ASSESSING GRID INTEGRATION OF PHOTOVOLTAIC SYSTEMS IN MALAYSIAN DISTRIBUTION NETWORKS USING LOAD FLOW ANALYSIS

PHANG SIEW WEY

A project report submitted in partial fulfillment of the requirements for the award of Master of Engineering (Electrical)

Lee Kong Chian Faculty of Engineering and Science University Tunku Abdul Rahman

5 April 2024

DECLARATION

I hereby declare that the dissertation is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UTAR or other institutions.

Signature : ___________

Name : PHANG SIEW WEY

ID No. : 22UEM00907

Date : 5 April 2024

APPROVAL FOR SUBMISSION

This dissertation/thesis entitled "**ASSESSING GRID INTEGRATION OF PHOTOVOLTAIC SYSTEM IN MALAYSIA DISTRIBUTION NETWORKS USING LOAD FLOW"** was prepared by **PHANG SIEW WEY** and submitted as partial fulfillment of the requirements for the degree of Master of Engineering (Electrical) at Universiti Tunku Abdul Rahman.

Approved by:

Signature : jwong

Supervisor : Ir. Dr. Wong Jianhui

Date : 05/04/2024

Signature : ___________________

Co-Supervisor : None

Date : None

ACKNOWLEDGEMENT

I would like to express my gratitude to all who contributed and supported the completion of this project. Above all I am grateful to my supervisor Dr. Wong Jian Hui for her invaluable guidance, advice, encouragement, and precious time throughout the whole process of this final project.

ABSTRACT

The proposal aims to address the global energy consumption along with the environmental effects, global climate change caused by the greenhouse gas carbon dioxide (CO_2) emissions from fossil fuel and coal fire power generation, the use of solar PV energy is growing exponentially due to its clean, pollution free, abundant, and inexhaustible nature, however in the grid-connected PV system has an acceptance quality level. This project proposal presents the study of the impacts of grid-connected photovoltaics (GCPV) on the distribution network system that are considered with voltage profile and load flow study with ETAP simulation software.

Grid-connected photovoltaic systems are promising especially to commercial entities connecting on distribution networks because electricity costs can be a significant operational expense. With the installation of PV systems, these customers with an opportunity to generate their electricity, thereby reducing the reliance on utility-provided power and potentially lowering electricity bills. At present, the sizing of the photovoltaic (PV) systems for commercial customers typically follows a simplified approach based on static load profiles, maximum demand of the premise, or monthly average consumption data. This conventional method often involves analyzing historical energy usage data to estimate the required capacity of the PV system, considering factors such as roof space availability, solar irradiance levels, and local climate conditions. However, this approach is unable to evaluate the dynamic and time-varying nature of both the electricity demand and PV generation, leading to suboptimal system designs and potential mismatches between supply and demand. As a result, such conventional sizing methods may

provide inaccurate estimations of the PV system's performance and may either overestimate or underestimate the ability to meet the commercial customer's electricity demand, resulting in inefficient energy utilization or insufficient power supply during critical periods.

As such, this thesis presents a study to investigate the performance of the PV systems of a commercial customer using time-series load flow analysis in ETAP simulation software. By incorporating a detailed time domain load profile and solar generation pattern into the simulation software, time series load flow analysis enables a more accurate assessment of the interactions between PV generation and commercial electricity demand throughout the day.

TABLE OF CONTENTS

CHAPTER

LIST OF TABLE

LIST OF FIGURES

LIST OF ABBREVIATION

CO_2	Carbon Dioxide
PV	Photovoltaic
PSH	Peak Sun Hour
GCPV	Grid Connected Photovoltaic
KeTSA	Ministry of Energy and Natural Resources of Malaysia
RE	Renewable Energy
GDP	Goods Domestic Product
NEM	Net Energy Metering
EC	Energy Commissioning
SEDA	Sustainable Energy Development Authority
IA	Implement Agency
LSS	Large Scale Solar
ITRPV	International Technology Roadmap for Photovoltaics
Ag	Access gateway
SiNx	Silicon Nitride
Al	Alumimium
TFSC	Thin Film Solar Cell
CdTe	Cadmium Telluride
a-Si	Armorphous Silicon
CIGS	Copper Indium Gallium
BIPV	Building Integration Photovoltaics
CIGS	Copper-Indium-Gallium-Selenide
GaAs	Gallium Arsenide

DRES	Decentralised Renewable Energy System
LV	Low Voltage
HV	High Voltage
AC	Alternative Current
DC	Direct Current
kW	Kilo-Watt
kVAR	Kilo-Var
MW	Mega-Watt
THD	Total Harmonic Distortion
IEEE	Institute of Electrical and Electronics Engineers
Isc	Short Circuit Current
I_L	Load Current
TDD	Total Demand Distortion
PCC	Point of Common Coupling
MSB	Main Sub-Board
TNB	Tenaga Nationa Berhad
BIOTEMP	Bio-Based Temperature
ONAN	Oil Nature Air Nature
ONAF	Oil Nature Air Force
AVR	Auto Voltage Regulator
XLPE	Cross-Linked Polyethylene
SWA	Steel Wire Armored
PVC	Polyvinyl Chloride
Cu	Copper
MPPT	Maximum Power Point Tracking

Mag	Magnitude
PF	Power Factor
PL	Real Power
QL	Reactive Power
R	Resistance
P	Resistivity of copper in meters
A	Area
L	Length

CHAPTER 1

INTRODUCTION

1.1 General Introduction

Traditional fossil fuels such as coal and diesel electricity generation are combustion release greenhouse gases carbon dioxide (CO2). Which caused environmental impacts and climate change. (Tobnaghi, 2016). In 2021, the Ministry of Energy and Natural Resources of Malaysia (KeTSA) has aimed to set a target to reach 31% of renewable energy (RE), such as solar, biomass, and hydropower in the overall installed capacity mix by 2025. This objective aligns with Malaysia's international climate pledge to decrease its economy-wide carbon intensity (relative to Gross Domestic Product GDP) by 45% by the year 2030."

The Net Energy Metering (NEM) scheme, spearheaded by the Ministry of Energy and Natural Resources (KeTSA), overseen by the Energy Commission (EC), and implemented by the Sustainable Energy Development Authority (SEDA) Malaysia, was introduced by the Government (KoohiKamali et al., 2010).

Net Metering or Net Energy Metering (NEM 3.0) program by (SEDA) to encourage and boost the usage of renewable energy. In recent years, the price of solar power systems has decreased, and received a good response from commercial, industrial, and residential to engage in these opportunities to generate solar energy used in their electrical compliances and equipment, the excess electricity generated by the solar energy could be export to the grid, This exported electricity credits will be deduced from the electricity bill.

Due to the wide application areas of the PV panel installations that are permitted and eligible such as building rooftops (factories, residential and car parks) and the Large-scale Solar Photovoltaic Plant (LSS) ground-mounted systems as follow the guidelines on large-scale solar photovoltaic plant for connection to electricity network.

Eventually, it helps to reduce the amount of energy loss in transmission electricity, this also reduces the size of utility power plants and the number of transmission lines that must be constructed over the nation. The PV power system can be applied to remote or urban areas, there are two main applications including stand-alone PV systems and grid-connected systems. (Farhoodnea et al., 2012). The stand-alone PV system can be applied to remote areas. where there is always from the power utility power sources.

However, the PV is weather-dependent, it depends on the solar irradiance and the shading. The integration of Solar PV systems into the utility grid network process may create various types of power quality issues such as voltage profile against the voltage drop,(Mahela & Ola, 2016) voltage rise in traditional networks, power flow, harmonic, low load power factor and stability, Therefore, power system case study is required to determine the type of systems that can serve in different applications.

1.2 PROBEM STATEMENT

The photovoltaic effect is the direct conversion of light into solar electricity, Photovoltaic systems can be categorized as off-grid and on-grid. The Off-grid photovoltaic system also known as a stand-alone system where this system is designed to generate electricity without being connected to the grid. It typically consists of solar panels, a charge controller, batteries and an inverter. The On-Grid solar system is interconnected to the utility, it can access the electricity during the cloudy or rainy weather. When the solar electricity generates excess energy it can be sent back to the grid with compensation for that electricity. Therefore, proper system study of the application is necessary to improve and overcome power quality issues.

1.3 OBJECTIVES

This project proposal aims to study the impact of the PV system connected to the grid in power quality issues of the distribution network and to understand the PV solar system connected to the grid with the case study in ETAP software:

i.) To develop a simulation model for a commercial customer connected on the distribution network.

ii.) To investigate power demand and voltage profile with time domain.

CHAPTER 2

LITERATURE REVIEW

2.1 Background Impact of Grid-Connected Photovoltaic System

Solar cell technology, also known as photovoltaic (PV) technology, it has emerged during the Industrial Revolution with French physicist Alexandre Edmond Becquerel's demonstration of the photovoltaic effect. Which is the ability effect the solar cell to convert sunlight into electricity.. (MATTHEW SABAS, 2016). The solar panel technology advances through research and development, the process of manufacturing costs have decreased, and companies have resumed producing commercial bifacial modules since 2010, according to the International Technology Roadmap for Photovoltaics (ITRPV) predicts that by 2017, the global market share of bifacial technology will increase and expand from its previous level.

Despite advancements, PV systems encounter significant challenges. These challenges include high costs of investment, low efficiency, overloading of feeders, harmonic pollution, and reliability issues, which causes to slow down their widespread adoption. In addition, the variations in solar irradiation can lead to power fluctuations and voltage flicker, those negative factors impacting highly within the power grid.

2.2 There are three main types of solar panels:

2.2.1 Monocrystalline Solar Panel

A monocrystalline solar panel is a solar panel made of monocrystalline solar cells, it consists of a single-crystal silicon ingot of high purity. which is then sliced into thin wafers similar to those used in semiconductor electronic components. As the cell is constituted of a single crystal, it allows the electrons more space to move efficiently for a better electricity flow. These panel life span can up to 25 years or more. (Jacob Marsh, 2023)

