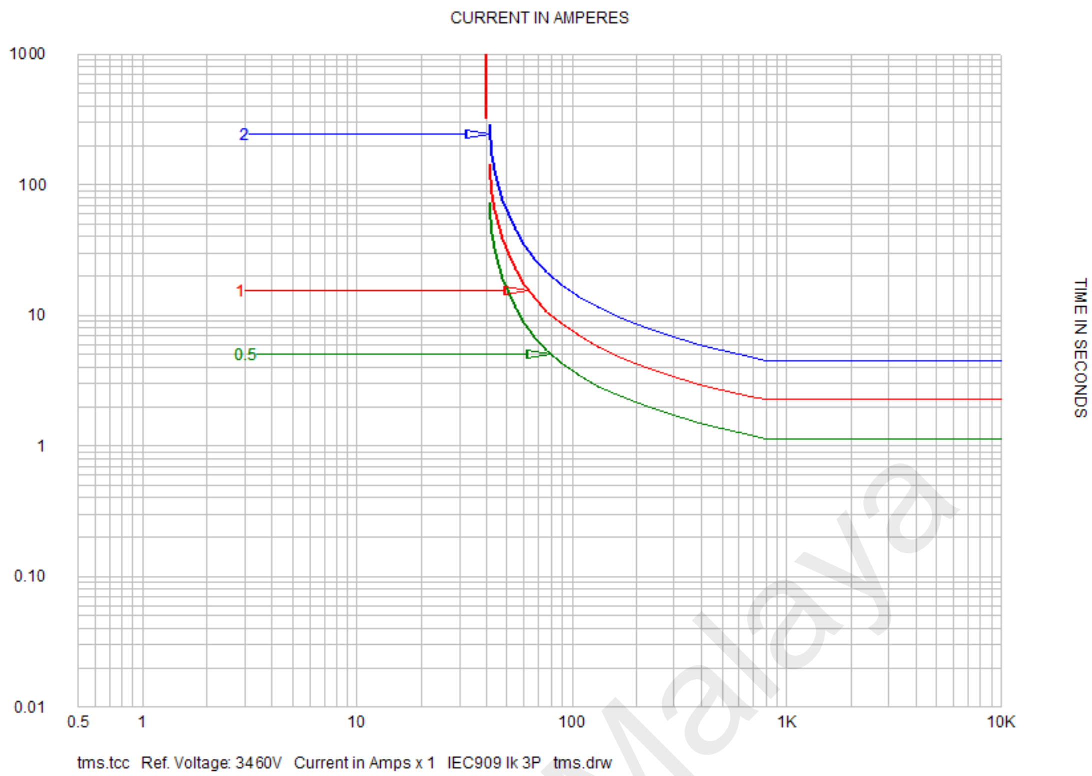

Figure 2.8: Time multiplier setting on IDMT curves

2.5.7 Principles of discrimination

In protection relay discrimination, only the nearest relay to the fault will operates to isolate the smallest possible area in the shortest time possible. This can be achieved by making each upstream relays slower than its downstream relay. Grading margin between 2 successive relays will be around 300ms as according to IEC 60909.

CHAPTER 3: METHODOLOGY

3.1 Compressor gas station load list analysis

The table 3.1 is a load list required to be installed within the Gas Compressor Station. These loads are based on the required gas specification which covers performance and safety of the system during operation and maintenance. Fitting to the design effectiveness, practicality as well as costing optimization, the load has been categorized into three (3) categories, which are Continuous, Intermittent and Standby. Continuous is defining as all loads that may continuously be required for normal operation, including lighting. Intermittent and spares is defining as the loads required for intermediate pumping, storage, loading etc. as well as with all electrical spares of electrically driven unit. Standby is defining as the loads required in emergencies only on those of normally but not running electrically driven units (e.g: pumps).

Therefore, the maximum running load and the peak load of the station can be calculated as below:

Maximum normal running load = (100% of all continuous loads) + (30% of all intermittent loads or largest individual intermittent load, whichever is higher)

Peak load = (100% of all continuous loads) + (30% of all intermittent loads or largest individual intermittent load, whichever is higher) + (10% of all standby loads or largest individual standby load, whichever is higher)

Table 3.1: Overall electrical load in the gas compressor station

Equipment Description	Voltage (V)	Phase	Motor Load Rating (kW)	Load Factor	Efficiency	Power Factor	Absorbed Load (kW)	Operating Load								
								Continuous			Intermittent			Standby		
								kW	kVA	kVAR	kW	kVA	kVAR	kW	kVA	kVAR
ENCLOSURE FAN - COMPRESSOR 1	415	3	5.60	0.90	0.85	0.73	5.04	5.93	8.12	5.55						
AIR INLET SCAVENGE MOTOR - COMPR. 1	415	3	5.60	0.90	0.85	0.73	5.04	5.93	8.12	5.55						
LUB OIL COOLER A - COMPRESSOR 1	415	3	5.60	0.90	0.85	0.73	5.04	5.93	8.12	5.55						
LUB OIL COOLER B - COMPRESSOR 1	415	3	5.60	0.90	0.85	0.73	5.04	5.93	8.12	5.55						
PRE/POST A.C. LUB OIL PUMP - COMPR. 1	415	3	7.50	0.70	0.85	0.73	5.25							6.18	8.46	5.78
STARTER MOTOR - COMPRESSOR 1	415	3	112.00	1.85	0.93	0.82	207.20							222.8	271.7	155.51
GAS COOLER FAN A COMPRESSOR 1	415	3	37.00	0.80	0.91	0.78	29.60	32.53	41.7	26.1						
GAS COOLER FAN B COMPRESSOR 1	415	3	37.00	0.80	0.91	0.78	29.60	32.53	41.7	26.1						
GAS COOLER FAN C COMPRESSOR 1	415	3	37.00	0.80	0.91	0.78	29.60				32.53	41.70	26.1			
GAS COOLER FAN D COMPRESSOR 1	415	3	37.00	0.80	0.91	0.78	29.60							32.53	41.70	26.10
VENT FAN 1A COMPRESSOR BUILDING 1	415	3	2.80	0.70	0.85	0.73	1.96							2.31	3.16	2.16
VENT FAN 1B COMPRESSOR BLDG 1	415	3	2.80	0.70	0.85	0.73	1.96							2.31	3.16	2.16
OVERHEAD CRANE AT COMPRESSOR BUILDING 1	415	3	11.50	0.70	0.85	0.73	8.05							9.47	12.97	8.87
ENCLOSURE FAN COMPRESSOR 2	415	3	5.60	0.90	0.85	0.73	5.04	5.93	8.12	5.55						
AIR INLET SCAVENGE MOTOR - COMPR. 2	415	3	5.60	0.90	0.85	0.73	5.04	5.93	8.12	5.55						

LUB OIL COOLER A - COMRPESSOR 2	415	3	5.60	0.90	0.85	0.73	5.04	5.93	8.12	5.55						
LUB OIL COOLER B - COMPRESSOR 2	415	3	5.60	0.90	0.85	0.73	5.04	5.93	8.12	5.55						
PRE/POST LUB OIL PUMP - COMP. 2	415	3	7.50	0.70	0.85	0.73	5.25							6.18	8.46	5.78
STARTER MOTOR - COMPRESSOR 2	415	3	112.00	1.85	0.93	0.82	207.20							222.8	271.7	155.51
GAS COOLER FAN A COMPRESSOR 2	415	3	37.00	0.80	0.91	0.78	29.60	32.53	41.70	26.10						
GAS COOLER FAN B COMPRESSOR 2	415	3	37.00	0.80	0.91	0.78	29.60	32.53	41.70	26.10						
GAS COOLER FAN C COMPRESSOR 2	415	3	37.00	0.80	0.91	0.78	29.60				32.53	41.70	26.10			
GAS COOLER FAN D COMPRESSOR 2	415	3	37.00	0.80	0.91	0.78	29.60							32.53	41.70	26.10
VENT FAN 2A COMPRESSOR BUILDING 2	415	3	2.80	0.70	0.85	0.73	1.96							2.31	3.16	2.16
VENT FAN 2B COMPRESSOR BLDG 2	415	3	2.80	0.70	0.85	0.73	1.96							2.31	3.16	2.16
OVERHEAD CRANE AT COMPRESSOR BUILDING 2	415	3	11.50	0.70	0.85	0.73	8.05							9.47	12.97	8.87
ENCLOSURE FAN - COMPRESSOR 3	415	3	5.60	0.90	0.85	0.73	5.04	5.93	8.12	5.55						
AIR INLET SCAVENGE MOTOR - COMPR. 3	415	3	5.60	0.90	0.85	0.73	5.04	5.93	8.12	5.55						
LUB OIL COOLER A - COMPRESSOR 3	415	3	5.60	0.90	0.85	0.73	5.04	5.93	8.12	5.55						
LUB OIL COOLER B - COMPRESSOR 3	415	3	5.60	0.90	0.85	0.73	5.04	5.93	8.12	5.55						
PRE/POST A.C. LUB OIL PUMP - COMPR. 3	415	3	7.50	0.70	0.85	0.73	5.25							6.18	8.46	5.78
STARTER MOTOR - COMPRESSOR 3	415	3	112.00	1.85	0.93	0.82	207.20							222.8	271.7	155.51
GAS COOLER FAN A COMPRESSOR 3	415	3	37.00	0.80	0.91	0.78	29.60	32.53	41.70	26.10						

GAS COOLER FAN B COMPRESSOR 3	415	3	37.00	0.80	0.91	0.78	29.60	32.53	41.70	26.10						
GAS COOLER FAN C COMPRESSOR 3	415	3	37.00	0.80	0.91	0.78	29.60				32.53	41.70	26.10			
GAS COOLER FAN D COMPRESSOR 3	415	3	37.00	0.80	0.91	0.78	29.60							32.53	41.70	26.10
VENT FAN 3A COMPRESSOR BUILDING 3	415	3	2.80	0.70	0.85	0.73	1.96							2.31	3.16	2.16
VENT FAN 3B COMPRESSOR BLDG 3	415	3	2.80	0.70	0.85	0.73	1.96							2.31	3.16	2.16
OVERHEAD CRANE AT COMPRESSOR BUILDING 3	415	3	11.50	0.70	0.85	0.73	8.05							9.47	12.97	8.87
AIR COMPRESSOR A	415	3	30.00	0.75	0.91	0.78	22.50	24.73	31.70	19.84						
AIR COMPRESSOR B	415	3	30.00	0.75	0.91	0.78	22.50				24.73	31.70	19.84			
FUEL GAS HEATER	415	3	30.00	0.50	0.95	0.98	15.00	15.79	16.11	3.21						
UNINTERRUPTIBLE POWER SUPPLY UPS-103	415	3	3.00	0.50	0.85	0.90	1.50	1.76	1.96	0.85						
UNINTERRUPTIBLE POWER SUPPLY UPS-104	415	3	3.00	0.50	0.85	0.90	1.50							1.76	1.96	0.85
UNINTERRUPTIBLE POWER SUPPLY BYPASS	415	3	3.00	0.50	0.85	0.90	1.50							1.76	1.96	0.85
BATTERY CHARGER BC-101	415	3	5.00	1.00	0.85	0.85	5.00	5.88	6.92	3.65						
BATTERY CHARGER BC-102	415	3	5.00	1.00	0.85	0.85	5.00				5.88	6.92	3.65			
IMPRESSED CURRENT BATTERY CHARGER	415	3	3.70	0.80	0.85	0.85	2.96	3.48	4.10	2.16						
120VDC BATTERY CHARGER BC-105	415	3	4.00	0.80	0.85	0.85	3.20				3.76	4.43	2.33			
120VDC BATTERY CHARGER BC-205	415	3	4.00	0.80	0.85	0.85	3.20				3.76	4.43	2.33			
120VDC BATTERY CHARGER BC-305	415	3	4.00	0.80	0.85	0.85	3.20				3.76	4.43	2.33			

YARD LIGHTING (PHOTO CELL CONTROLLED)	415	3	35.00	1.00	0.95	0.95	35.00	36.84	38.78	12.11						
PIPE RACK LIGHTING	415	3	3.00	1.00	0.95	0.95	3.00	3.16	3.32	1.04						
UTILITY GAS HEATER	415	3	4.00	0.50	0.95	0.95	2.00	2.11	2.22	0.69						
DRAIN PUMP	415	3	1.10	0.70	0.85	0.73	0.77				0.91	1.24	0.85			
APU RADIATOR FAN	415	3	30.00	0.75	0.91	0.78	22.50							24.73	31.70	19.84
AUX. BUILDING LOAD	415	3	56.26	0.70	0.85	0.95	39.38	46.33	48.77	15.23						
COMPRESSOR BUIDLING 1 LOAD	415	3	8.85	0.70	0.95	0.95	6.20	6.52	6.86	2.14						
COMPRESSOR BUIDLING 2 LOAD	415	3	8.85	0.70	0.95	0.95	6.20	6.52	6.86	2.14						
COMPRESSOR BUIDLING 3 LOAD	415	3	8.85	0.70	0.95	0.95	6.20	6.52	6.86	2.14						
GUARD HOUSE LOAD	240	1	0.63	0.70	0.80	0.80	0.44	0.55	0.69	0.41						
SWITCH HOUSE	240	1	0.76	0.50	0.85	0.95	0.38							0.45	0.47	0.15

Referring to Table 3.1 and Table 3.2, the maximum value of normal running operation load and peak load of the Gas Compressor Station is calculating as per below:

Maximum normal running load (kVA) = (100% of all continuous loads) + (30% of all intermittent loads or largest individual intermittent load, whichever is higher) = 522.84 kVA + (30% x 178.25 kVA) = 576.32 kVA.

Peak load (kVA) = (100% of all continuous loads) + (30% of all intermittent loads or intermittent largest load, whichever is higher) + (10% of all standby loads or largest individual standby load, whichever is higher) = 522.84 kVA + (30% x 178.25 kVA) + (10% x 1059.56) = 1761.06 kVA.

Table 3.2: Minimum amount of power required at the gas compressor station

Load Description	Total kVA	Total kW	Total kVar
Maximum normal running load	576.32	468.63	321.69
Peak load	682.28	554.18	384.03
10% margin for future growth	68.23	55.42	38.40
Minimum install power supply required	**750.50**	**609.59**	**422.44**

As shown in Table 3.2, the maximum normal running power required for Gas Compressor Station is 576.32kVA and the minimum generator size to be installed is 750 kVA. The nearest size available in the market is 1000kVA (depends on the manufacturer and project long lead item timeliness acceptance) or 800kW at power factor 0.8.

3.2 Electrical power system modeling

In this project, the power system is consists typically of generators, transformers, cables, bus bars, different auxiliary and main equipment as a load. All of these can be represented by equivalent circuits. The capital investment involved in a power system is so great that proper precautions must be taken to ensure that the equipment not only operates as efficient as possible but also protected from accidents, severe drop in voltage and loss of lives. Hence, the power system modelling and analysis must be carried out to achieve network reliability and sustainability.

Within this section, the power system modeling will be modeled in a ETAP Power System software platform by using all the parameters that are involved. The parameters involved will be explained in this section. Once the modeling has been completed, the same model will be used to perform the load flow analysis, motor starting analysis, short circuit analysis and protection relay coordination studies.