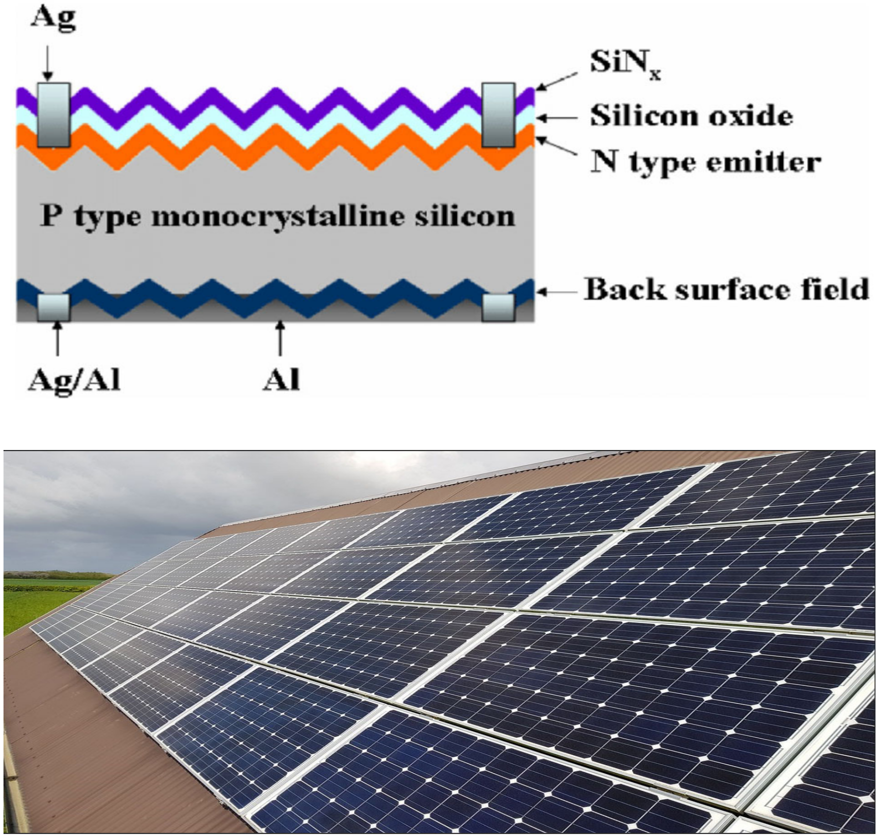
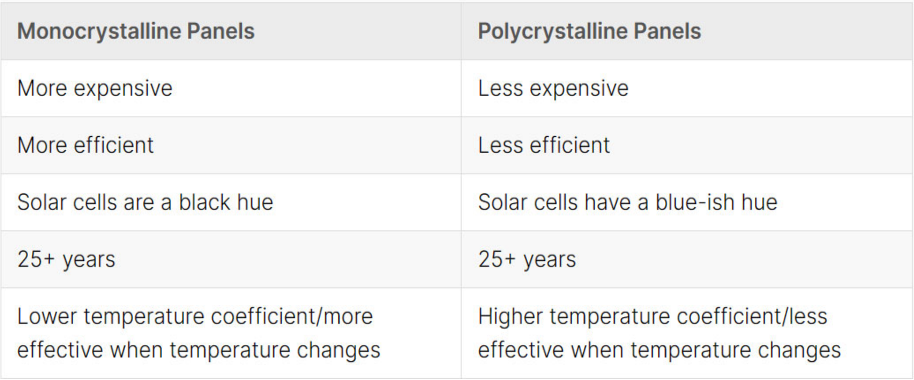


Figure 2.1. Monocrystalline Roof Top Installation

2.2.2 Polycrystalline Solar Panel

Polycrystalline solar panels, also known as poly panels, are constructed using individual polycrystalline solar cells. These cells are made from silicon fragments instead of using a single silicon crystal. The manufacturer's process melts many silicon fragments together to form wafers for the panel. polycrystalline panels have a blue-colored appearance due to their multiple silicon crystals.

Figure 2.2. Polycrystalline Ground Mounted Installation



Monocrystalline Panels	Polycrystalline Panels
More expensive	Less expensive
More efficient	Less efficient
Solar cells are a black hue	Solar cells have a blue-ish hue
25+ years	25+ years
Lower temperature coefficient/more effective when temperature changes	Higher temperature coefficient/less effective when temperature changes

Table 2.1. Monocrystalline and Polycrystalline Solar Panel

2.2.3 Thin-film Solar Panel

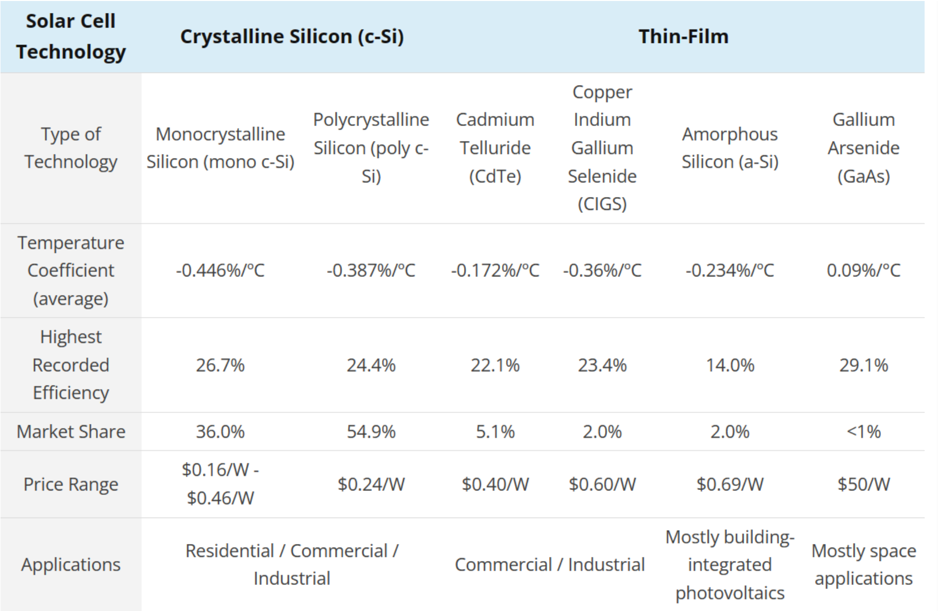
The thin-film solar cells (TFSC) are lightweight, thin, and flexible in size. It can be manufactured by using different materials, such as glass, metal, cadmium telluride (CdTe), Armorphous Silicon (a-Si), and copper indium gallium (CIGS),

Most thin-film solar cells are classified as *second generation*, These thin-film solar panel technologies offer higher efficiency and lower cost. Unlike traditional solar panels, thin solar cells are much lighter more flexible, and cheaper compared to the traditional solar panels.

Crystalline silicon (c-Si) technology is the most widely used material and will probably keep having the major share in the market due to its high-rated efficiency and low manufacturing prices.

Overall, thin solar cell technologies in the future increasing its market share will depend on continued research to achieve improvement in their efficiency, stability, reliability, and friendly environmental applicability to make it a better option in a wide range of applications not only on large-scale but also in small scale for commercial, industrial and residential sectors.

Figure 2.3 Thin-film Solar Panel



Solar Cell Technology	Crystalline Silicon (c-Si)		Thin-Film			
Type of Technology	Monocrystalline Silicon (mono c-Si)	Polycrystalline Silicon (poly c-Si)	Cadmium Telluride (CdTe)	Copper Indium Gallium Selenide (CIGS)	Amorphous Silicon (a-Si)	Gallium Arsenide (GaAs)
Temperature Coefficient (average)	-0.446%/ºC	-0.387%/ºC	-0.172%/ºC	-0.36%/ºC	-0.234%/ºC	0.09%/ºC
Highest Recorded Efficiency	26.7%	24.4%	22.1%	23.4%	14.0%	29.1%
Market Share	36.0%	54.9%	5.1%	2.0%	2.0%	<1%
Price Range	$0.16/W - $0.46/W	$0.24/W	$0.40/W	$0.60/W	$0.69/W	$50/W
Applications	Residential / Commercial / Industrial		Commercial / Industrial		Mostly building-integrated photovoltaics	Mostly space applications

Table 2.2: Comparison of Monocrystalline and Polycrystalline Solar Panel

Monocrystalline solar panels are made from a single crystal structure, which provides the electrons more space to move for a better electricity flow. As a result, they tend to be more efficient than other types. However, the price is higher compared to others.

Crystalline solar panels also called multi-crystalline panels are made of multiple silicon crystals fused. The price is cheaper compared to monocrystalline solar panels. However, the crystalline solar panels are less efficient than monocrystalline.

2.3 Stand Alone Solar PV

Stand-alone solar PV systems are not connected to the utility grid rely on solar power only and are normally used in remote and rural areas. Their capacity is milli watt to a few kilowatts. The system can be only the solar panel and a load or included with the batteries as energy storage. The charge controller is used to charge the batteries and prevent them batteries from over charged. The energy stored in the batteries can be used during the poor weather and night time. The inverter inverts the battery's energy from DC voltage range to AC voltage and frequency in the desired range.

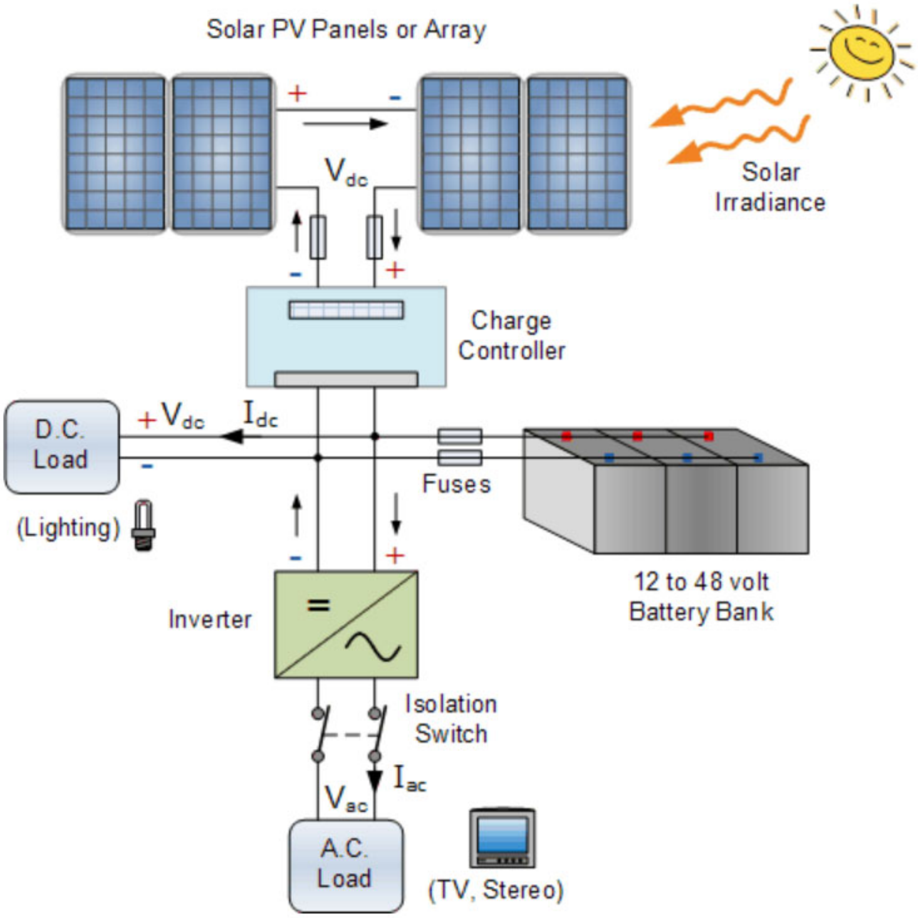


Figure 2.4. Stand-alone Solar Power System

2.4 Grid Connected PV System

A grid connected PV system is one where the photovoltaic PV panels are connected to the utility grid through a power inverter unit allowing them to operate in parallel with the electric utility grid. The conventional power network is designed to supply electric power the consumer through generation plants to generate the electricity power step-up to high voltage by step-up transformers to transmit through the transmission line from hight voltage step down to medium and low voltage distribution networks to various customers. (Mahela & Ola, 2016)

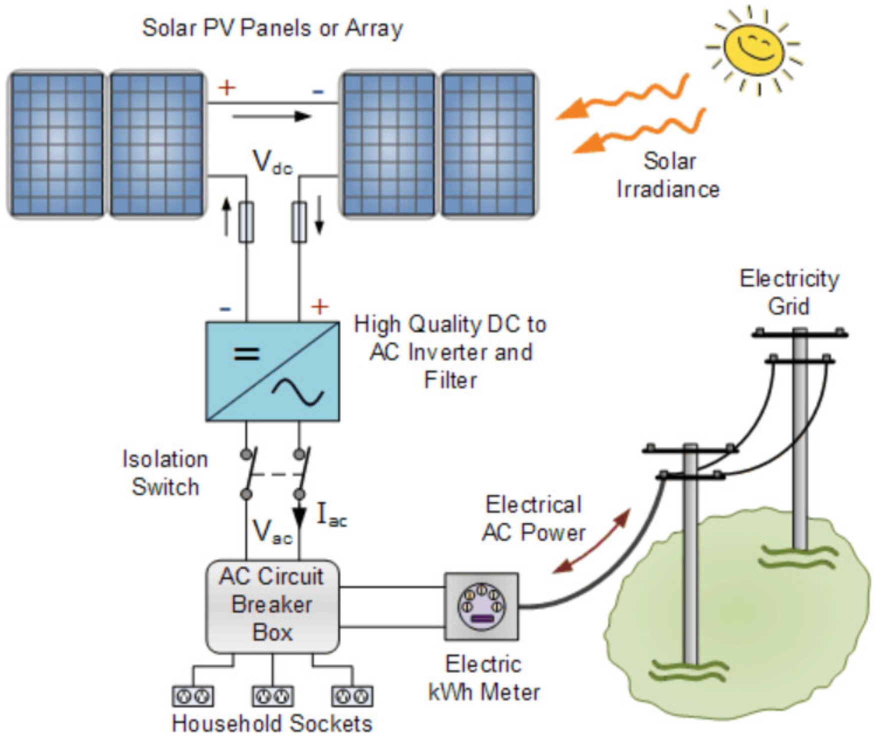


Figure 2.5. Grid-connected Photovoltaics Solar Power System

The impact on the grid connected photovoltaics (GCPV) become a technical challenges such as power quality, voltage regulation, low power factor, power system fault, switching and synchronization with the conventional grid.

2.5 Power Quality

Power quality is a general term to describe how the voltage supply in the electrical system to the equipment with a definition guide line of the acceptable level within the standard.

These also help determine what voltage range is required to operate equipment effectively, which is essential to the efficient and reliable operation of sensitive electronic loads.(Farhoodnea et al., 2012)

Basically there are categorized 4 groups:

1. Voltage variation
    - i) Short variation
        - Voltage Sag
        - Voltage Swell
        - Interruption
    - ii) Long Duration
        - Over Voltage
        - Under Voltage
        - Sustained Interruption
2. Harmonic Distortion:
    - Total Harmonic
    - Individual Harmonic
3. Transient:
    - Large capacitive switching
    - Lighting over voltage induced
4. Steady state voltage variation:
    - Voltage unbalance
    - Voltage regulation

2.6 Voltage Profile

The voltage profile in grid-connected PV usually varies according to the solar system design, irradiation, and temperature. it poses challenges to their grid integration, especially at high concentrations on the LV grid such as is the case with residential, industrial, and commercial. production curve of the grid-connected PV with the typical electricity usage patterns of residential and industrial can lead to voltage stability issues along the feeder or congestion at the substation. This may cause a reduction in the power quality of the grid.(Laveyne et al., 2020)

There are some common issues that arise in grid-connected PV systems, such as the output of distributed photovoltaic is random and varies, Which makes the voltage unstable or imbalance of grid load causes more challenge and difficulty to adjust the voltage regulation of the distribution network, The medium and low voltage distribution transformers have no on-load voltage regulation capability, furthermore, there may have a large number of power electronic switching devices in the circuit, which will also generate the harmonics to present in the distribution system.

After the photovoltaic system is connected to the grid, the peak period of the power supply can provide support for the operation of the distribution network and reduce the load pressure. Once the photovoltaic system has a high output and the load is low, an overvoltage phenomenon has occurred.

2.7 Power System Monitoring

Power system monitoring is a device to measure and monitor the electrical system network condition including detecting system abnormality, alarm, event logging, history trending data, disturbance record, harmonic, maximum minimum demands, and power measurement.

2.7.1 Harmonic

Harmonics are the integer multiple of the fundamental frequency of 50Hz. A perfect sine wave of 50Hz is always expected in the power system, however, the harmonic is caused by nonlinear load such as switching devices, power inverters, rectifiers, computers, arcing devices (welders, arc furnaces) iron saturating devices (transformer) etc…. The harmonic produced can cause to overheating on the transformers, capacitor banks, and motors. (Al-Shetwi et al., 2020)

By definition, total harmonic distortion (THD) of current or voltage is equal to the effective value of all the harmonic divided by the effective value of the fundamental value.(Jo et al., 2013).

$$THD_V = \sqrt{\frac{\sum_{k=2}^{N-1} V_k^2}{V_1}}, \quad THD_I = \sqrt{\frac{\sum_{k=2}^{N-1} I_k^2}{I_1}}$$

eq….1

Where N is the maximum number of harmonics, the k of voltage and current harmonic is the order of the harmonics.(Zobaa & Abdel Aleem, 2014).

According to the IEEE Std 519. The total voltage harmonic distortion THD $_{Vn}$ is below then 5.0%. and each individual is limited to 3%. (Blooming et al., n.d.).

Bus Voltage at PCC, Vn (kV)	**Individual harmonic voltage distortion (%)**	**Total voltage harmonic distortion, THD $_{Vn}$**
Vn < 69	3.0	5.0
69 ≤ Vn ≤161	1.5	2.5
Vn > 161	1.0	1.5

Table 2.3: Harmonic Voltage Distortion Limits in Percent of Normal Fundamental Frequency Voltage. (Source: IEEE Std. 519-1992, Table 11.1).

Maximum Harmonic Current Distortion in Percent of I_L						
Individual Harmonic Order (Odd Harmonics)						
Isc/I_L	**h < 11**	**11 ≤ h ≤ 17**	**17 ≤ h ≤ 23**	**23 ≤ h ≤ 25**	**35 ≤ h**	**TDD**
< 20	4.0	2.0	1.5	0.6	0.3	5.0
20 – 50	7.0	3.5	2.5	1.0	0.5	8.0
50 – 100	10.0	4.5	4.0	1.5	0.7	12.0
100 – 1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0

Table 2.4: Current Distortion Limits for General Distribution Systems (120V – 69000V) IEEE Std: 519-1992, Harmonic Current Limits.

All the electrical equipment shall follow the limited to these values of current distortion, regardless of actual Isc / I_L. Even harmonics are limited to 25% of the odd harmonic limits above. (Makram et al., 1993)

Where:

- Isc= Maximum short-circuit current at the point of common coupling (PCC).
- I_L = Maximum demand load current (fundamental frequency component) at PCC.

- TDD = Total demand distortion (RSS), harmonic current distortion in % of maximum demand load current (15 or 30 minutes demand).

2.8 Protection Coordinate Between PV and Grid

The protection of the PV connected to the Grid plays an important role in preserving reliable operation in the electrical network system, When PV is integrated into the grid network system, they will distribute energy sources and adversely affect the protection coordination in the distribution network.

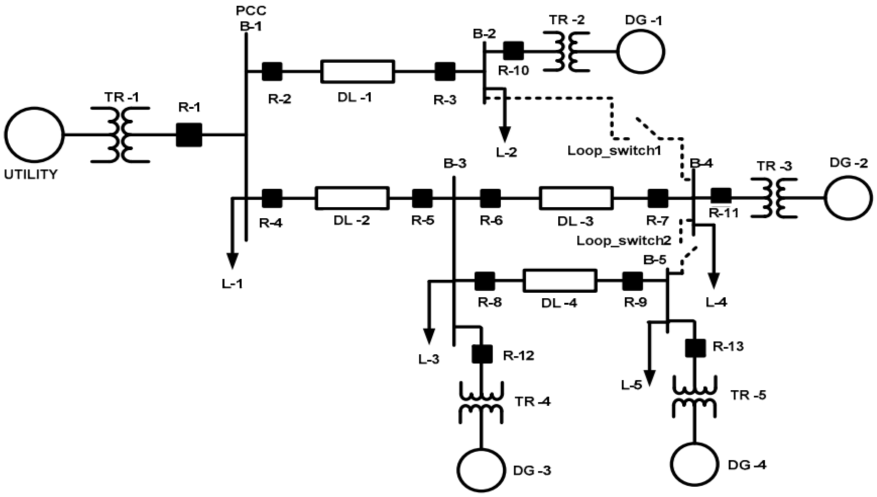


Fig 2.6. Single-line Diagram for Microgrid Connection

To ensure the safe and reliable operation of PV connected to the grid utility of the micro-grid shown in Figure 2.6, the (backup protection) functions must be provided, Which protection parameters setting and configuration of the protection numerical relay will protect against fault and coordinate in the designed network system when primary protection fails. During the fault incident, both primary and backup protection functions will be picked up or start simultaneously. However, the primary protection function sends a tripping signal to isolate the fault circuit through the circuit breaker. If the failure of the primary protection function to isolate the faulty circuit, then the backup protection function will send another tripping signal to isolate the faulty circuit with a time margin delay of 0.2 sec.

Normally overcurrent with directional relay is applied for fault protection when there is bidirectional power flow with GCPV or parallel circuit in the distribution network(Kar et al., 2016).

The directional overcurrent relay will work as primary protection in its zone and as a limit of back work or reverse current flow between the PV with grid-connected system. (Fani et al., 2018)From the Fig.1. it is observed that R6 and R7 are primary relay for fault in distribution line 3 (DL3), and R7 can also be backup relay for fault in DL2 and DL4. However, the load flow, and fault analysis in the GCPV systems need to be considered in the protection coordination between PV generation and utility (Saad et al., 2018).

CHAPTER 3

Simulation Model of the Grid-connected PV Systems on Distribution Network for A Commercial Customer

3.1 Introduction of Simulation Model

The systems of Grid-connected PV on distribution networks for commercial such like industries play a pivotal role in enhancing the global energy transition goal to reducing the CO2 net emission and electricity costs for businesses. An actual case study was chosen for a factory from Shah Alam industrial area in Malaysia. A PV Solar 540kWp rooftop installation connected to the existing 415V Main Switchboard (MSB). The steady-state and time domain load flow simulation studies are performed by using ETAP to investigate the impact on the voltage profile of the system.

3.2 Electrical Distribution in a Factory

There is an 11kV incomer from the utility provider, namely Tenaga National Berhad (TNB), and two 11kV outgoing feeders to transformers No.1 and 2. The two 11kV / 415V transformers to 415V LV MSB1 and 2. The solar panel is connected to the 415V MSB no.1 and 2 with 540kW as shown in the single line below.