3.2.1 Utility 11kV modelling

The utility is modeled using Power Grid Editor and will be treated as infinite bus due to the large spinning reserve that it has. The required parameters need to be filled is shown in Figure 3.1.

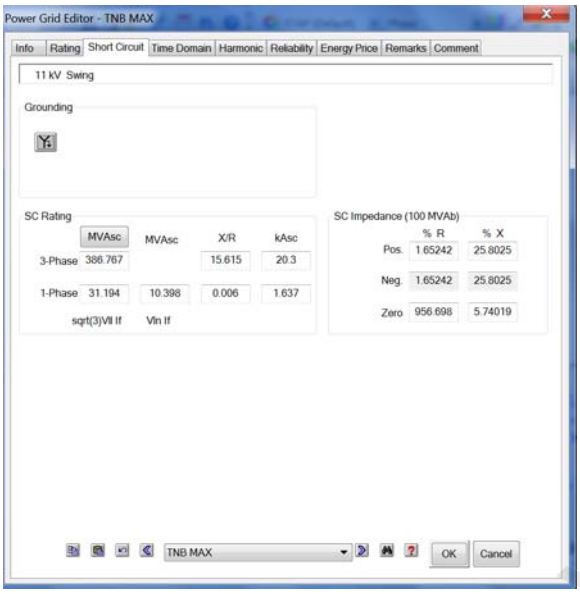

Figure 3.1: Modeling main incoming utility as power grid

Figure 3.1 shows the value of MVAsc is calculated based on the formula below;

MVAsc(3p)= 1.732 x kV (nominal voltage) x Isc(3p)

MVAsc(1p)= 1.732 x kV (nominal voltage) x Isc(1p)

3.2.2 Diesel engine generator modelling

The Diesel generator is modeled using Synchronous Generator Editor as shown in Figure 3.2 and Figure 3.3. The parameters are based from the standard industry manufacturer 100kVA with 0.85 power factor, rated kVA base; Sub transient X_d" = 12%, transient X_d' = 20% and steady state X_d = 22%.

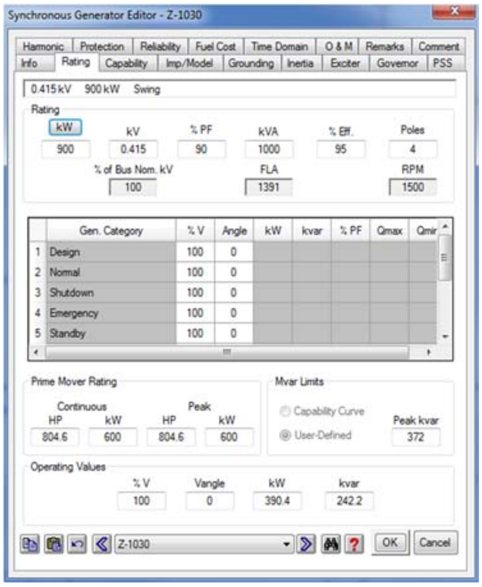

Figure 3.2: Modelling of generator rating

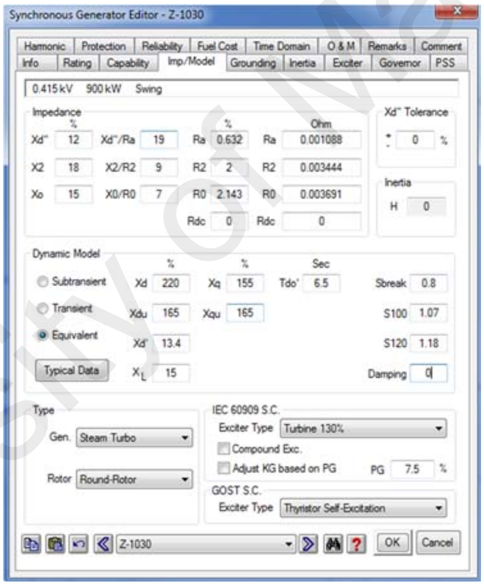

Figure 3.3: Modelling of generator reactance data, based on a standard industry manufacturer

3.2.3 Busbar modeling representing switchboard

In ETAP, there are two (2) busbars represent as switchgear, MCC 100 and 11kV Utility, each of these busbars can be configured as in Figure 3.4 and Figure 3.5 respectively.

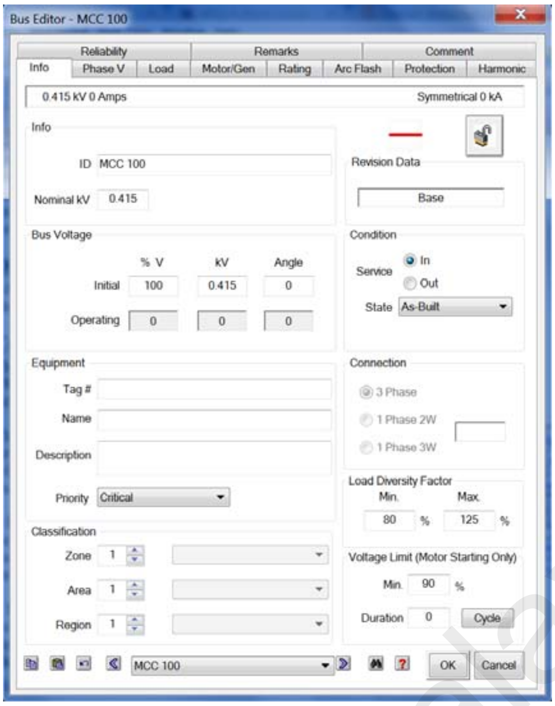

Figure 3.4: Modeling of 415V switchboard

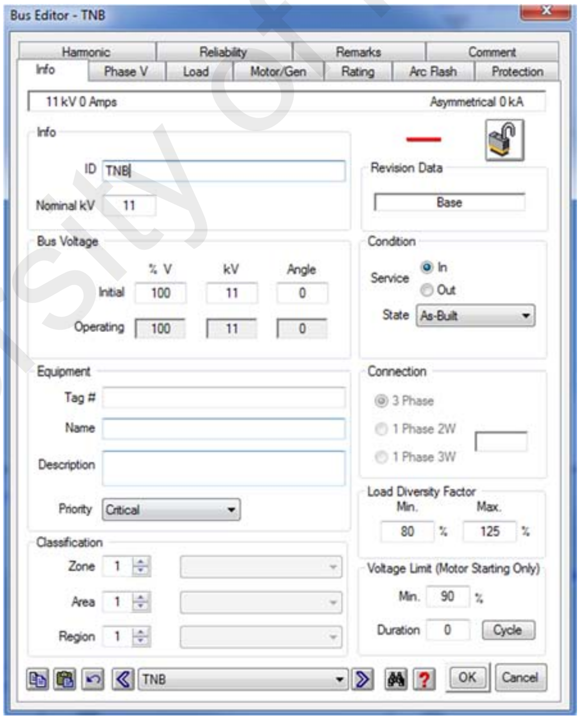

Figure 3.5: Modeling of 11kV switchgear

3.2.4 Electrical load modeling

Two types of electrical load, which are dynamic and static load, and are modeled in the Lumped Load Editor and Static Load Editor respectively. For the largest motor in the installed system, it will be separately modeled for the largest motor starting study to ensure the voltage drop is within acceptable limit. The ratio of locked rotor current to the motor rated current is 7 for the largest motor and for the lumped motors as 5 (International Electrotechnical Commission, 2002). Those motor rating less than 1000hp, the starting power factor is taken as 0.2 for motors (IEEE, 1980). Table 3.2 shows the modeled single and lumped electrical loads in ETAP software and Table 3.5 shows the power cable parameters modeled.

Table 3.3: Electrical load modeling in ETAP software

No.	**MCC-100**
1	Load Motor Sump General Standby (LMGS)
2	Load Motor Sump General Intermittent (LMGI)
3	Load Motor Sump General Continuous (LMGC)
4	Load Static Sump General Standby (LSGS)
5	Load Static Sump General Intermittent (LSGI)
6	Load Static Sump General Continuous (LSGC)
7	Load Static Building 1 (LSB1)
8	Load Static Building 2 (LSB2)
9	Load Static Building 3 (LSB3)
10	Motor Starter Compressor 1 (MSC1)
11	Compressor Continuous 1 (CC1)
12	Compressor Intermittent 1 (CI1)
13	Compressor Standby 1 (CS1)
14	Motor Starter Compressor 2 (MSC2)
15	Compressor Continuous 2 (CC2)
16	Compressor Intermittent 2 (CI2)

17	Compressor Standby 2 (CS2)
18	Motor Starter Compressor 3 (MSC3)
19	Compressor Continuous 3 (CC3)
20	Compressor Intermittent 3 (CI3)
21	Compressor Standby 3 (CS3)

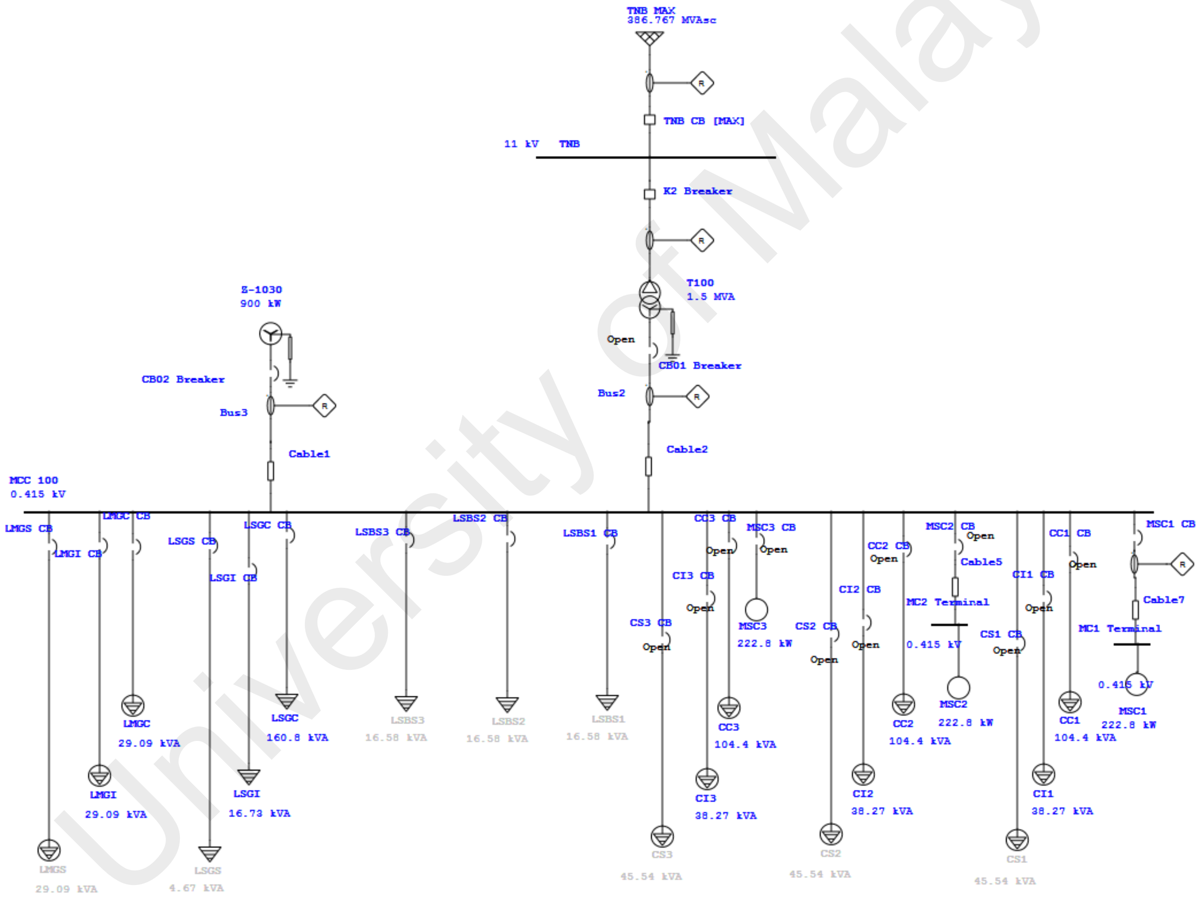

Figure 3.6: Final output of the power system model from ETAP software

3.3 Load flow studies

The load flow was carried out using ETAP power system software. All power system components have been modeled as per available data and respective standard model formats available in the ETAP.

At all loads running under steady state operating conditions, the following criteria shall be met;

1. No overloading for electrical such as Diesel Engine Generator (Z-1030), Transformer (T-100) or branch element.
2. Nominal voltage variation at all loads shall not exceed ±5 % under normal running condition.

For this study, Newton-Raphson Method is chosen to perform the iterations up to 99 times and with a precision (convergence) of 0.0001.

3.3.1 Load flow study scenario

Load flow study must always fit with the operation philosophy. The two (2) identify conditions are during normal operation and during standby operation using standby Diesel Engine Generator (Z-1030). Another conditions compulsory to be included in this study is during no-load operation. The following are the load flow study scenarios and its condition preferences:

<u>Scenario 1 – Normal Operating Condition</u>

This scenario simulate the system is feed from 11kV Utility then been stepped down through transformer and distributed to connected loads. At this condition, the Diesel Engine Generator (Z-1030) will be offline.

Scenario 2 – Diesel Engine Generator Operating Condition

This scenario simulates the failure (offline mode) of incoming supplies 11kV Utility. Now the entire electrical system is depend on the Diesel Engine Generator (Z-1030).

3.4 Largest motor starting studies

Both Load Flow and Largest Motor Starting study are the same in algorithm and calculation steps but in Load Flow Study, the simulation is during the steady state condition and for the Largest Motor Study, the simulation is during the Largest Motor being started.

During the largest motor starting, the motor terminals must not be deviated from the motor rated voltage -20% and at the LV switchboard busbar voltage must be maintained within 15% of its rated voltage (IEEE, 1980). The Diesel Engine Generator (Z-1030) must able to operate in response to voltage dip due to largest motor starting.

For the worst case scenario, the direct on line (DOL) starter will be using as a starting method with starting current 7xFLC.

In the ETAP software, there are two (2) types of motor starting modules, which are the Static Motor Starting Module and Dynamic Motor Starting Module. In the Dynamic Motor Starting Module, the motor are dynamically modeled and used to verify if a motor can be started and how much time is needed for the motor to achieve its rated speed, as well as to find out the effects of voltage sags/dips on the system. In the Static Motor Starting Module, the locked-rotor impedance represents the motors during acceleration time, simulating the worst effect on normal operating loads. This is appropriate for checking the impact of motor starting on the system when the dynamic model is unavailable.

3.4.1 Motor starting study scenario

The largest motor in the system is the Compressor Motor Starter rated at 222.82kW. This motor needs to be started with normal operating condition, which is from utility and with Diesel Engine Generator operating condition. Below is the description of the largest motor:

Motor description	=	Compressor Motor Starter
Motor rating	=	222.80kW
Motor full load ampere	=	364A
Running power factor	=	0.85
Starting power factor	=	0.3
Motor efficiency	=	94%

3.5 Short circuit studies

A short circuit study is an analysis of an electrical system on the short circuit current flows to electrical system when there is a fault occurs. The electrical equipment in the system should be rated higher than the calculated short circuit for it to withstand the impact from the high magnitude of short circuit current. The sources of the short-circuit current are:

1. Utility
2. Local generators
3. Local motors

And the fault can be categorized into two (2) types:

1. Balanced or symmetrical (three phase)
2. Unbalanced or unsymmetrical (one or more phases with or without earth connection)

The simulation for the short circuit analysis is performed by selecting all the buses, as being faulted for all types of electrical fault as below:

1. Three (3) phase fault
2. Line to line fault
3. Line to ground fault
4. Double line to ground fault

3.5.1 Short circuit study scenario

The short circuit analysis will be based on both conditions:

1. Utility online and Diesel Engine Generator offline
2. Diesel Engine Generator online and Utility offline

Short circuit analysis determine the magnitude of prospective fault current, on which has the highest short circuit current value will be selected for the equipment short circuit rating.

3.6 Relay Coordination studies

Over-currents in a power distribution system can occur as a result of both normal (motor starting, transformer inrush, etc.) and abnormal (ground fault, line-to-line fault, etc.) conditions. In either case, the basic purpose of current-sensing protective devices is to detect the abnormal over-current with proper coordination, to operate selectively and to protect equipment properly by minimizing the outage of the rest of the system.

3.6.1 Data collection and mapping

To perform a coordination study, the following information is collected and modeled:

1. A single-line diagram of the power system involved, showing the type and rating of the protective devices and their associated current transformers.

2. The impedance in ohms, percent or per unit of all power transformers, rotating machines and feeder circuits.
3. The starting current requirements of motors.
4. The grid short circuit MVA.

3.6.2 Conductors

Continued over currents increase the resistance heating (I^2R) of conductors and can decrease cable insulation life and cause failures. Conductors are normally protected by overcurrent protective devices, with the pickup settings based on the cable ampacity.

The conductor short-time heating limits, based on short-circuit currents or on allowable emergency overload currents, are additional points that should be plotted to ensure that the protective devices provide adequate protection for the conductor.

In coordinating system protection, the conductor should be able to withstand the maximum through-fault current for a time equivalent to the tripping time of the upstream protective device. Another factor in protecting the circuit cable is the maximum short-circuit current available at the extremity of the cable circuit. The conductor insulation should not be damaged by the high conductor temperature resulting from current flowing to a fault beyond the cable termination. As a guide in preventing insulation damage, curves of conductor size and short circuit current based on temperatures that damage insulation are available from cable manufacturers. In coordinating system protection, the cable should be able to withstand the maximum through short-circuit current for a time equivalent to the tripping time of the primary relay protection or total clearing time of the fuse. Many times this requirement determines the minimum conductor size applicable to a particular power system. If it is not possible to select a device that will protect the cable insulation, it is recommended that a conductor large enough to carry the current without insulation damage be used

3.6.3 Motors

Motor protection points that are generally plotted on the overcurrent coordination curve include root-mean-square (rms) asymmetrical starting current, locked-rotor current, acceleration time, allowable stall time, and full-load current. The motor starting curve normally shows the symmetrical starting current, but the initial starting current is asymmetrical with the maximum occurring at a 0.5 cycle. Peak-current-sensing protective devices are sensitive to this current. Therefore, engineering judgment should be used when choosing the protective device type and settings to account for the asymmetrical current during startup to prevent false tripping of the short-circuit protective device. A typical rms asymmetrical starting inrush current would be about 1.76 times the symmetrical locked-rotor current. The point on the voltage waveform influences this inrush factor on each phase when the contactor closes, the X/R ratio of the power system, and the X/R ratio of the motor. This inrush factor could be as high as 2 to 3 times for stiff power systems for large high-efficiency motors. The locked-rotor current should be obtained from manufacturer's data. The acceleration time of the motor, based on the normal means used to start the motor and driven load, should be plotted. The motor acceleration time can be obtained from the motor manufacturer. The motor permissive stall time, which may be given as both hot and cold stall times, should be plotted as well. The overcurrent protection should give enough time delay to allow the motor to start, but not so much that the operating time at locked-rotor current is above the permissive stall times. If the acceleration time is above the stall time, special relaying considerations may be required. The motor full-load current should be plotted, and a benchmark should also be plotted for the maximum permitted overcurrent device setting for overload protection. Motor overload and short-circuit protection are often provided by a combination of devices. On low-voltage systems, this combination is usually an overload relay with a current-limiting fuse or an overload relay with a low-voltage circuit breaker. The overload relay should be selected (or set) based on the full-load current and service factor of the motor. The fuse or circuit breaker should be selected or set to protect the motor circuit during short circuits, but should not interrupt normal starting currents. As a result, the time-current characteristic (TCC) of the combination device must fall below and to the left of the motor thermal limit curve and fall above and to the right of the motor starting curve.

3.6.4 Coordination settings and criteria

There are two basic adjustable settings on all inverse time relays; one is the current setting usually known as the Plug Setting Multiplier (PSM) and the other is Time Multiplier Setting (TMS).

$$PSM = \frac{\Pr imary\,current}{\Pr imary\,setting\,current} = \frac{\Pr imary\,current}{\mathrm{Re}\,lay\,current\,setting \times CT\ Ratio} = \frac{\Pr imary\,current}{\Pr imary\,operating\,current}$$

$$TMS = \frac{T_{op}}{T_m}$$

Where,

T_{op} = The required time of operation

T_m = The time operation at TMS = 1.0 for maximum fault current

3.6.5 Selection of PSM

The pick-up values of phase over current inverse time relays are normally set 20% above the maximum equipment rated current, provided that sufficient short circuit current was available. Earth fault inverse time relays are subjected to residual current, which allows a much more sensitive setting.

For inverse time over current relays, the current setting should be done at the minimum fault current because if the relays are sensitive for the minimum fault current, it will automatically sense maximum fault current.

Following equations to be used to calculate PSM of protective relay.

$$IF > P.O.C > (I_{RL} + I_{STM} + I_{FLM})$$

Where,

P.O.C = Desired primary operating current of relay

I_{RL} = Maximum running load current

I_{STM} = Highest starting drive starting current

I_{FLM} = Highest starting full load current

I_F = Minimum fault current relay to sense

$$Pick\,Up \geq \frac{\text{Pr}\,imary\,Operating\,Current\,(P.O.C.)}{C.T.Ratio}$$

3.6.6 Selection of TMS

The relay farthest from the source should be set to operate in the minimum possible time. For succeeding relays towards the source a time delay step should be given. For inverse time over-current relays the time setting should be done at the maximum fault current. If the relay has proper selectivity at the maximum fault current, it will automatically have a higher selectivity at the minimum fault current, as the curve was more inverse at lower fault currents.

Following equations to be used to calculate TSM of protective relay.

$$t_1 = t_0 + t_d$$

Where,

t_1 = Desired operating time

t_0 = Downstream relay / fuse operating time

t_d = Discrimination in time

$$\frac{Desired\ relay\ operating\ time\ t1}{\mathrm{Re}lay\ operating\ time\ @\ selected\ PSM\ and\ TMS = 1.0} = Desired\ TMS\ setting$$

Time discrimination is taken as 200 – 300 msec for relay to relay or fuse to relay considering the time intervals mentioned in Table 3.4 (Note: All short-circuit currents considered for relay co-ordination are calculated based on IEC-60909, 2001 standard. The CTI mentioned in Table 3.4 are taken from IEEE Standard 242-2001).

Table 3.4: Composition of time discrimination between relays

Components	**Coordination Time Interval (CTI)**	
	Electromechanical	**Static**
Circuit breaker operating time	0.08 s	0.08 s
Relay over travel	0.10 s	0.00 s
Relay tolerance and setting errors	0.12 s	0.12 s
Total CTI	**0.30 s**	**0.20 s**

CHAPTER 4: RESULTS AND DISCUSSIONS

This chapter will explain in detail all the results and discussions that has been obtained for a load flow studies, largest motor starting study, short circuit study and protection coordination study. The modelling of the power system for different cases for the compressor station was performed as explained in Chapter 3.

4.1 Load flow studies

As explained in Chapter3, three (3) cases of load flow studies are performed for the compressor station during normal operations, standby DEG operations and no-load condition. Load flow studies are performed for the normal operating condition (power supplied by utility), standby DEG (power supplied from DEG during failure of Utility connected system) and for no-load condition at the compressor station. The objectives of load flow studies is to define the following issues:

a. To make sure all equipment including cables ate sized correctly and loaded within their capacity without any overloading at steady state
b. To make sure the bus voltages are within +/- 5% for all steady state operating conditions including no-load conditions
c. To select transformer tap settings or to study the requirement for an on load tap changer
d. To study the real and reactive power flows in the system and system losses

The results and discussions of the load flow studies for the three (3) cases are explained in this section.

4.1.1 Results of load flow scenario 1

Figure 4.1 shows the apparent power and current in the system and figure 4.2 shows the real and reactive power in the system during utility in service.

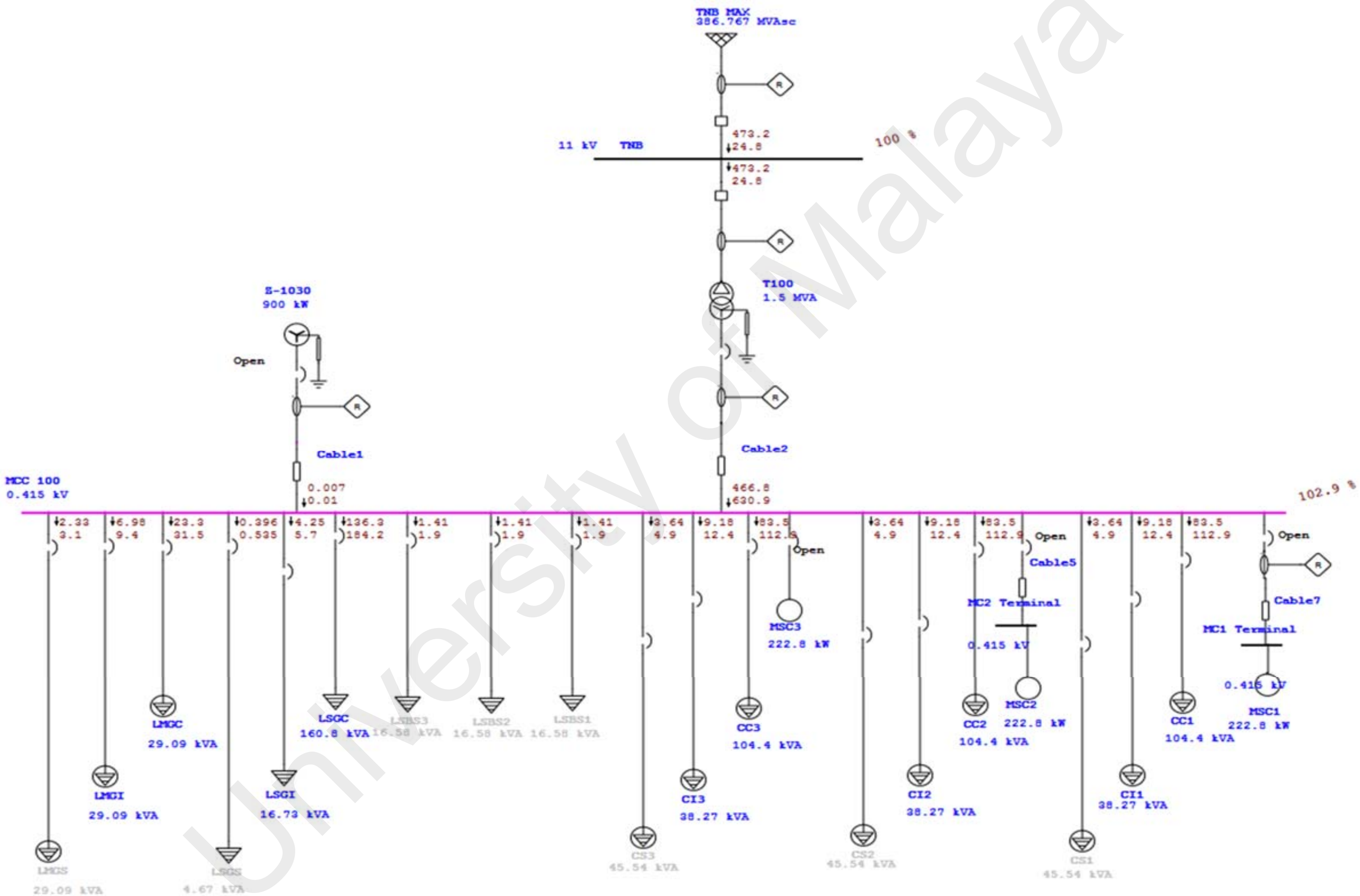

Figure 4.1: Apparent power and current in the system, scenario 1

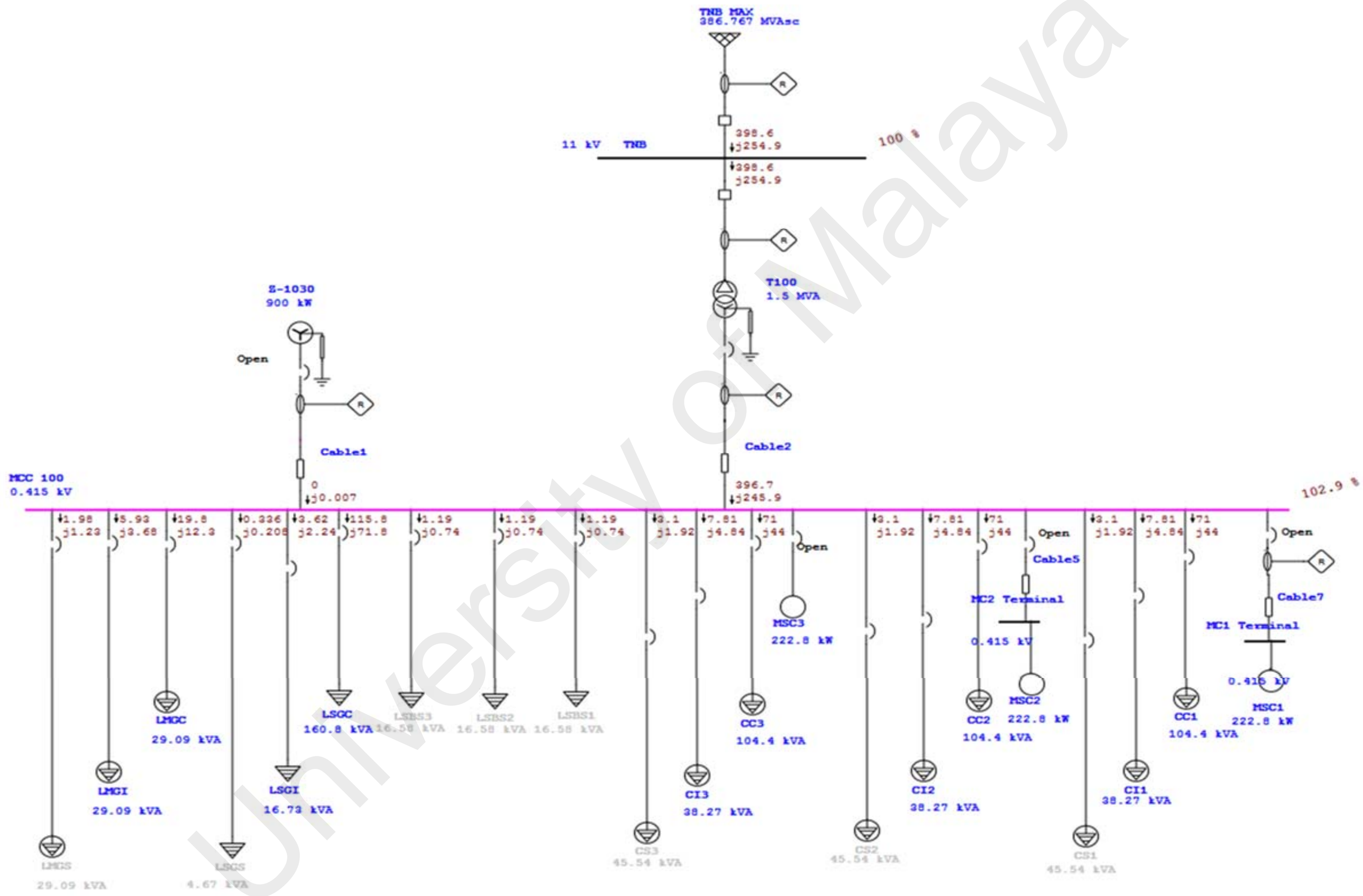

Figure 4.2: Real and reactive power flow in the system, scenario 1

Table 4.1 shows the summary of percentage of steady state voltage drop at the various busses in the system and Table 4.2 shows the percentage of all equipment loading in the system.