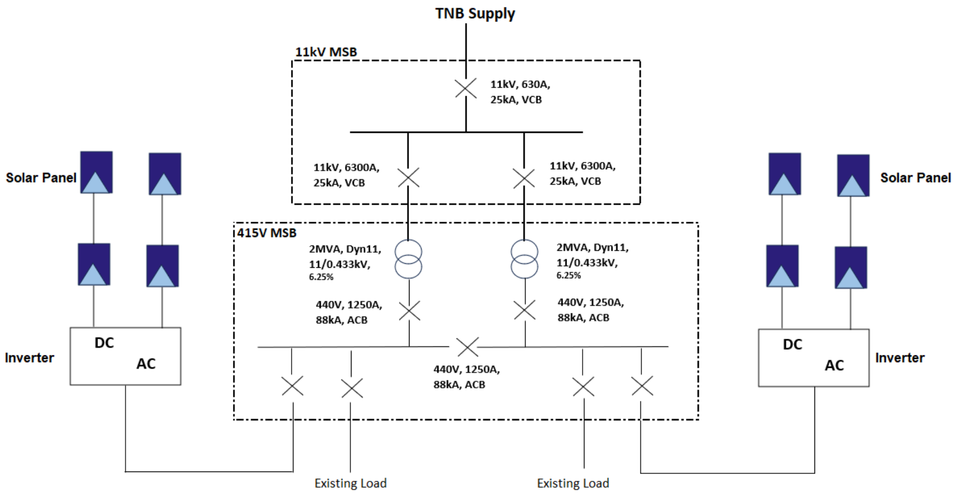
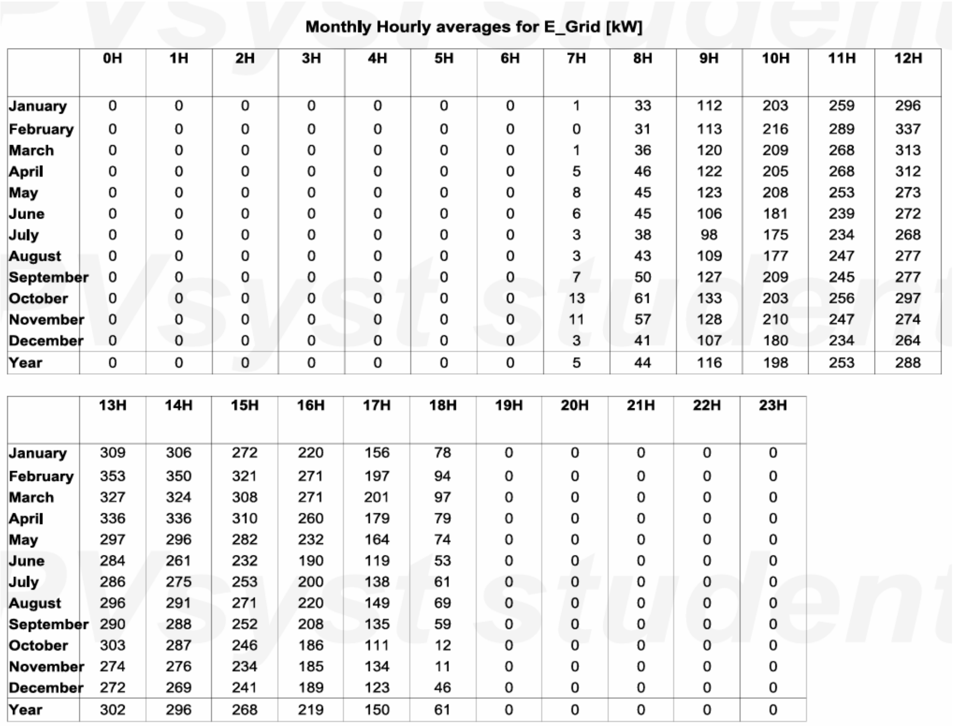


Figure 3.1 Singe-line Diagram

3.2.1 Figure of Simulation Model

To assess the impact of the present grid-connected PV system, data information, and specifications availability were obtained from the factory for this project case studies. The simulation model is based on load flow analysis and time domain series in ETAP as an AC dynamic modeling tool.

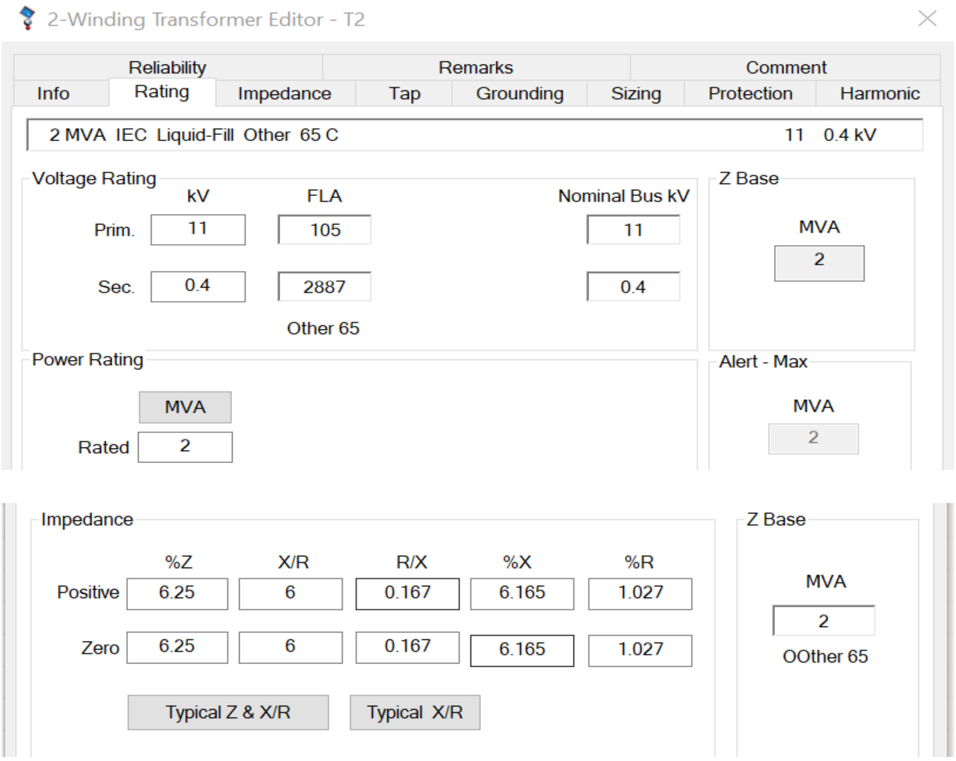
The data of monthly hourly average PV (kW) results are simulated by PVsyst in Table 3.1. This is according to the details of data and specifications given by the factory. The monthly hourly average PV (kW) is a reference for the ETAP time domain load flow simulation.



Monthly Hourly averages for E_Grid [kW]

	0H	1H	2H	3H	4H	5H	6H	7H	8H	9H	10H	11H	12H	13H	14H	15H	16H	17H	18H	19H	20H	21H	22H	23H
January	0	0	0	0	0	0	0	1	33	112	203	259	296	309	306	272	220	156	78	0	0	0	0	0
February	0	0	0	0	0	0	0	0	31	113	216	289	337	353	350	321	271	197	94	0	0	0	0	0
March	0	0	0	0	0	0	0	1	36	120	209	268	313	327	324	308	271	201	97	0	0	0	0	0
April	0	0	0	0	0	0	0	5	46	122	205	268	312	336	336	310	260	179	79	0	0	0	0	0
May	0	0	0	0	0	0	0	8	45	123	208	253	273	297	296	282	232	164	74	0	0	0	0	0
June	0	0	0	0	0	0	0	6	45	106	181	239	272	284	261	232	190	119	53	0	0	0	0	0
July	0	0	0	0	0	0	0	3	38	98	175	234	268	286	275	253	200	138	61	0	0	0	0	0
August	0	0	0	0	0	0	0	3	43	109	177	247	277	296	291	271	220	149	69	0	0	0	0	0
September	0	0	0	0	0	0	0	7	50	127	209	245	277	290	288	252	208	135	59	0	0	0	0	0
October	0	0	0	0	0	0	0	13	61	133	203	256	297	303	287	246	186	111	12	0	0	0	0	0
November	0	0	0	0	0	0	0	11	57	128	210	247	274	274	276	234	185	134	11	0	0	0	0	0
December	0	0	0	0	0	0	0	3	41	107	180	234	264	272	269	241	189	123	46	0	0	0	0	0
Year	0	0	0	0	0	0	0	5	44	116	198	253	288	302	296	268	219	150	61	0	0	0	0	0

Table 3.1 Monthly Hourly Average for PV System Energy Generated



2 MVA IEC Liquid-Fill Other 65 C 11 0.4 kV

Voltage Rating

	kV	FLA	Nominal Bus kV
Prim.	11	105	11
Sec.	0.4	2887	0.4

Other 65

Z Base: MVA 2

Power Rating: MVA Rated 2

Alert - Max: MVA 2

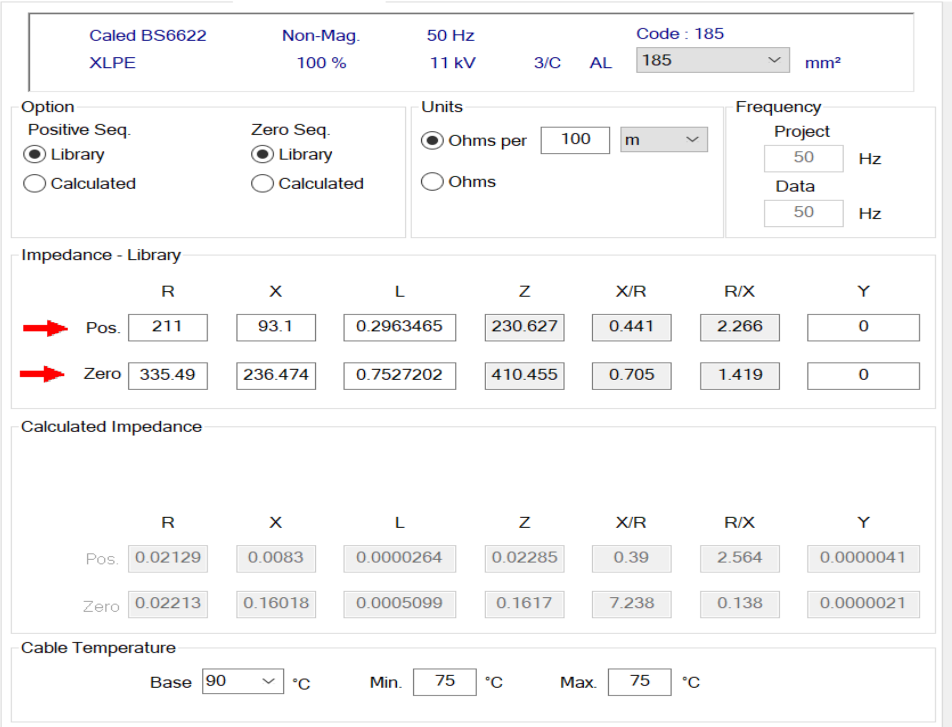
Impedance

	%Z	X/R	R/X	%X	%R
Positive	6.25	6	0.167	6.165	1.027
Zero	6.25	6	0.167	6.165	1.027

Z Base: MVA 2

OOther 65

Figure 3.2 Transformer Specification and Parameters



Caled BS6622 Non-Mag. 50 Hz Code : 185

XLPE 100 % 11 kV 3/C AL 185 mm²

Option

Positive Seq.: ● Library ○ Calculated

Zero Seq.: ● Library ○ Calculated

Units: ● Ohms per 100 m ○ Ohms

Frequency: Project 50 Hz; Data 50 Hz

Impedance - Library

	R	X	L	Z	X/R	R/X	Y
Pos.	211	93.1	0.2963465	230.627	0.441	2.266	0
Zero	335.49	236.474	0.7527202	410.455	0.705	1.419	0