Table 4.1: Summary of percentage of steady state voltage drop during scenario1

Location	System Voltage	Percentage of voltage drop (%)
MCC 100	415 V	2.9
TNB	11kV	0

Table 4.2: Loading equipment in the system during scenario1

Equipment	Rating	Steady state loading	Percentage of loading (100%)
Cable 2	1662 A	630 A	37.94
T100	1500kVA	473kVA	31.5

Table 4.3 shows the system losses by equipment and the overall system losses.

Table 4.3: System losses during scenario1

Equipment	Losses	
	kW	kVar
Cable 2	0.4	0.3
T100	1.4	8.7
TOTAL LOSSES	**1.8**	**9**

4.1.2 Results of load flow scenario 2

Figure 4.1 shows the apparent power and current in the system and figure 4.2 shows the real and reactive power in the system during utility in service.

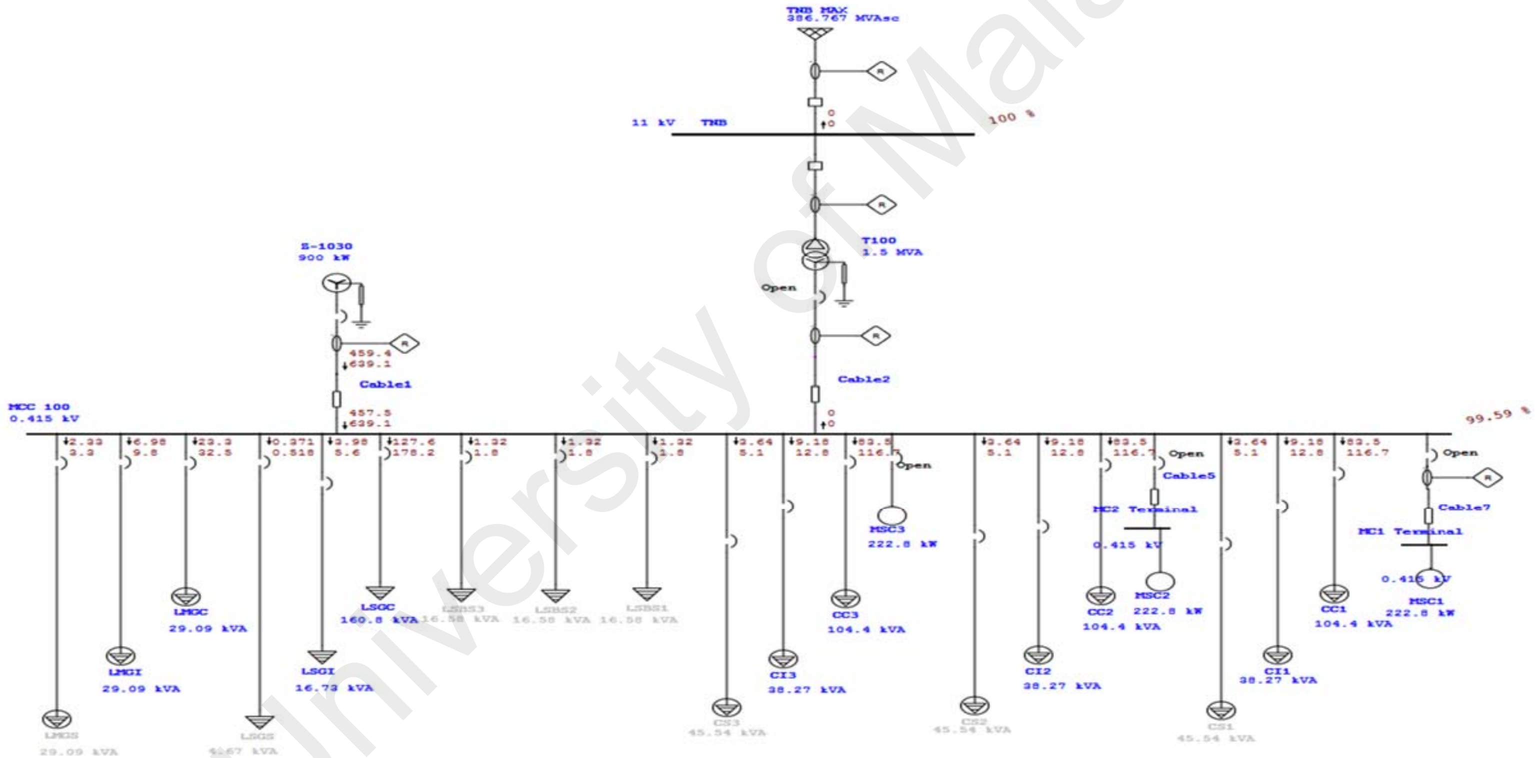

Figure 4.3: Apparent power and current in the system, scenario 2

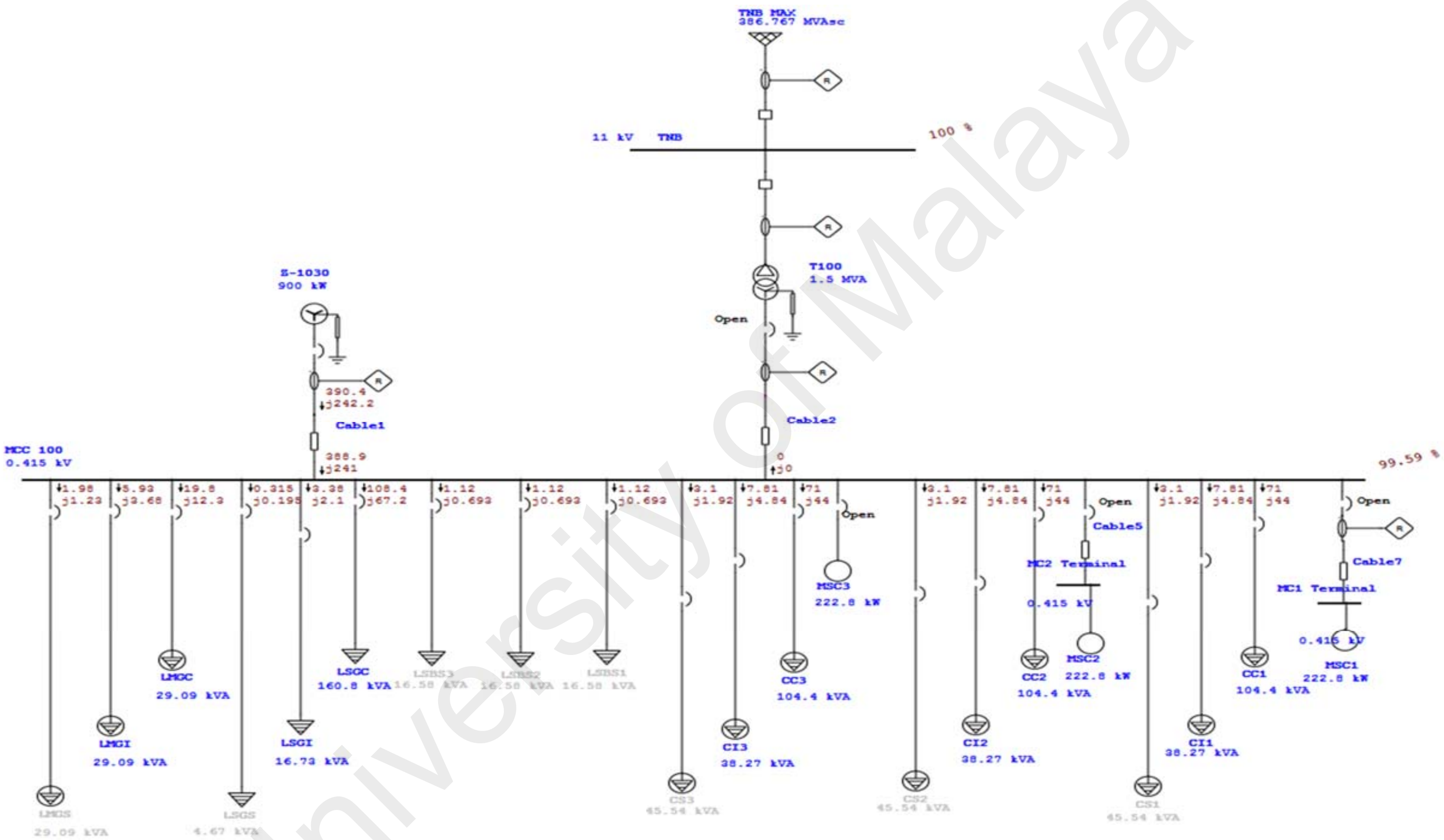

Figure 4.4: Real and reactive power flow in the system, scenario 2

Table 4.4 shows the summary of percentage of steady state voltage drop at the various busses in the system and Table 4.5 shows the percentage of all equipment loading in the system.

Table 4.4: Summary of percentage of steady state voltage drop during scenario2

Location	System Voltage	Percentage of voltage drop (%)
MCC 100	415 V	0.41

Table 4.5: Loading equipment in the system during scenario 2

Equipment	Rating	Steady state loading	Percentage of loading (100%)
DEG	1391 A	640 A	46.01
Cable 1	1024 A	640 A	62.40

Table 4.6 shows the losses from each equipment and the total system losses during the standby DEG operation

Table 4.6: System losses during scenario 2

Equipment	Losses	
	kW	kVar
Cable 1	-0.389	-0.241
TOTAL LOSSES	**-0.389**	**-0.241**

4.1.3 Discussion on load flow study during utility operations and DEG operations

Based on Table 4.1, it can be observed that the percentage of steady state voltage drop at the various busses in the system is within 5%. All the loads which are connected to the 415V LV switchboard (MCC 100) will be subjected to a voltage approximately 402.9V (2.9% voltage drop) at steady state. This will ensure all the running motors will not be drawing a higher current than their rated capacity motors behave as constant kVA loads that will draw higher current when connected to a lower voltage than the rated. From Table 4.2, it can be seen that at steady state all the equipment loading is below their rating and the highest loaded equipment at 37.94% is Cable 2 and the lowest loaded equipment is the transformer at 31.5%. Table 4.3 shows the system kW and kVar losses and the total real power losses are 1.8kW and reactive power losses are 9kVar.

During the DEG in service, it can be observed from Table 4.4 that the percentage of steady state drop at the 415V LV switchboard (MCC 100) is about 413V (0.41% voltage drop). From Table 4.5, it can be seen that at steady state all the equipment loading is below their rating and the highest loaded equipment at 62.40% is Cable 1 and the lowest loaded equipment is the DEG at 46.01%. Since the loading for DEG is below 50%, it will reduce the lifetime of the engine because its prime mover and will lead to premature engine failures. Therefore it is advisable to reduce the DEG rating so it can be operated within 85 – 95% loading to avid premature failures in engine based generators.

4.2 Largest motor starting studies

The motor starting study was performed for the largest motor which is the air compressor for direct on-line starting (DOL). The motor starting is repeated for both during utility in service and DEG in service. Other types of starting methods are not assessed as the studies is focusing only at DOL. Starting power factor is selected as 0.20 for all motor starting methods (IEEE, 1980). This section will explain all the effects to the system during the largest motor starting with various starting methods to assess the robustness of the system based on the criteria explained in section 3.4.

4.2.1 Results DOL starting during utility and DEG in service

DOL starting is performed for the largest motor which is the air compressor. The percentage of locked rotor current is selected as 700% from the motor full load current. Figure 4.7 and Figure 4.8 shows the voltage drop, real and reactive power flow in the system during the DOL motor starting for normal operations and standby DEG operations.