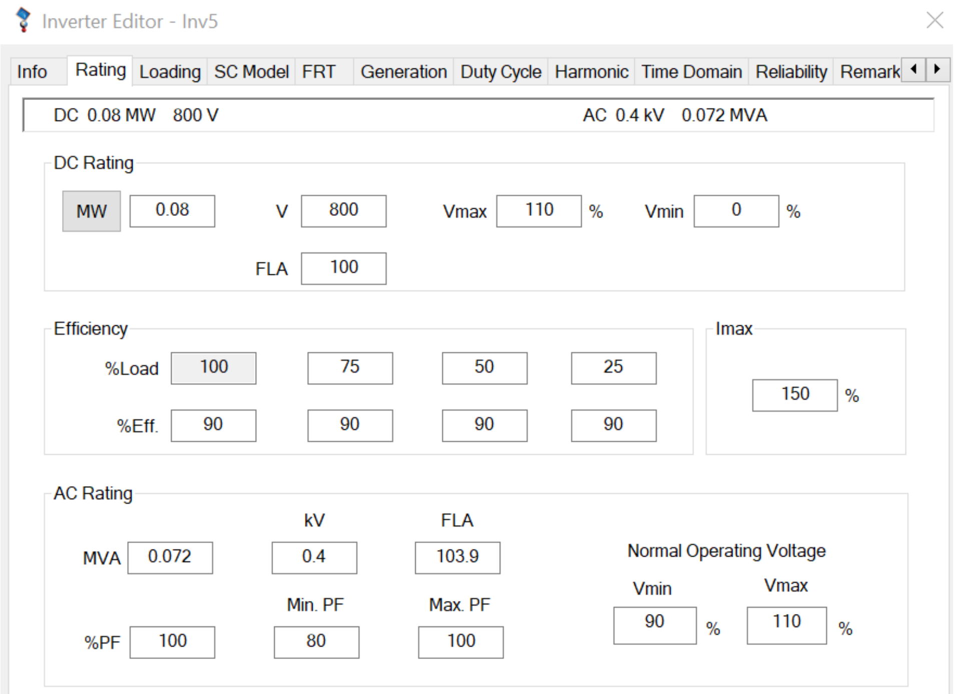
Calculated Impedance

	R	X	L	Z	X/R	R/X	Y
Pos.	0.02129	0.0083	0.0000264	0.02285	0.39	2.564	0.0000041
Zero	0.02213	0.16018	0.0005099	0.1617	7.238	0.138	0.0000021

Cable Temperature

Base 90 °C Min. 75 °C Max. 75 °C

Figure 3.3 11kV Cable Specification and Parameters



DC 0.08 MW 800 V AC 0.4 kV 0.072 MVA

DC Rating

MW 0.08 V 800 Vmax 110 % Vmin 0 %

FLA 100

Efficiency

%Load	100	75	50	25
%Eff.	90	90	90	90

Imax 150 %

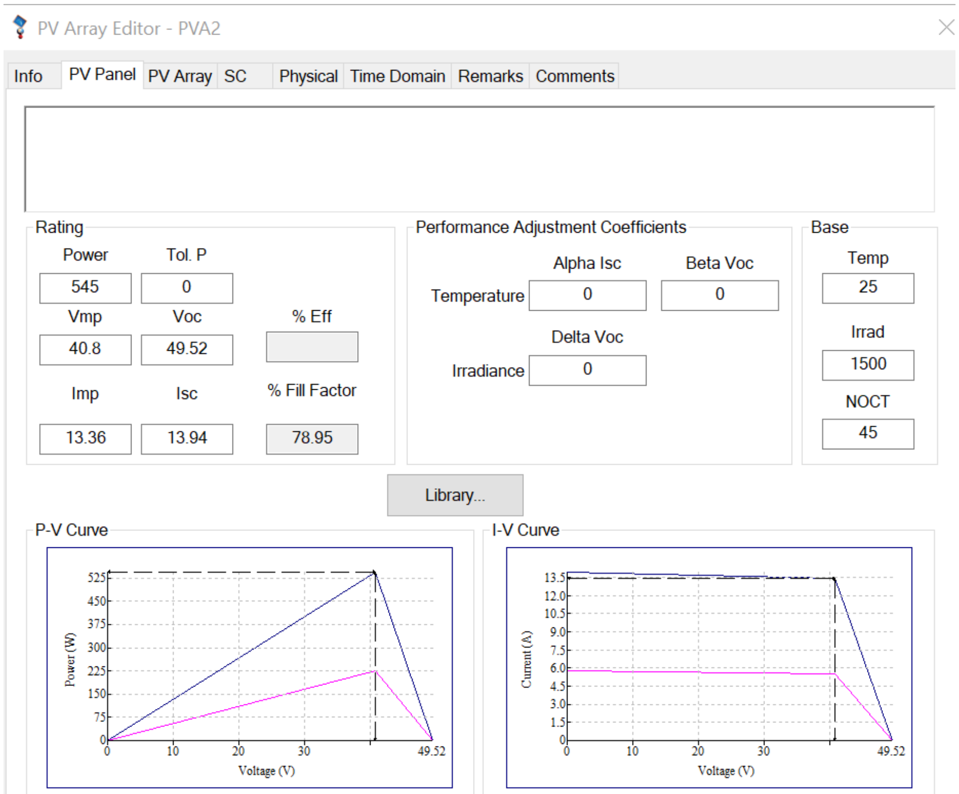
AC Rating

MVA 0.072 kV 0.4 FLA 103.9

%PF 100 Min. PF 80 Max. PF 100

Normal Operating Voltage: Vmin 90 % Vmax 110 %

Figure 3.4 Inverter Specification and Parameters



Rating

Power	Tol. P	% Eff
545	0	

Vmp	Voc
40.8	49.52

Imp	Isc	% Fill Factor
13.36	13.94	78.95

Performance Adjustment Coefficients

	Alpha Isc	Beta Voc
Temperature	0	0

	Delta Voc
Irradiance	0

Base

Temp: 25

Irrad: 1500

NOCT: 45

Figure 3.5 PV Panel Specification and Parameters

3.2.2 Oil Type Distribution Transformer

The oil-type distribution transformers are used in distribution systems, power plants, industries, and commercial buildings. The specific features include copper or aluminum winding, epoxy or porcelain bushings, protection gauges for winding, and oil temperature alarm and trip. pressure relief, oil level, and Buchholz relay protection.

The transformer nameplate contains information and the transformer specification to show in the details of the transformer which also includes the serial number for reference and identification as below in Table 3.2

Manufacturer :	ABB	HV :	11000V
Type :	ONAN	LV :	400V
Class :	A	HV Current :	105A
kVA :	2000	LV Current :	2887A
Imp :	6.25%	Oil Temp Rise :	60°C
Wind. Temp Rise :	55°C	Vector group :	Dyn11

Table 3.2 Transformer Nameplate Details

3.2.3 Transformer Insulation Oil

Transformer or insulation oil is used for transformer cooling and insulation purposes. Most of the oil type transformer in the market is using mineral oil, which is the most common liquid used, it provide the optimal balance between cost and technical properties. The important properties are specified in IEC 60296. (Flashpoint 145 °C, density 0,88 kg/dm3, relative permittivity 2,2). Other fluids are reserved for special request for applications where the high-risk area or a fire-prone zone, and the cost is typically 5-6 times more expensive than silicon oil. The main purpose of using other fluids is to improve risk of fire and environmental impact. BIOTEMP is biodegradable which is based on sunflower oil and is less flammable and thermally efficient. It’s an idea to apply in environmentally sensitive areas (Flashpoint 330 °C, density 0,91 kg/dm3, relative permittivity 3,2.). (Transformer Handbook, n.d.)

Figure 3.6 Oil Type Transformer (Typical IEC Product)

Machine load consumption is 40% of the transformer capacity rating in the factory. The transformer power rating is higher than the load to have a margin for future needs in expansion. The capacity or rating of a transformer depends on the insulation-tolerant design of the manufacturer. The life of the transformer can be extended if the operating load condition is below its insulation class temperature and rating. The class number is the maximum degree °C of the transformer insulation. Recommended for transformer oil and winding protection gauges thermometer setting as below Table3.3(Transformer Handbook, n.d.)

Type of temperature equipment	**Alarm**	**Tripping**
Oil thermometer setting	85°C	100°C
Oil thermometer setting, when combined with a winding temperature indicator	90°C	105°C
Winding temperature indicator setting	105°C	135°C

Table 3.3 Oil and Winding Thermometer Setting

The oil-type transformer cooling methods are normally Oil Nature Air Nature (ONAN) or Oil Nature Air Force (ONAN). ONAN transformer is suitable for lower loading and the ONAF transformer is applied to where ambient temperature and load is higher.

The permissible continuous symmetrical loading capacity at different ambient air temperatures for the Oil Natural Air Natural (ONAN) transformer as below in Table 3.4.

Constant ambient at temperature °C	0	+10	+20	+30	+40	+50	+60
Permissible continuous load factor % Temperature rise 60/65°C	116	108	100	91	82	72	--
Permissible continuous load factor % Temperature rise 50/55°C	-	119	110	100	89	77	64

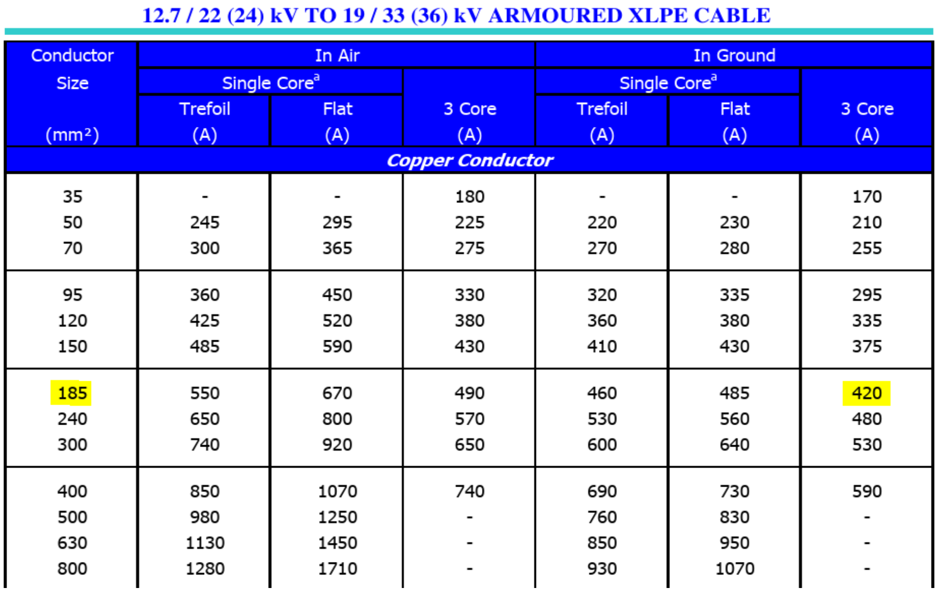
Table 3.4 Permissible Continuous Symmetrical Loading at Different Air Temperatures

3.2.4 Transformer Tap Changer

The 415V MSB panel incoming supply voltage from the 11kV / 415V transformer turn ratio can be adjusted by changing the tap changer tap in different positions to regulate the output voltage. There are a total of 5 tap positions and each tap is 2.5% different in turn ratio. The tap changer can be selected with an on-load tap changer or off-load tap changer during the ordering stage. Off-load tap changer should be operated only when the transformer is deactivated. On-load tap changer is usually controlled by the auto voltage regulator (AVR) to move the contact between the taps.

3.2.5 Power Cable

The power cable from the 11kV HV panel to the transformer is using 1 x 3C x 185mm^2 XLPE / SWA / PVC / CU CABLE. The distance between the 11kV transformer feeder panel to the transformer HV termination is 20 meters. The cable current rating for armored XLPE cupper conductor is below Table 3.5.