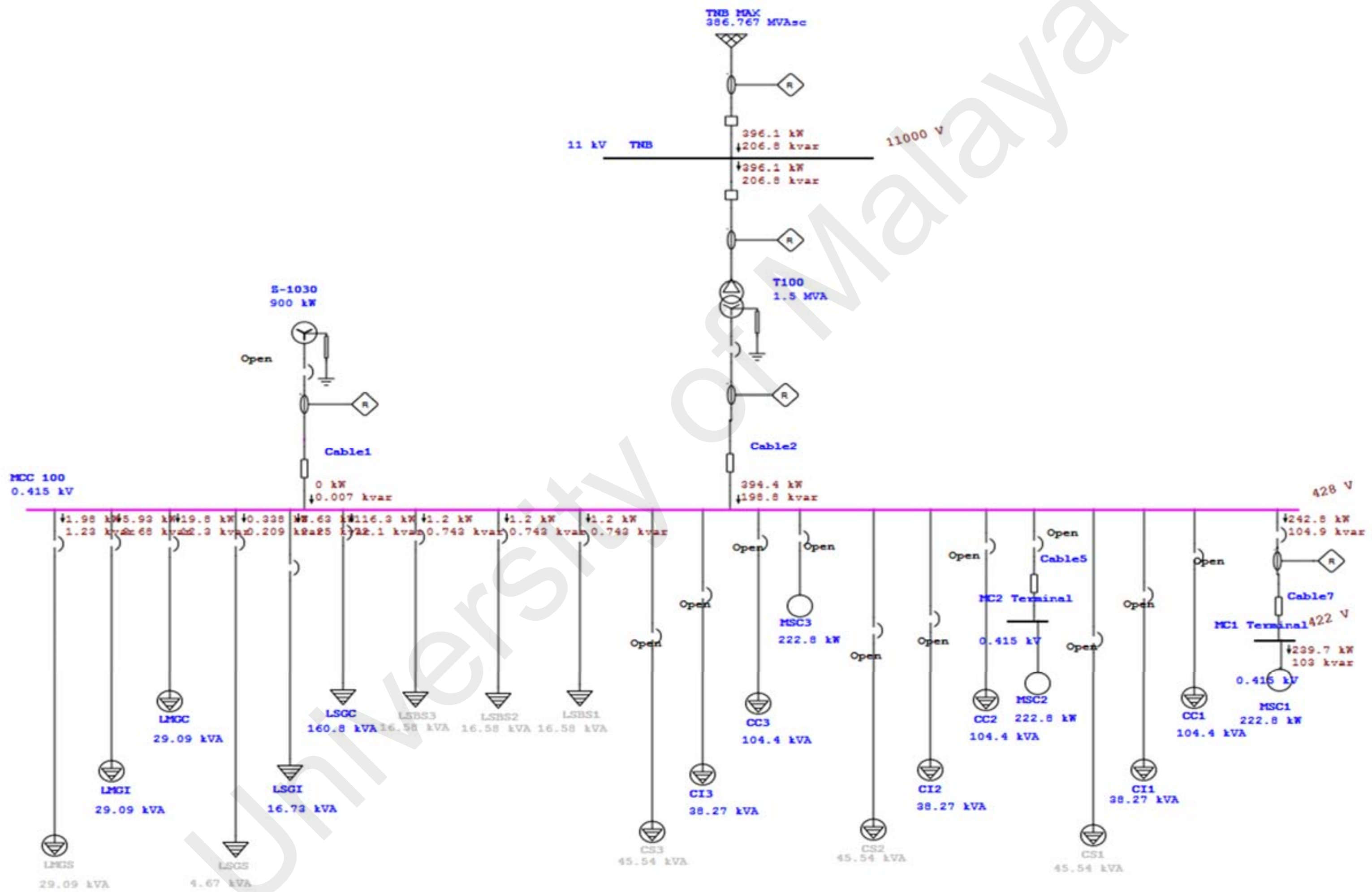

Figure 4.5: Single line diagram, largest motor starting, utility in service

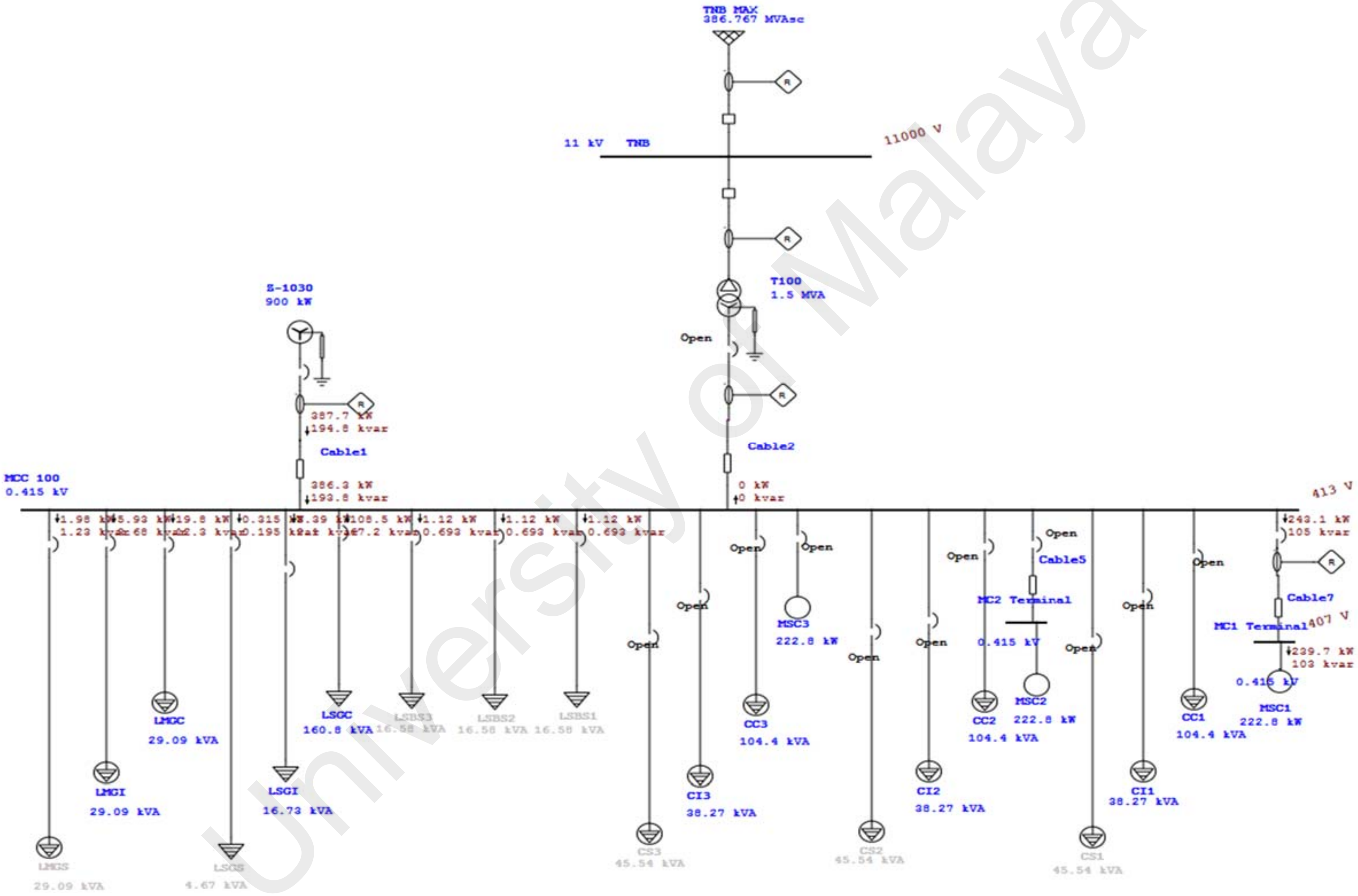

Figure 4.6: Single line diagram, largest motor starting, DEG in service

Table 4.7: Percentage of voltage drop at LV switchboard, motor terminal, starting current and source current

Voltage Drop at LV switchboard (%)		Voltage drop at motor terminal (%)		Motor starting current (A)		Source current (A)	
Utility	DEG	Utility	DEG	Utility	DEG	Transformer Output	DEG Output
+3.13	0.48	1.93	8	356.8	271.6	614.9	632

4.2.1.1 Voltage drop at LV switchboard and motor terminal during motor starting

The maximum allowed voltage drop at the LV switchboard is chose as 15% and at all times, the voltage at the LV switchboard shall not be lower than 85% of the rated voltage which is at 400V. Whereas the voltage drop at the motor terminal is chose as 20% and at all times the motor terminal shall have a minimum of 80% of rated voltage. The reason is because the air compressor motor is a NEMA Design B motor and has a 150% standard starting torque at full rated voltage (National Electrical Manufacturers Association, 2002). Torque changes with the square of voltage as per the following equation;

$$T_{starting} = 0.8^2 \times 150\% = 100\%$$

Thus, to achieve a successful motor starting, at least 80% of motor rated voltage are required at the motor terminal during the starting. From this, by allowing a typical motor feeder voltage drop of 5%, the required voltage at the LV switchboard is 85% of rated voltage. Another reason to maintain at least of 85% of rated voltage at the LV switchboard as the typical contactor dropout voltage is below 60-70 % of rated voltage (IEEE, 1980). The supply for the motor control circuits are commonly derived directly from the switchboard and to maintain contactor hold-in for all the motors connected to the same switchboard during the largest motor starting, 85% of the rated voltage will make sure they wouldn't be any contactor dropouts.

From Table 4.7 it can be observed that for DOL starting, during DEG in service, the voltage drop at the LV switchboard is 0.48% which is lower than 15% and the voltage drop at the motor terminal is 8% lower than the selected criteria of 20%. Thus, DOL starting is acceptable for the starting method. If the system operates within the acceptable standard during the DOL method, therefore other methods should be fined.

4.3 Short circuit studies

3 phase fault, line to ground fault, line to line fault and double line to ground fault simulations were performed for both normal operating condition and standby DEG operating condition. All the equipment in the power system are required to withstand the maximum short circuit current that possibly may happen in the system. This section will explain in detail the values of initial symmetrical rms short circuit current, I_k" and peak short circuit current, I_{peak}. All electrical equipment in the system has to be designed to withstand the short circuit current before tripping by the protection system. The short circuit simulations performed by simulating a fault at all busses.

4.3.1 Results short circuit study results

Figure 4.6 and Figure 4.7 shows the values of I_k" for 3 phase bolted short circuit at all busses in the system during the utility in service and DEG in service. A 3 phase bolted fault is simulated with the ground impedance set as zero.

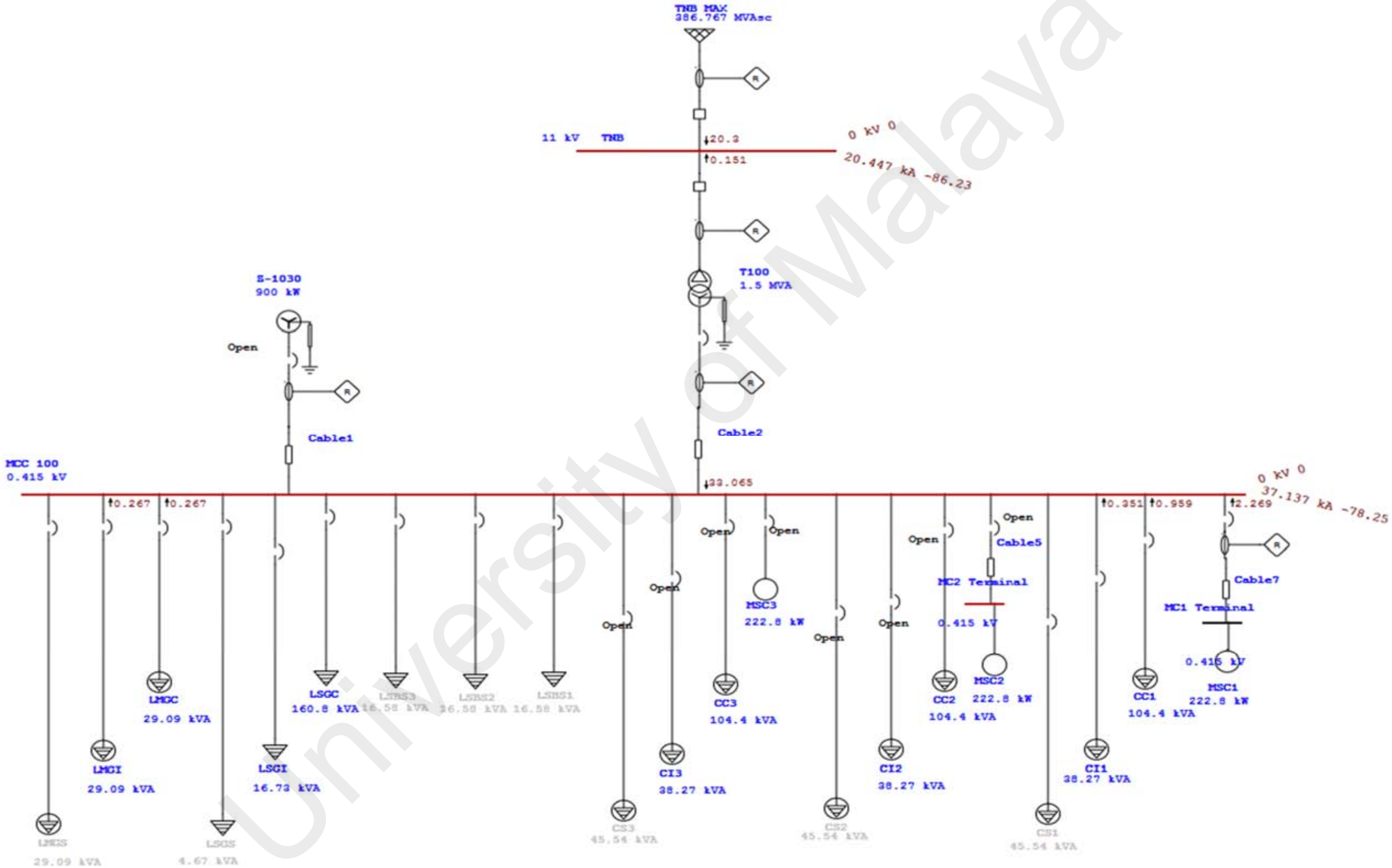

Figure 4.7: I_k" for 3 phase bolted short circuit at all busses during utility in service

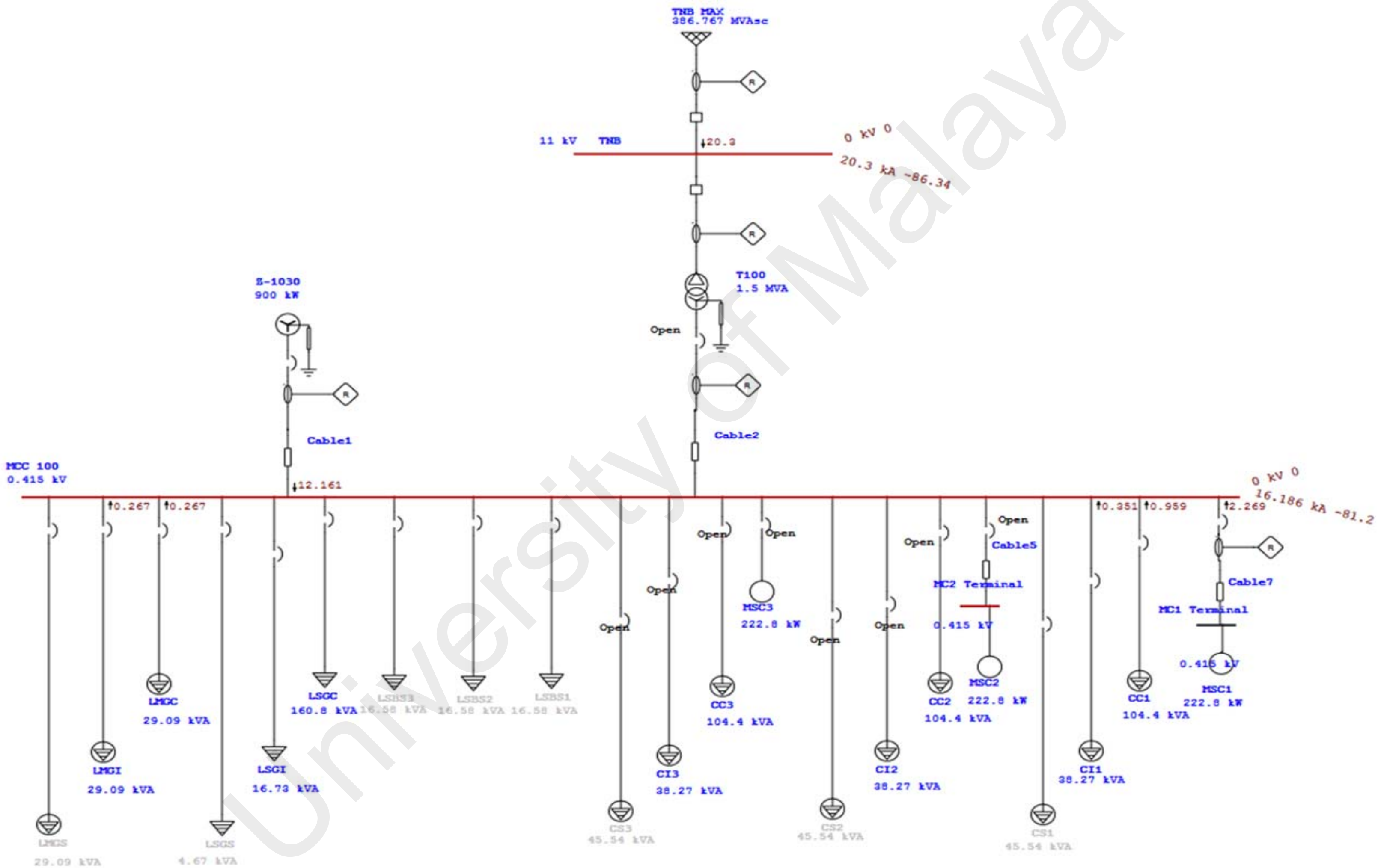

Figure 4.8: I_k” for 3 phase bolted short circuit during DEG in service

Figure 4.8 and Figure 4.9 shows the values I_k" for line to ground fault during utility in service and DEG in service.

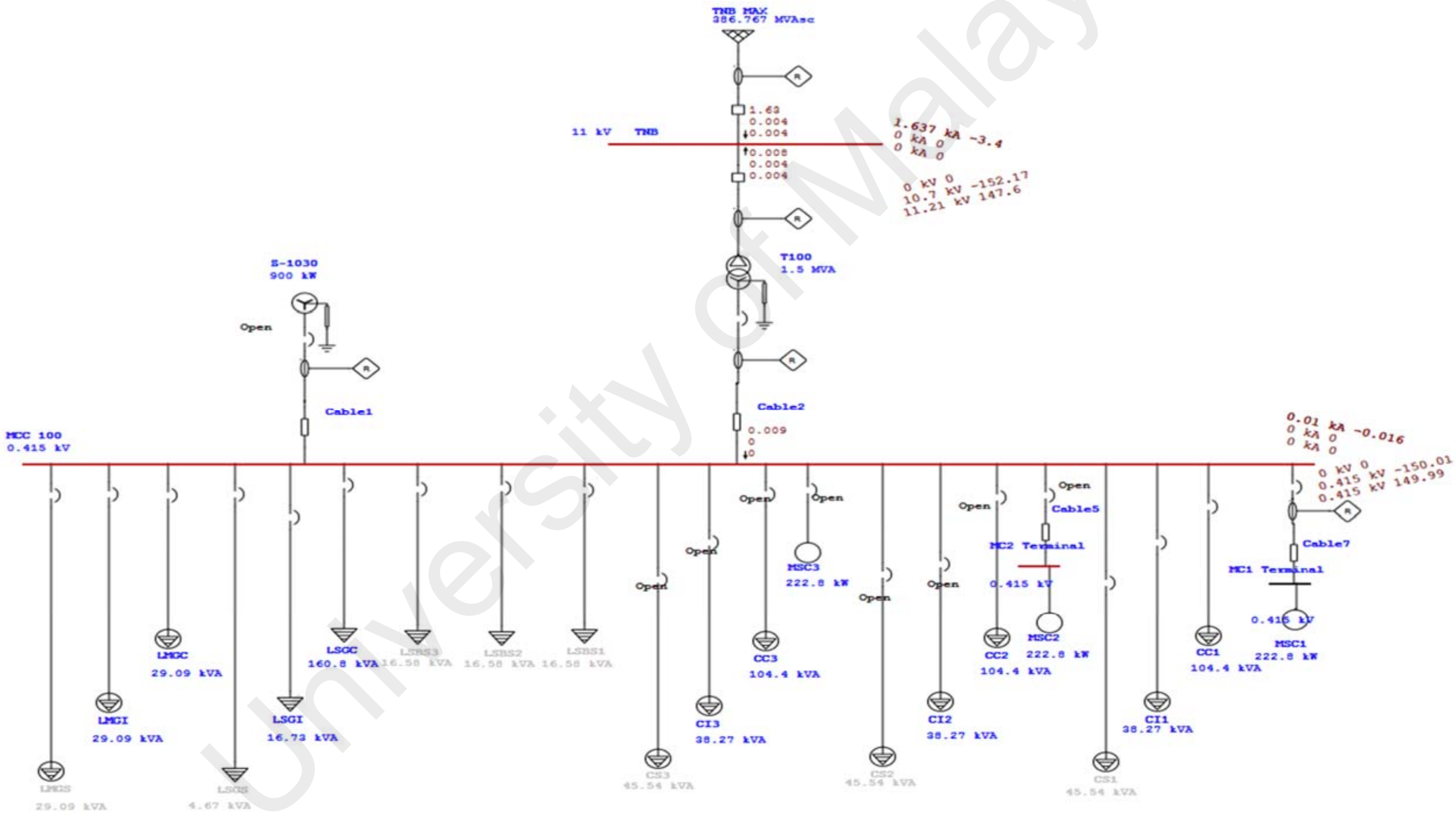

Figure 4.9: I_k" for line to ground fault during utility in service

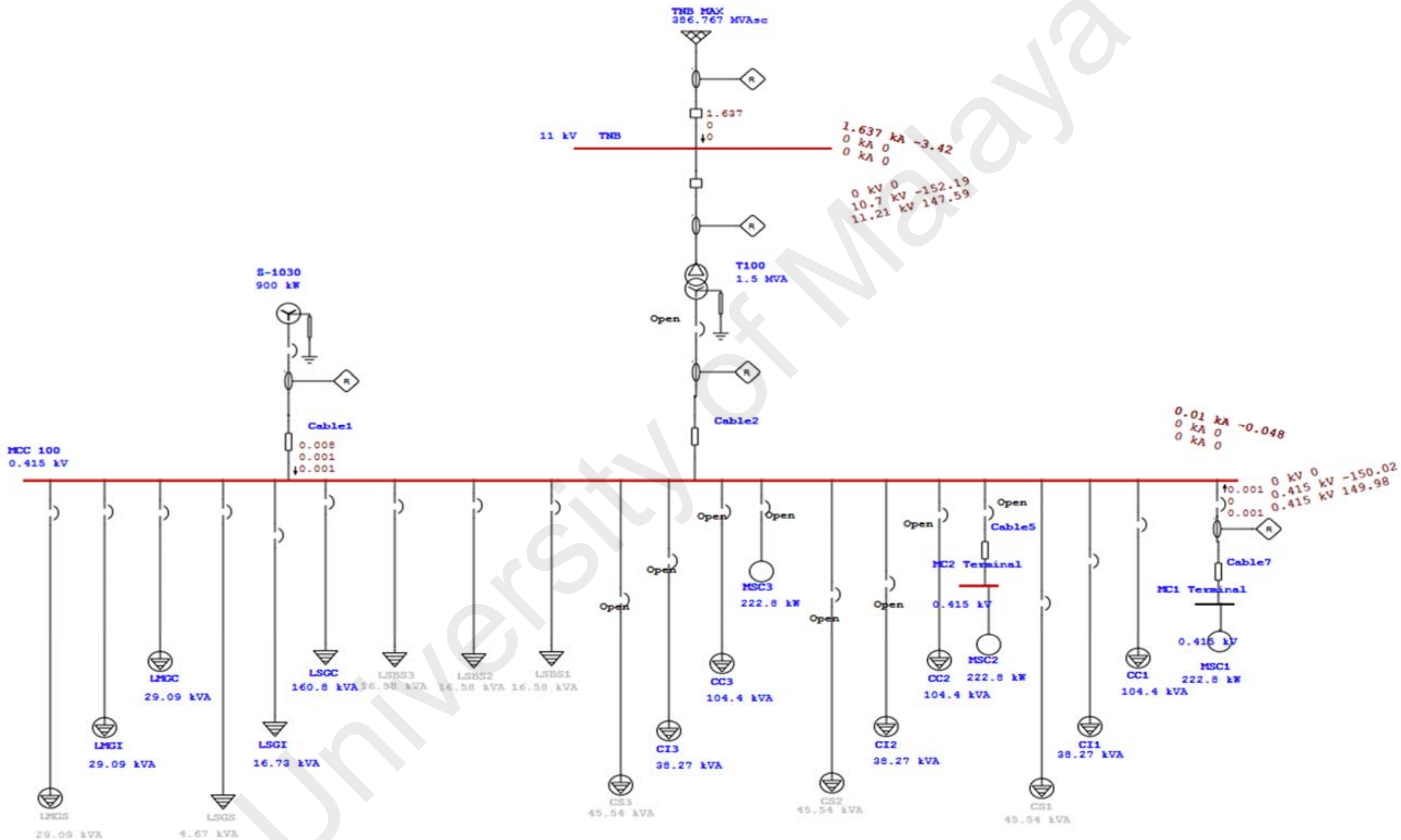

Figure 4.10: I_k" for line to ground fault during DEG in service

Figure 4.10 and Figure 4.11 shows the values I_k" for line to line fault during utility in service and DEG in service.

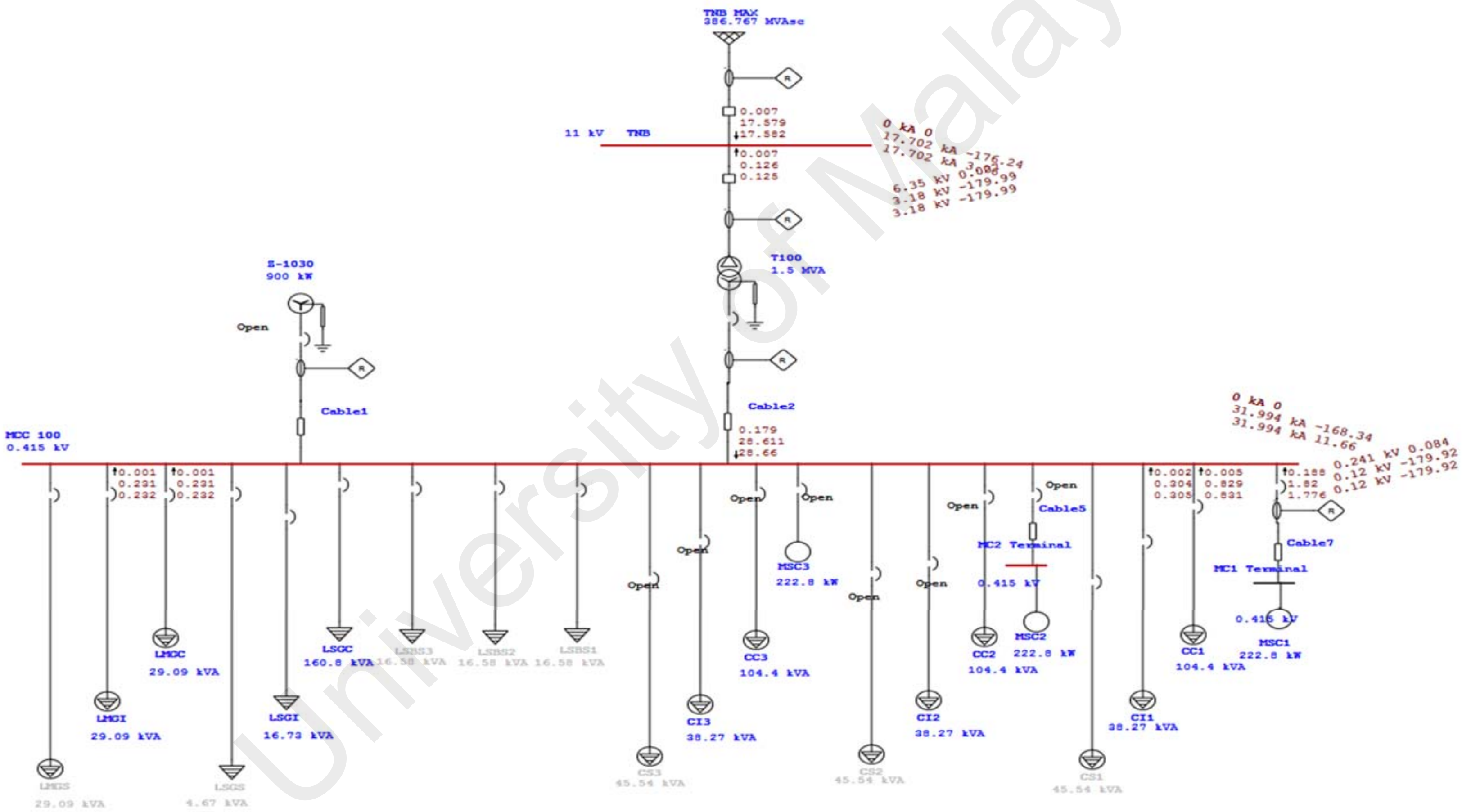

Figure 4.11: I_k" for line to line fault during utility in service

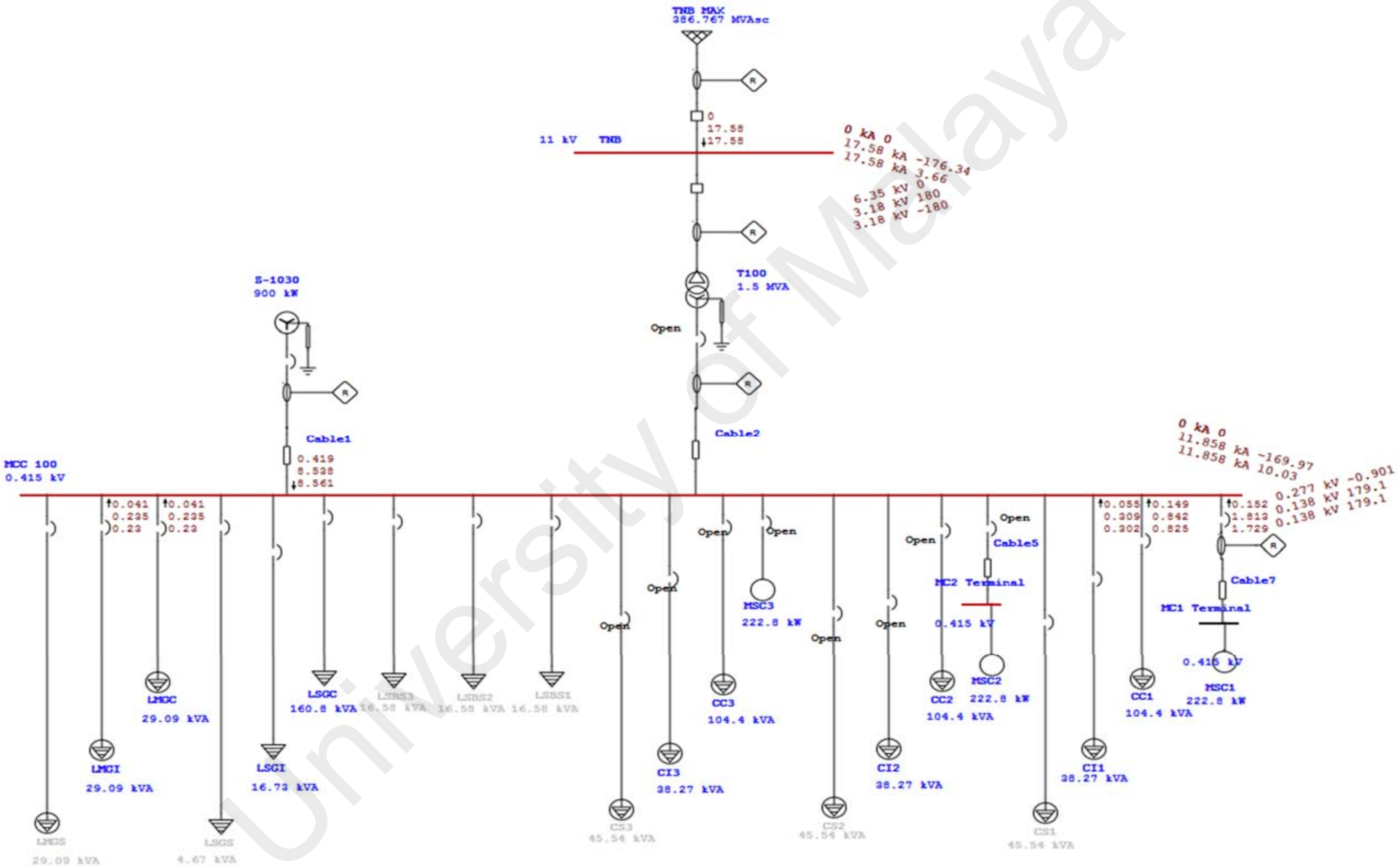

Figure 4.12: I_k” for line to line fault during DEG in service

Figure 4.12 and Figure 4.13 shows the values Ik" for double line to ground fault during utility in service and DEG in service