12.7 / 22 (24) kV TO 19 / 33 (36) kV ARMOURED XLPE CABLE

Conductor Size	In Air			In Ground		
	Single Core[a]			Single Core[a]		
(mm²)	Trefoil (A)	Flat (A)	3 Core (A)	Trefoil (A)	Flat (A)	3 Core (A)
Copper Conductor						
35	-	-	180	-	-	170
50	245	295	225	220	230	210
70	300	365	275	270	280	255
95	360	450	330	320	335	295
120	425	520	380	360	380	335
150	485	590	430	410	430	375
185	550	670	490	460	485	420
240	650	800	570	530	560	480
300	740	920	650	600	640	530
400	850	1070	740	690	730	590
500	980	1250	-	760	830	-
630	1130	1450	-	850	950	-
800	1280	1710	-	930	1070	-

Table 3.5 12.7kV Current Rating for Armoured XLPE Copper Cable

The cable resistance depends on several factors such as temperature, length, resistivity, and material, the cable resistance will be increased when the temperature is increased, So, it's temperature-dependent and Therefore, the resistance of a conductor should be calculated at the worst-case temperature. Normally +75°C is used for calculations.

R = $\frac{\rho\ x\ L}{A}$

Where R = Resistance in Ohm.

P= Resistivity of copper in meters (m)

A = Cross-section area of the conductor in square (m^2)

The cable cross-section area, per cable length at 75°C for copper is given in the Table below 3.6

Material	**185mm^2**	**240mm^2**
Copper	0.0002129	0.0001095

Table 3.6 Resistance Per-Cable Length (+75°C) for Copper

The components and its functions of a medium voltage cable are as below figure 3.3.

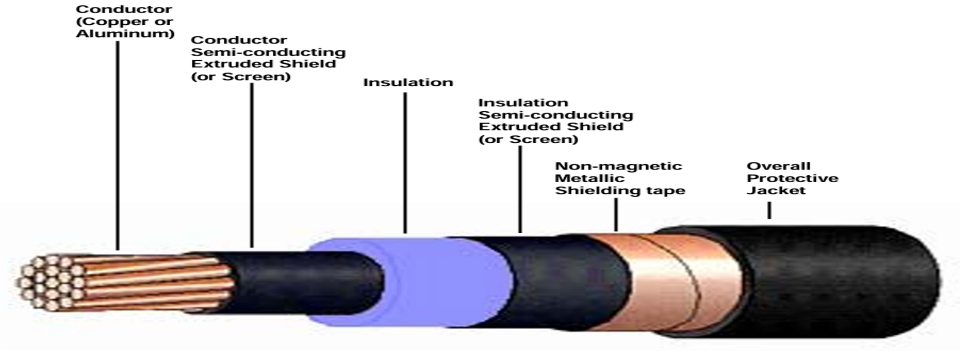


Figure 3.7 Typical Shield Power Cable Design

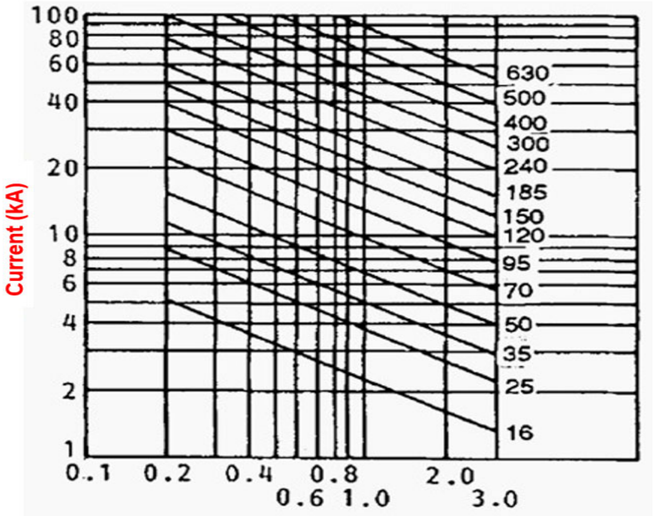


Figure 3.8 Duration of Short-Circuit Current (s) and Cable Size in mm2

3.2.6 Roof Top PV System

The rooftop solar panels installed are based on the PV system designed for commercially available components and calculations of its output under site-specific conditions. The design flow chart as shown in Figure 3.9 below. (Dr. Lim Boon Boon Han, 2022)

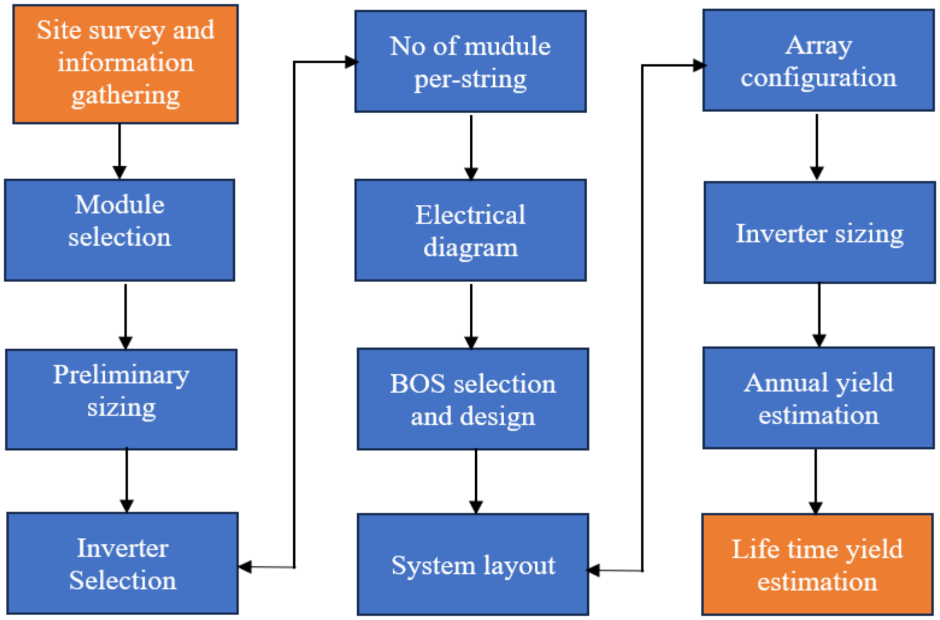


Figure 3.9 Flow Chat of PV System Design Procedure

3.2.7 Inverter

A solar inverter or photovoltaic (PV) inverter is connected to the 415V Main Switch Board (MSB). Which converts the variable direct current (DC) output of a photovoltaic solar panel sunlight irradiation into alternating current (AC) frequency to match the utility that can be fed to the existing connected load to reduce the electricity bill and obtain the credit when the solar supply excess energy to the utility. This credit can be used to further reduce the electricity bill.

Figure 3.10 Solar inverter module

The inverter is an important device in the grid-connected PV system, it consists of control, monitoring, communication, and measurement, The MT series has four MPPT provided to connect with the PV strings. The specific usage and application of this inverter are shown in Figure 3.11

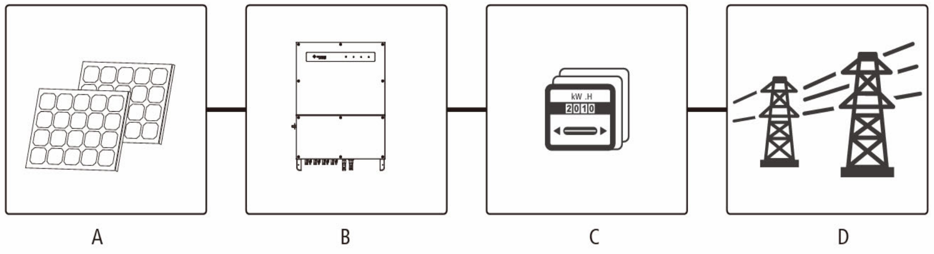
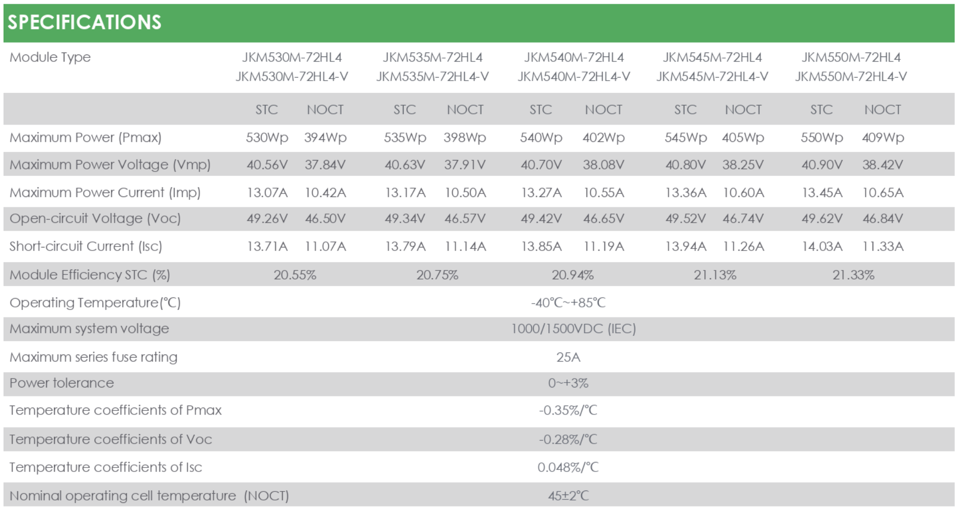


Figure 3.11 The Usage of Inverter Connection

3.2.8 No of Solar Panel Per-String.

The number of solar strings refers to multi-string connected to multiple solar panels. A string consists of a number of solar panels connected in series. The sizing of a number of solar panels to be connected to a string and how many strings for the inverter are calculated based on the PV-designed power is crucial to ensure the configuration is appropriate and efficient operation. The solar panel specification is below Table 3.7.



SPECIFICATIONS

Module Type	JKM530M-72HL4 JKM530M-72HL4-V		JKM535M-72HL4 JKM535M-72HL4-V		JKM540M-72HL4 JKM540M-72HL4-V		JKM545M-72HL4 JKM545M-72HL4-V		JKM550M-72HL4 JKM550M-72HL4-V	
	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT	STC	NOCT
Maximum Power (Pmax)	530Wp	394Wp	535Wp	398Wp	540Wp	402Wp	545Wp	405Wp	550Wp	409Wp
Maximum Power Voltage (Vmp)	40.56V	37.84V	40.63V	37.91V	40.70V	38.08V	40.80V	38.25V	40.90V	38.42V
Maximum Power Current (Imp)	13.07A	10.42A	13.17A	10.50A	13.27A	10.55A	13.36A	10.60A	13.45A	10.65A
Open-circuit Voltage (Voc)	49.26V	46.50V	49.34V	46.57V	49.42V	46.65V	49.52V	46.74V	49.62V	46.84V
Short-circuit Current (Isc)	13.71A	11.07A	13.79A	11.14A	13.85A	11.19A	13.94A	11.26A	14.03A	11.33A
Module Efficiency STC (%)	20.55%		20.75%		20.94%		21.13%		21.33%	
Operating Temperature(℃)	-40℃~+85℃									
Maximum system voltage	1000/1500VDC (IEC)									
Maximum series fuse rating	25A									
Power tolerance	0~+3%									
Temperature coefficients of Pmax	-0.35%/℃									
Temperature coefficients of Voc	-0.28%/℃									
Temperature coefficients of Isc	0.048%/℃									
Nominal operating cell temperature (NOCT)	45±2℃									

Table 3.7 Solar Panel Specification

Number of strings for the total solar panel 1018pcs installed on the rooftop.