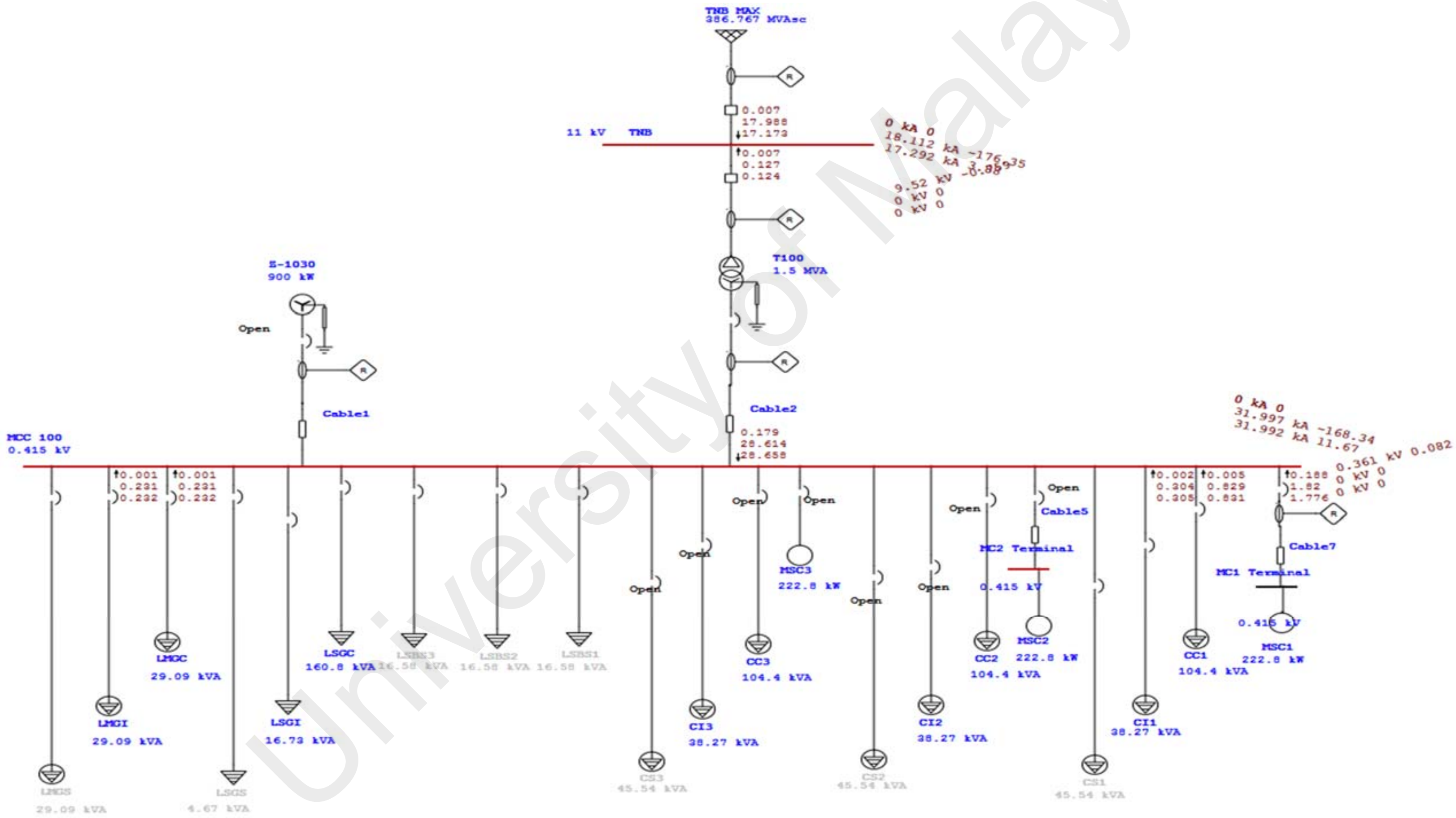

Figure 4.13: I_k" for double line to ground fault during utility in service

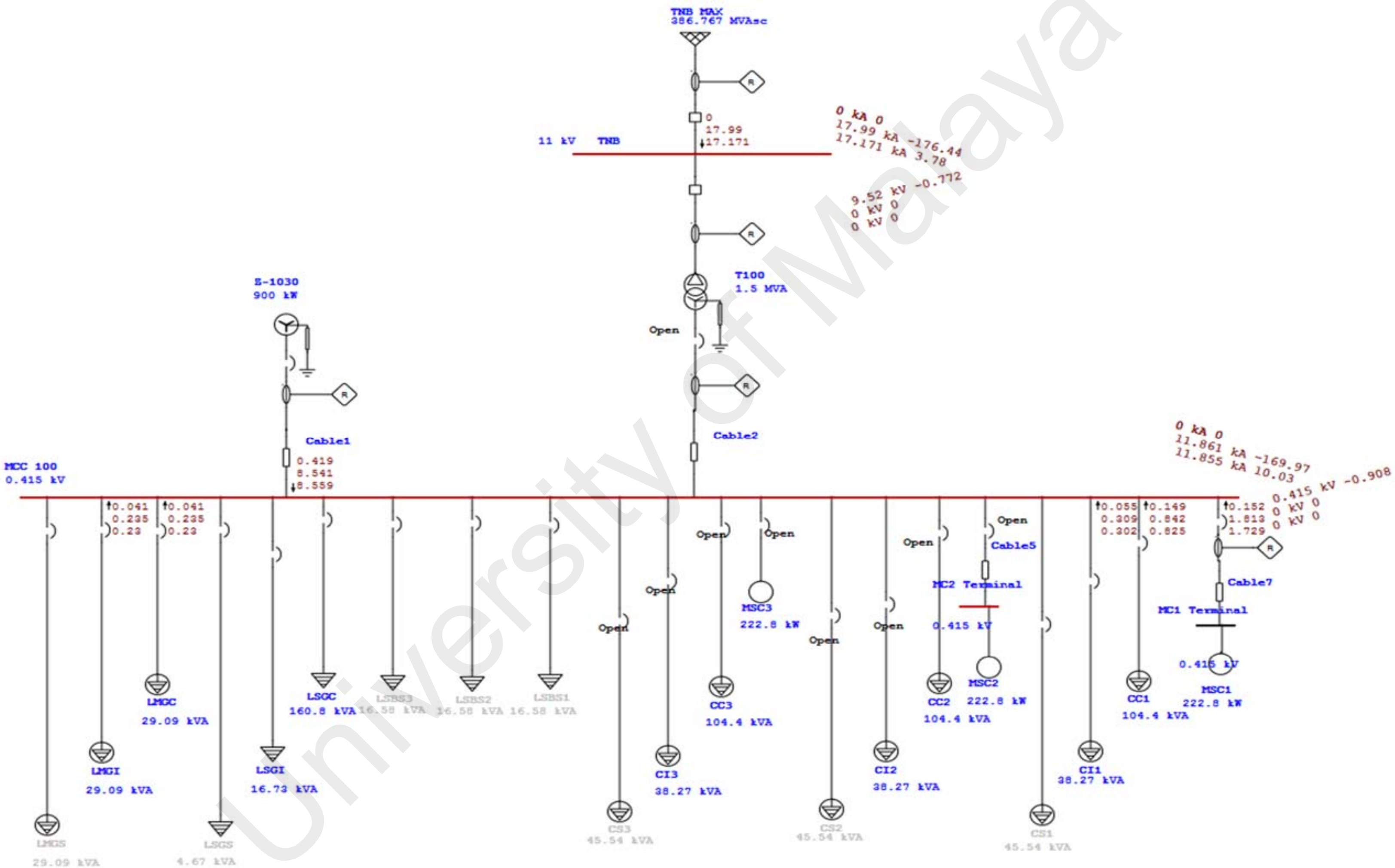

Figure 4.14: I_k" for double line to ground fault during DEG in service

Table 4.8 and Table 4.11 shows the values of initial symmetrical rms short circuit current, Ik" and peak short circuit current, Ipeak during normal and standby DEG operations.

Table 4.8: Initial symmetrical rms short circuit current, I_k" and peak short circuit current, I_{peak} at all busses during utility in service

Equipment	Voltage (V)	3-phase fault		Line - ground fault		Line – line fault		Double – line fault	
		Initial I_k" rms (kA)	Initial I_{peak} (kA)	Initial I_k" rms (kA)	Initial I_{peak} (kA)	Initial I_k" rms (kA)	Initial I_{peak} (kA)	Initial I_k" rms (kA)	Initial I_{peak} (kA)
MCC 100	415	37.14	81.46	0.01	0.02	31.99	70.18	31.99	70.19
TNB	11k	20.45	52.79	1.64	4.23	17.70	45.71	18.11	46.76

Table 4.9: Initial symmetrical rms short circuit current, I_k" and peak short circuit current, I_{peak} at all busses during DEG in service

Equipment	Voltage (V)	3-phase fault		Line - ground fault		Line – line fault		Double – line fault	
		Initial I_k" rms (kA)	Initial I_{peak} (kA)	Initial I_k" rms (kA)	Initial I_{peak} (kA)	Initial I_k" rms (kA)	Initial I_{peak} (kA)	Initial I_k" rms (kA)	Initial I_{peak} (kA)
MCC 100	415	16.16	35.14	0.01	0.02	11.85	25.71	11.86	25.75
TNB	11k	20.3	52.5	1.64	4.23	17.6	45.5	18.0	46.53

4.3.2 Discussion on motor starting studies

The objective in studying the short circuit current values is to select the correct short circuit withstand ability for all the equipment in the system. All the equipment has to be rated for a short circuit rating higher than the maximum short circuit current that can exist in the system during the faults. Typically, all low voltage equipment is required to withstand the rated short circuit level for at least 3 seconds while the high voltage equipment are required to withstand for at least 1 second before the protection system will be able isolate the faulted area.

Two types of short circuit current values are studied from the results of the simulation as can be seen in Table 4.8 for utility in service and Table 4.9 for DEG in service; which is the initial symmetrical rms short circuit current, I_k" and the peak short circuit current, I_{peak}. Table 4.10 shows the summary of the highest short circuit current that can happen in the system comparing values for the normal and DEG in service.

Table 4.10: Highest short circuit current in the system, type of fault and operating condition during the fault

Equipment	Voltage (kV)	Highest fault current		Type of fault	Operating condition
		Initial I_k" rms (kA)	Initial I_{peak} (kA)		
MCC 100	0.415	37.14	81.46	3 phase fault	Utility in service
TNB	11	20.45	52.79	3 phase fault	Utility in service

From Table 4.10 it can be seen that the highest type fault current at the 11kV TNB switchgear system is the 3 phase bolted fault and the highest type of fault current at the

415V MCC 100 switchboard is also 3 phase bolted fault. With this value, the system can determine the switchgear making duty as based on peak symmetrical peak current. Under the relay protection studies, this value will contribute in setting the instantaneous relays as well as the overcurrent relays.

Table 4.11 shows the selected short circuit ratings for the equipment. For the 6.6kV equipment, the peak withstand current is 2.5 times the rated initial rms current. This is based on IEC standard that requires all high voltage equipment with a frequency of 50Hz and below to be rated for a peak current of 2.5 times the initial rms current which has to be complied by all the equipment manufacturers (International Electrotechnical Commission, 2006). Whereas for the low voltage equipment the peak withstand current is by a factor n based on Table 4.12.

Table 4.11: Selected equipment short circuit rating

Equipment	Voltage (kV)	Selected rating		Time (seconds)
		Initial current withstand rms (kA)	Peak current withstand (kA)	
MCC 100	0.415	37.14	80	1
TNB	11	20.45	51	3

Table 4.12: Factor n for peak short circuit current withstand ability (International Electrotechnical Commission, 2000)

Initial rms value of short circuit current	Factor *n*
Less than 5kA	1.5
5-10kA	1.7
10-20kA	2