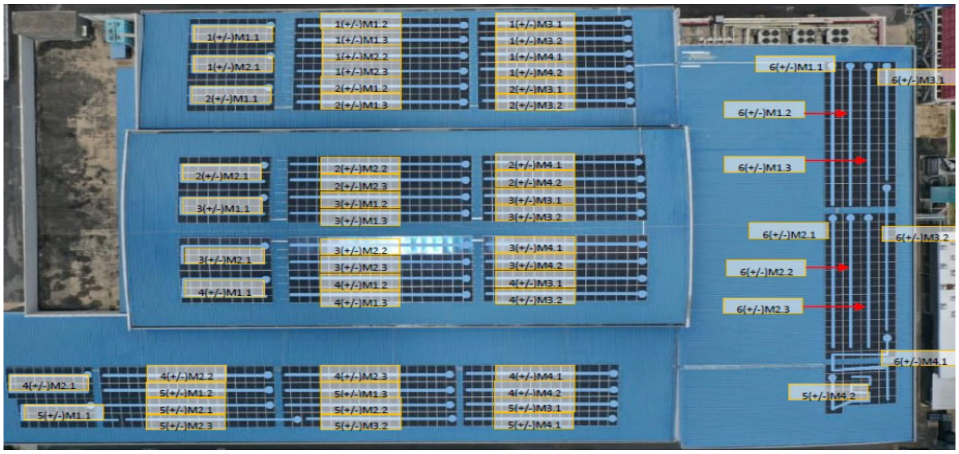


Figure 3.12 Roof-top Solar Installation

CHAPTER 4

CASE SIMULATION STUDIES AND RESULT GENERATION

4.1 Case Simulation Studies

In this scenario, the PV panels were isolated from the grid by both CB1 and CB2 breakers opened. The consumption of constant active and reactive loads at consumers MSB1 and MSB2 power supplies are taken from Transformer No.1 and No2 Utility source. The utility power factor value is reflected in the actual constant active and reactive load consumed in the power system. shown in Figure 4.1 the utility is reflected with the actual load consumed of active and reactive power and Figure 4.2 shows the power factor and its current loading.

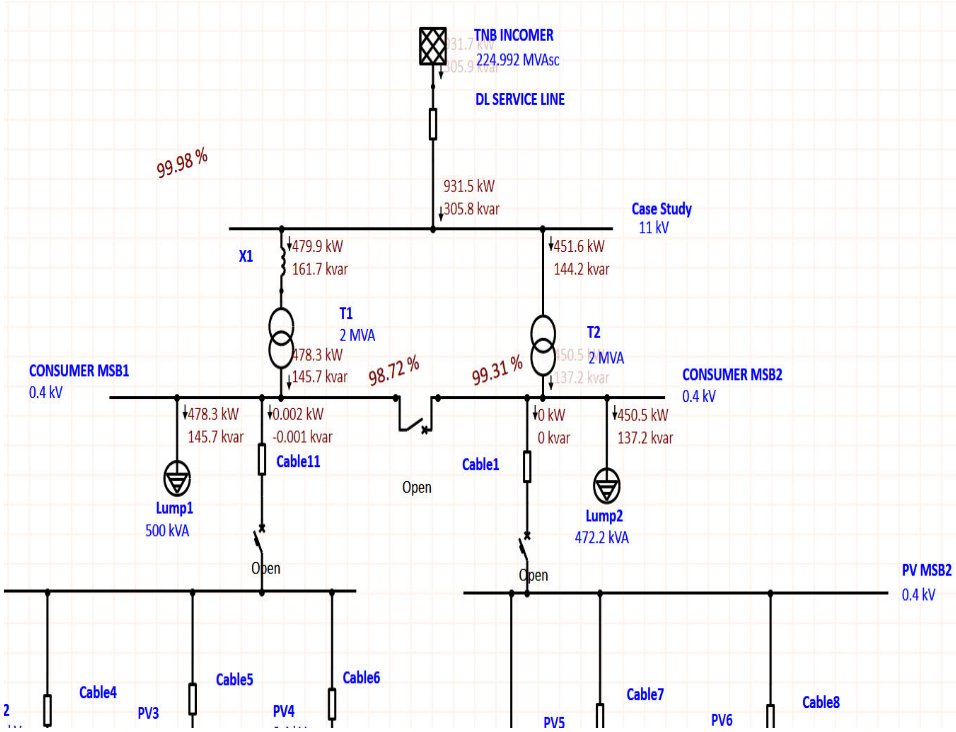


Figure 4.1 Active and Reactive Power with PV Solar Panels Isolated

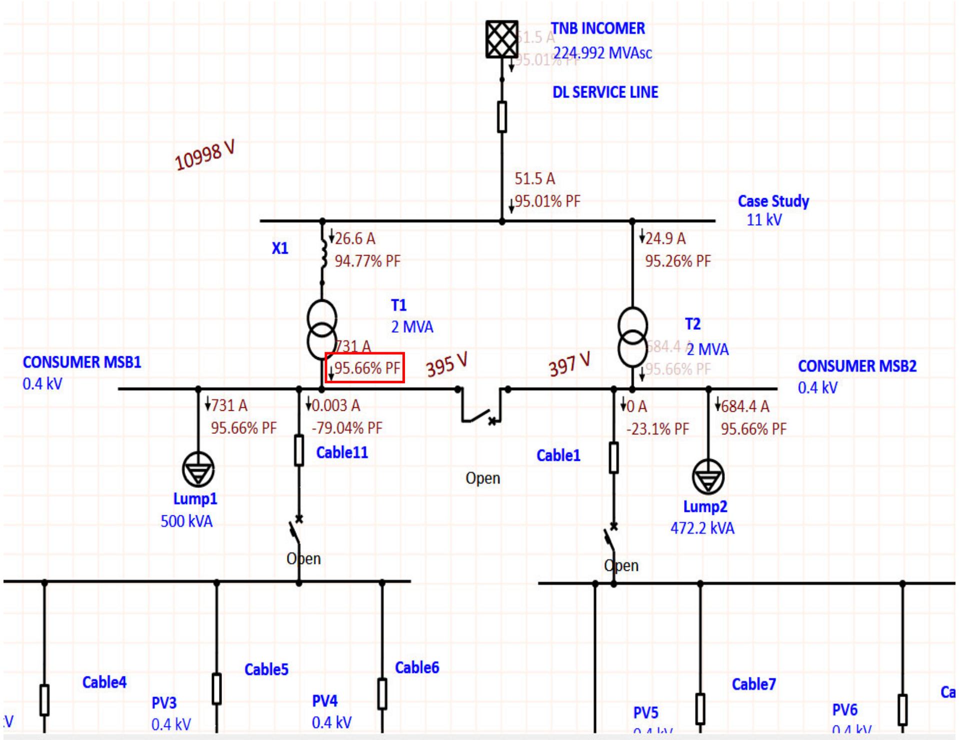


Figure 4.2 Current and Power Factor with PV Solar Panels Isolated

The simulated report of the load flow results shows that the power factor value reading from the utility point is reflected in the actual constant active and reactive load consumed in the power system.

Bus ID	Voltage kV	% Mag	kW	kVar	%PF
Utility Bus	10.998kV	99,98	941	308	95.01%
Consumer MSB1	395V	98.72	478.3	145.7	95.66%
Consumer MSB2	397V	99.31	450.5	137.3	95.66%
PV MSB1	395V	1.00	0	0	0
PV MSB2	397V	1.00	0	0	0

Table 4.1 Current and power factor with PV Solar panels isolated

Case 1:

The PV panel generates active power to the loads, and the energy metering measurement at the utility point may experience of low power factor value even if the reactive load profile does not change.

The power factor measurement can be calculated by the active and reactive power to the load, respectively;(da Silva Benedito et al., 2021).

$$PF = \frac{PL}{\sqrt{PL^2+QL^2}} \qquad \text{eq.}\ldots 2$$

The utility source supply to the consumer MSB No.1 which is connected load is 500kVA, the PV1 inverters provide 400kW, 0.956PF to the load, and the rest is supplied by the Tx. No 1 2MVA from the utility power supply. The consumer MSB No2 connected load2 is 472kVA, 0.956PF. The PV2 inverters provided 200kVA and the rest was supplied by the Tx. No2 2MVA from the utility power supply. The power factor at consumer MSB 1 and 2 are 0.479PF and 0.87.7PF.

The results show the low power factor at consumer MSB1 after the PV1 active power is supplied to the load. The increase of 400kW PV1-generated active power caused the low power factor from 0.95PF to 0.479PF. The low power factor at consumer MSB2 is 0.877PF which is not so significant compared to consumer MSB No.1. The increase of PV2-generated active power is 200kW to cause the power factor from 0.956 to 0.877PF at consumer MSB 1. The ETAP load flow simulation as shown in Figures 4.3 and 4.4

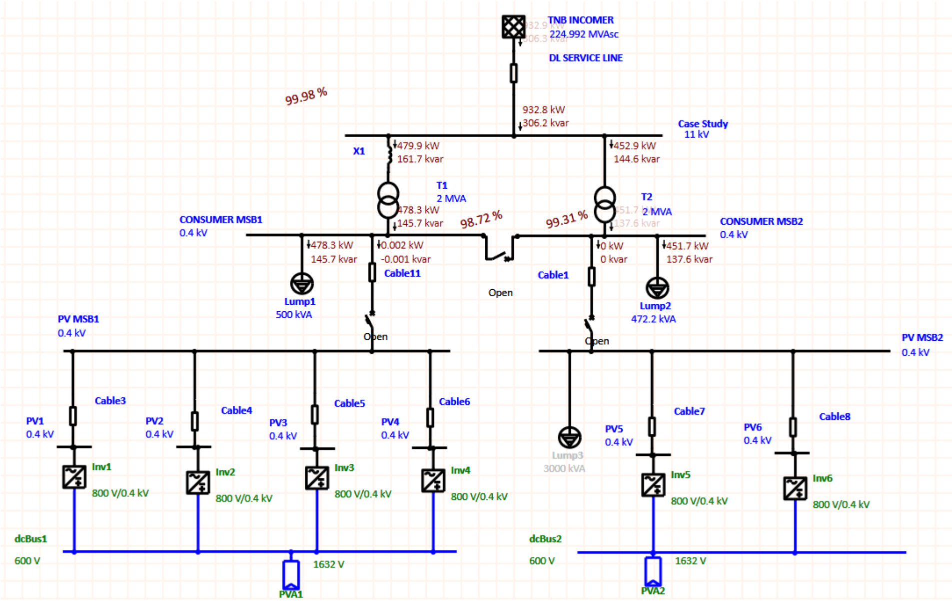


Figure 4.3 Active and Reactive Power with PV Solar Grid Connected System

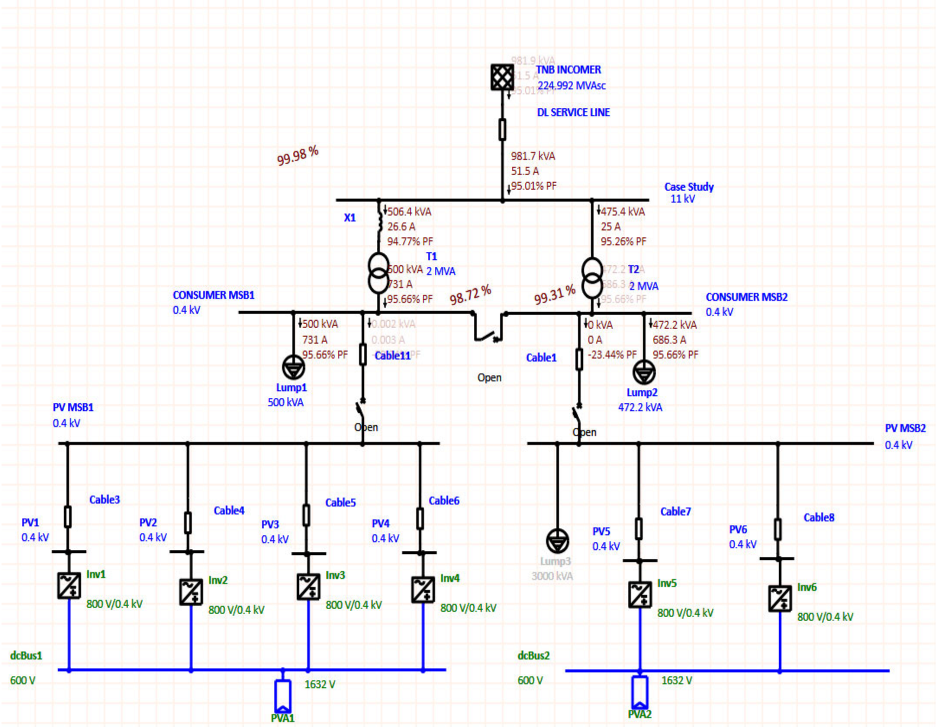


Figure 4.4 Current and Power Factor with PV Solar Grid Connected System

The simulated report of the load flow results shows that the power factor value reading from the utility point is low power factor value when PV solar and grid are connected as shown in Table 4.2.