20-50kA	2.1
More than 50kA	2.2

4.4 Protection relay coordination studies

4.4.1 Protection relay coordination result during utility in service

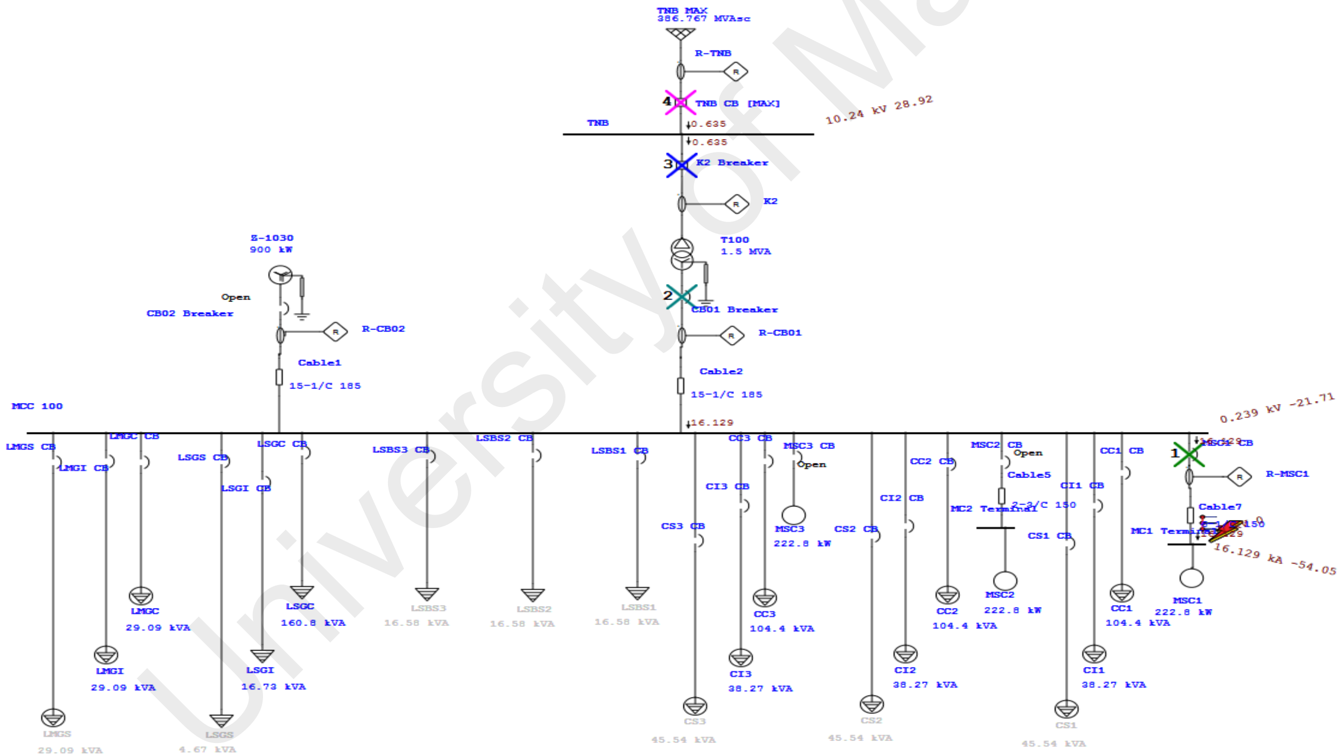

Figure 4.15: Relay coordination, utility in service

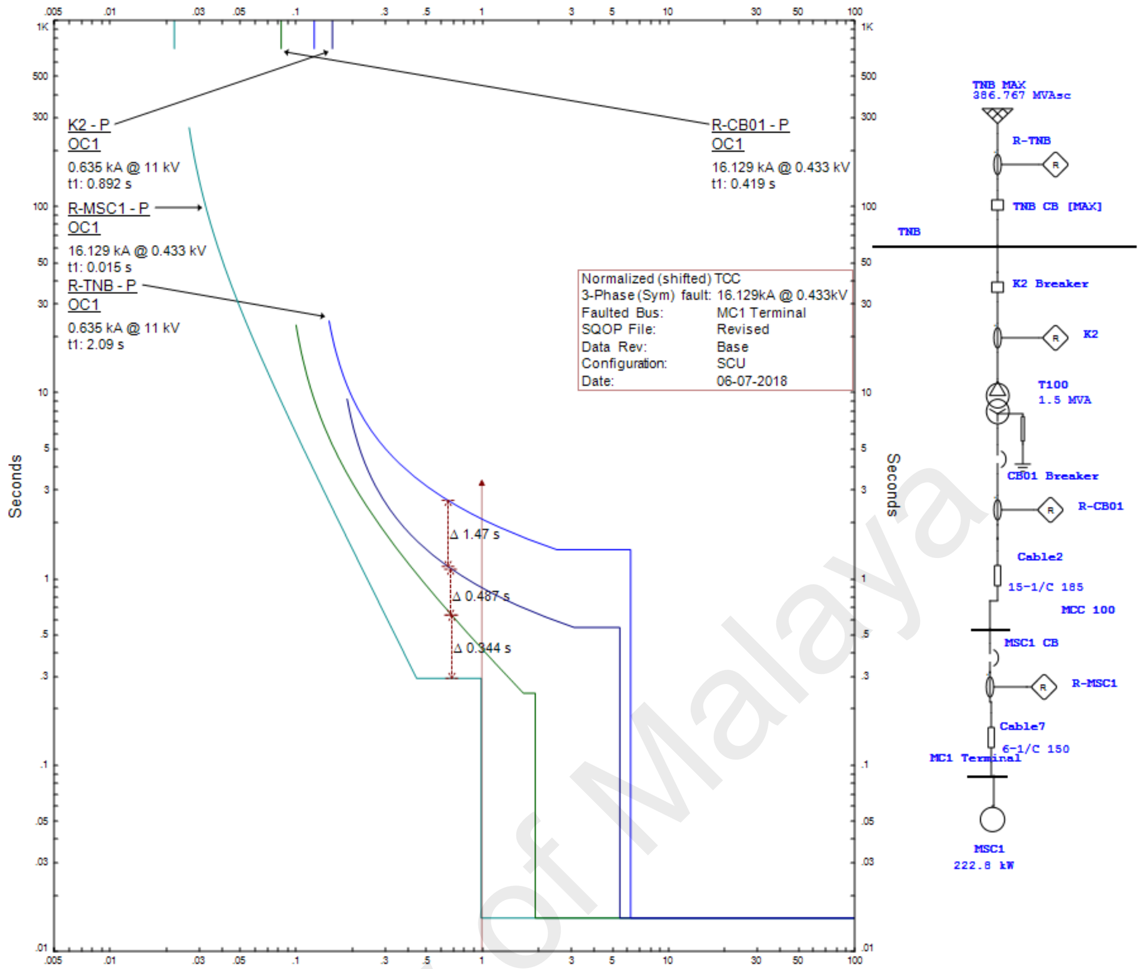

Figure 4.16: TCC, utility in service

Table 4.13: Sequence of operation, utility in service

Time (ms)	Relay ID	I_f (kA)	T1 (ms)	Condition
291	R-MSC1	15.691	291	Overcurrent
301	MSC1 CB		10	Tripped
432	R-CB01	15.691	432	Overcurrent
492	CB01 Breaker		60	Tripped
906	K2	0.618	906	Overcurrent
1006	K2 Breaker		100	Tripped
1850	R-TNB	0.635	1850	Overcurrent
1950	TNB CB		100	Tripped

As shows in Figure 4.15, the relay coordination is correctly configured when the fault occurs at the last point at downstream which is at motor compressor 1. The minimum time margin between two successive relays is 0.2sec (static relay). The instantaneous overcurrent setting for transformer primary shall be set to at least 125% of the maximum fault current at LV busbar, above the transformer inrush current and below the transformer damage curve. From Table 4.13 the sequence of relay operation due to the fault is shows and the time operation at TNB CB is 1.95sec, which is less than 2sec as a limit from the upstream.

4.4.2 Protection relay coordination result during DEG in service

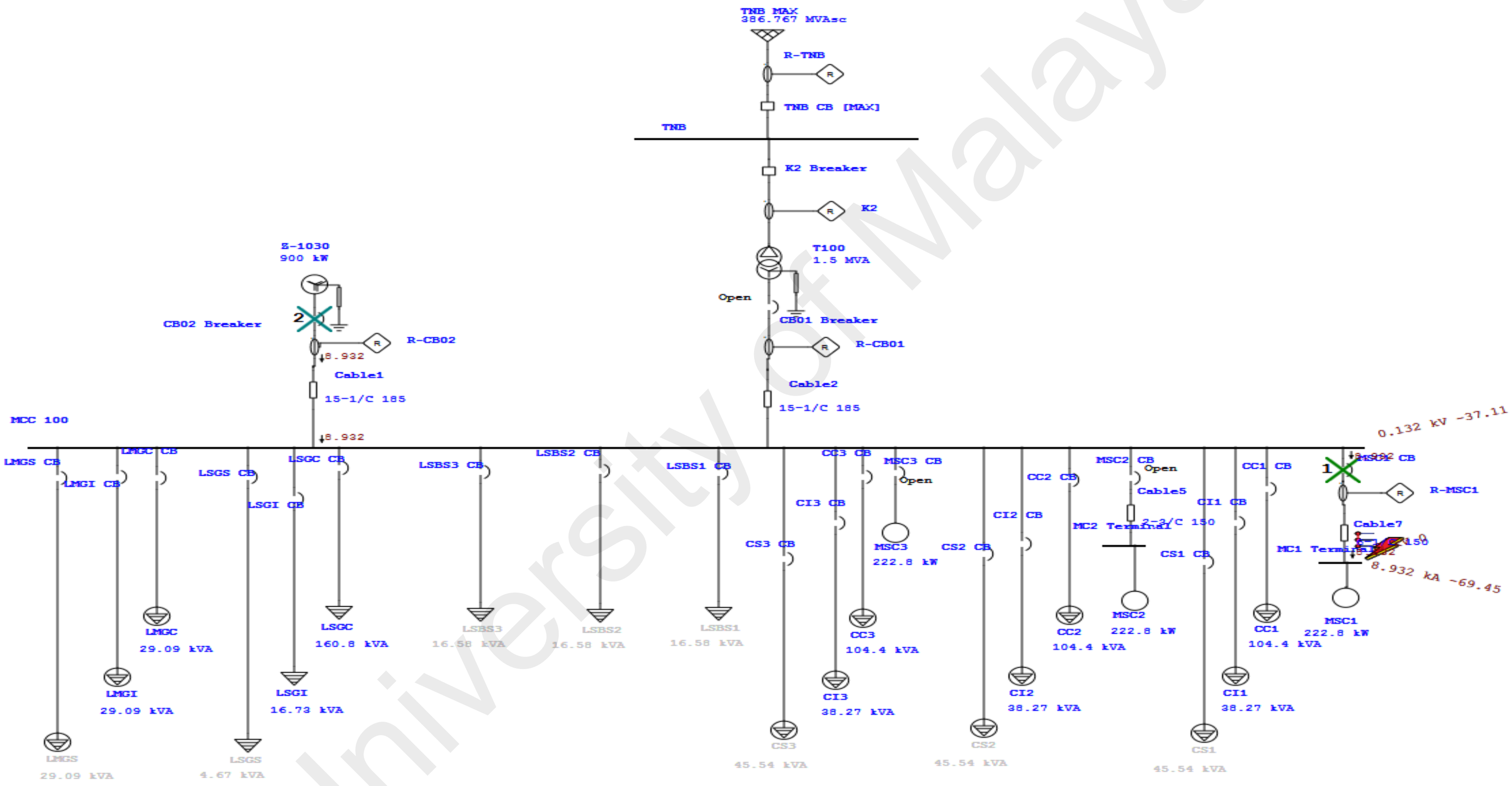

Figure 4.17: Relay coordination, DEG in service

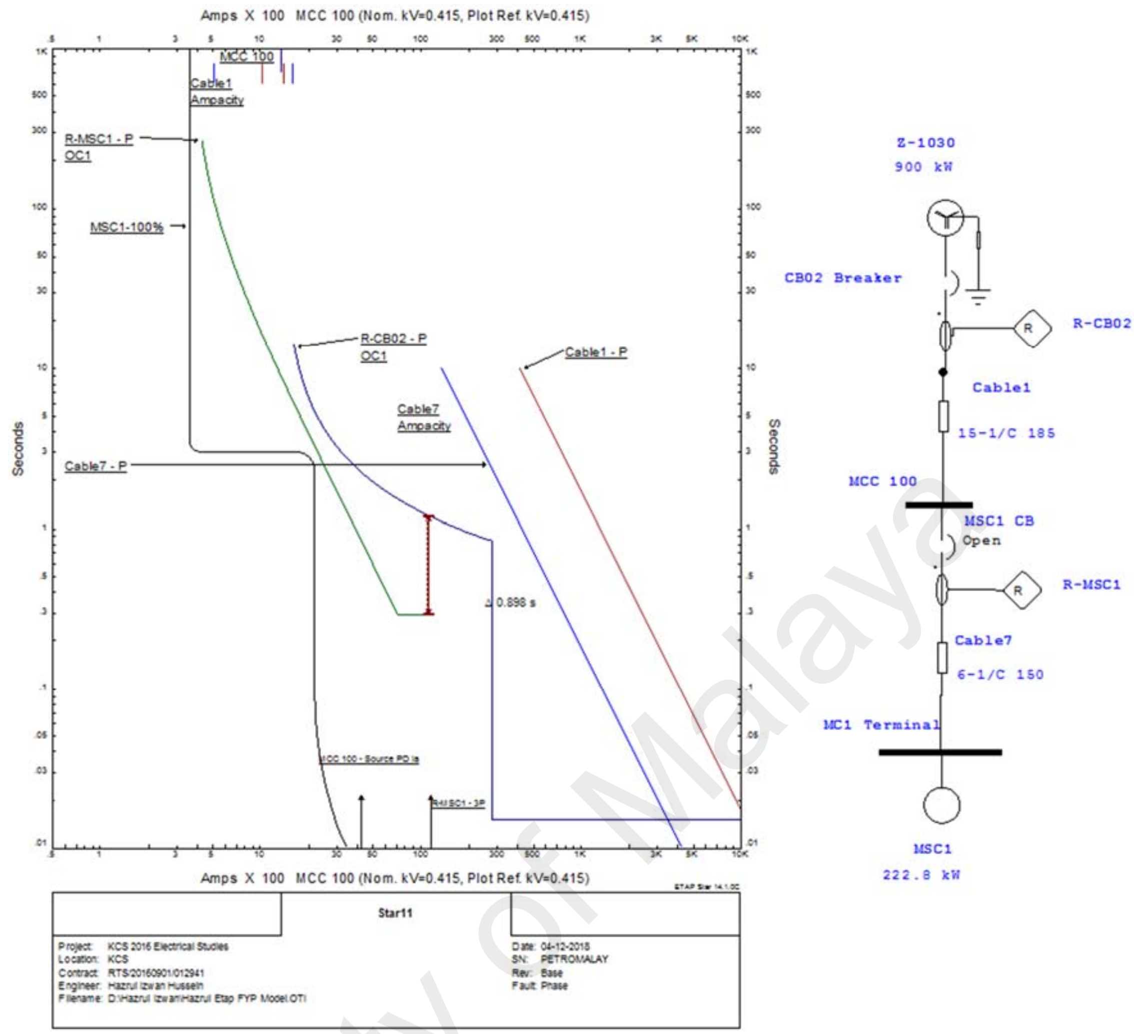

Figure 4.18: TCC, DEG in service

Table 4.14: Sequence of operation, DEG in service

Time (ms)	Relay ID	I_f (kA)	T1 (ms)	Condition
291	R-MSC1	8.932	21	Overcurrent
301	MSC1 CB		10	Tripped
1345	R-CB02	8.932	1345	Overcurrent
1405	CB02 Breaker		60	Tripped

As shows in Figure 4.17, the relay coordination is correctly configured when the fault occurs at the last point at downstream which is at motor compressor 1. The minimum time margin between two successive relays is 0.2sec (static relay). From Table 4.13 the sequence of relay operation due to the fault is shows and the time operation at CB 02 is 1.49sec which is less than 2sec as a limit during DEG in service.

CHAPTER 5: CONCLUSION

Three types of power system studies were performed for gas compressor station which are the load flow studies, largest motor starting studies, short circuit studies and relay protection coordination studies using ETAP Power Systems Software for both operating condition of the gas compressor station; utility in service (power supplied from Utility *TNB*) and DEG in service (during failure of utility).

Based on the load flow studies, it can be concluded that the sizing transformer, diesel engine generator and switchgears are adequate without any under/over loading and the steady state voltage deviation at the gas compressor station is also within the intended +/- 5% of rated voltage. No any on-load tap changers or any reactive power compensation techniques were required to control the system voltage during no load conditions. Based on the largest motor starting study, a DOL starter is selected to start the largest motor on the gas compressor station which is the motor starter for instrument air compressor. The DOL will have the least impact to the system in terms of short time equipment overloading and voltage drop during the instrument air compressor starting and will contribute in achieving a robust power system network on the gas compressor station. The short circuit studies performed were able to provide the maximum short circuit current that will be experienced by the system during fault at any points on the system and will be useful in specifying the short time short circuit withstand ability of all the electrical equipment on the gas compressor station during a fault. A fault happening in an electrical system is quite impossible to be avoided. Thus, all the equipment in an electrical network must be designed to withstand the maximum fault level for a certain time period before tripping by the protection system. The relay coordination setting through the ETAP has displayed the acceptable refinement between relay and its backup relay. With the limit of 2sec from the upstream has giving and enough time for the downstream relay to be coordinated and executed.

It can be concluded that all the objective of this research specified in Section 1.3 has been achieved. The power system studies performed will be useful for the electrical consultants to design an optimized, reliable and robust electrical system on the gas compressor station.

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