Bus ID	**Voltage kV**	**% Mag**	**kW**	**kVar**	**%PF**
Utility Bus	10.999kV	99.99	331	291	75.46%
Consumer MSB1	396V	99.02	478.3	145.7	47.89%
Consumer MSB2	398V	99.43	450.7	137.3	87.71%
PV MSB1	397V	99.25	399.3	0.187	100%
PV MSB2	398V	99.55	199.7	0.091	100%

Table 4.2 Load Flow Report of PV Solar Grid Connected System

4.2 Solution to Overcome the Low Power Factor in the GCPV

Alternative measurement scheme:

This is the way by which an additional digital energy meter2 to be installed between the PV system and the CCP Common coupling point, to obtain the actual PF of the load as shown in Figure 5. The sum of both Meter1 and Meter2's active and reactive power can be calculated as shown in the Eq2 formula. (da Silva Benedito et al., 2021)

$$PF = \frac{PL}{\sqrt{PL^2 + QL^2}} \qquad \text{eq....2}$$

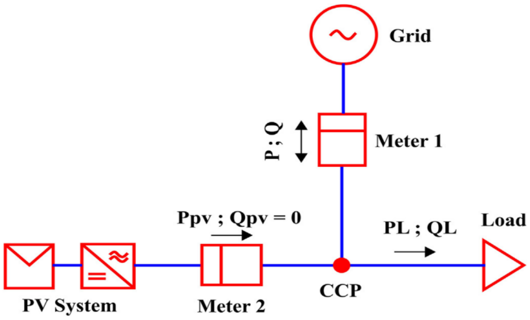


Fig 4.5 Alternative Measure Scheme for GCPV without Reactive Power Compensation.

4.2.1 Reactive Power Compensation Through PV Inverter

An external controller to compare and check the active power P and reactive power Q of the Meter1 from the utility, whenever if the PF of the utility is less than the Load Power Factor, the controller will send a signal to PV inverter to generate reactive power export to the load. So the Meter1 reading of reactive power Q will be reduced in order to keep the power factor at the desired level.(Smith et al., 2011)

4.3 Impact of PV Integration for Normal Topology

The parameters of load consumption from the factory with ETAP software to perform analyses of the impact for PV integration to the normal topology at different levels and loading conditions. During full load conditions, the PV Solar generates energy to improve the voltage profile across the buses, and no load conditions PV Solar generates energy to export power to the grid and voltage slightly higher than the normal condition. The solar panel details and the hourly power data as shown in Tables 4.3 and 4.4

Solar Panel Details:

Model:	Monocrystalline Perc Module
Type :	Jinko Solar
Power Rating :	540Wp
Quantity :	1018
Cell Size :	182 x182mm
Panel Dimensions :	2278 x 1134 x 35mm
Area (m^2)	2341.4

Table 4.3 Solar Panels Installation Data

The measured kW average value of Jan24 of the PV inverter output is shown as below Table 4.4:

Date	Hour	PV Generated (kW)	Hour	PV Generated (kW)
Jan 2024	0	0	12	296
Jan 2024	1	0	13	309
Jan 2024	2	0	14	306
Jan 2024	3	0	15	272
Jan 2024	4	0	16	220
Jan 2024	5	0	17	156
Jan 2024	6	0	18	78
Jan 2024	7	1	19	0
Jan 2024	8	33	20	0
Jan 2024	9	112	21	0
Jan 2024	10	203	22	0
Jan 2024	11	259	23	0

Table 4.4 PV Solar Panels Power Output Data

The simulation is performed with hourly time series, and the corresponding values of the load profiles are simulated for each time step with no load and different level conditions. The voltage at 415V consumer MSB bus varies slightly according to the load and PV solar grid connected as shown in Figure 4.6.

Case 2:

The simulation with normal load condition results showing the voltage without sun light and the PV solar energy is zero during these periods of time, the voltage level at the 415V MSB bus is constant. and hence when the sunlight started from 7:00am. the voltage at 415V MSB improving at the peak sun hours.

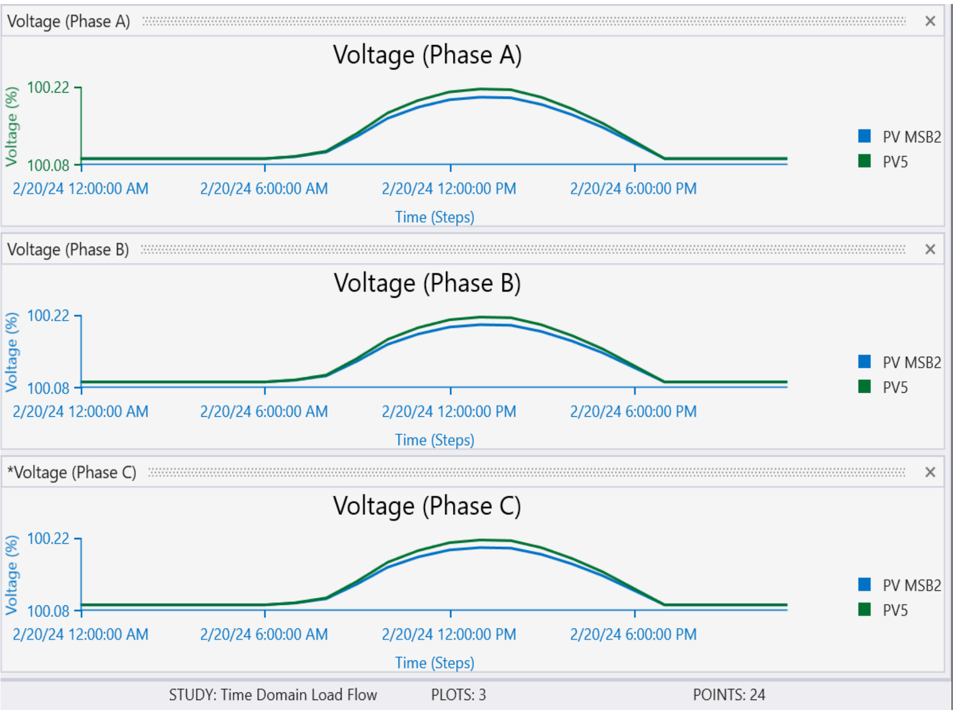


Figure 4.6: No Load Condition

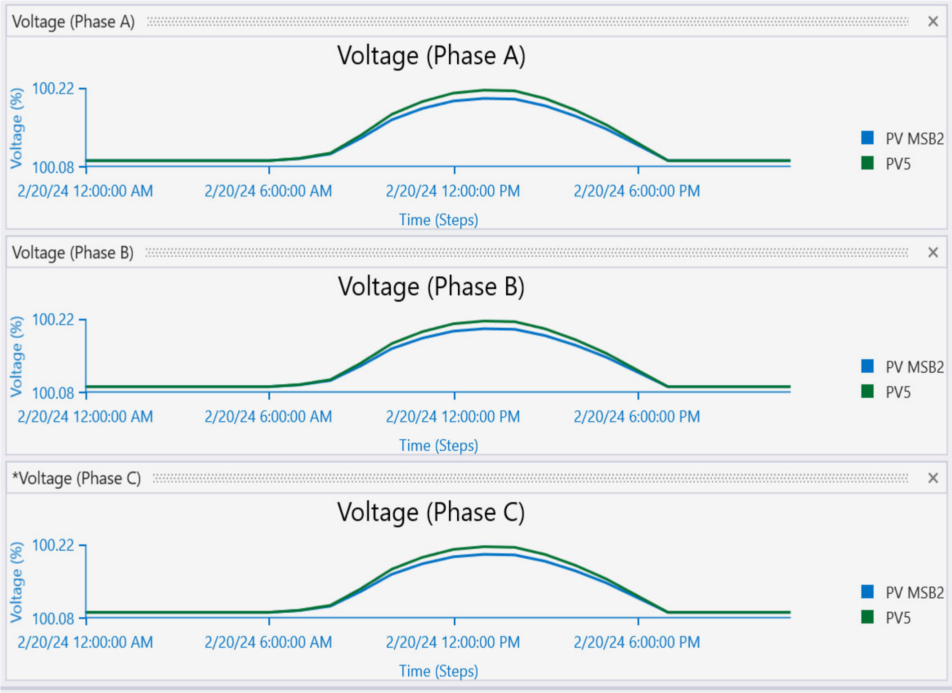


Figure 4.7 Normal Load Condition

Case 3:

When the 0.2MW loading with the grid connected PV system. The voltage level at 415V MSB consumer bus are 99.93% when no sun light and 100.024% at the peak sun hours as shown in below Figure 4.8.

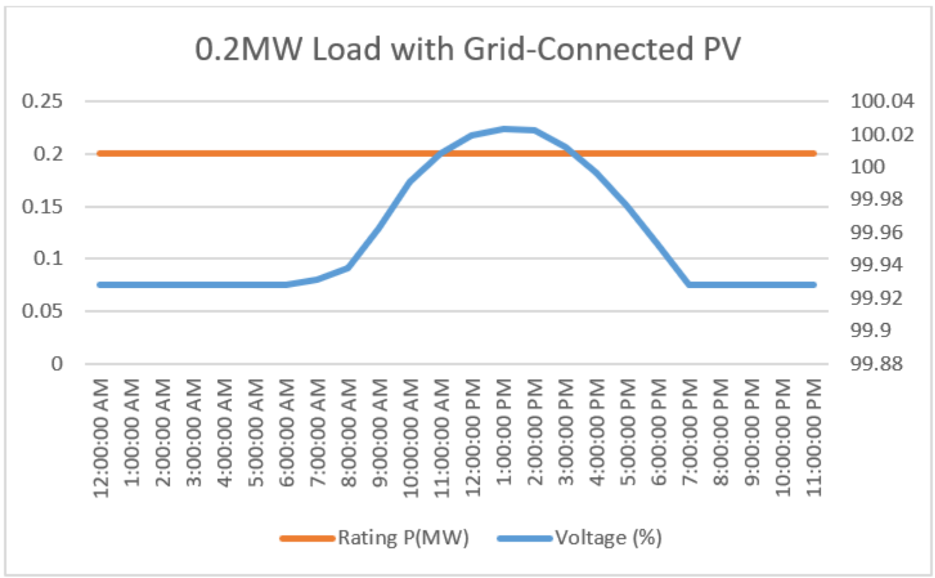


Figure 4.8. 0.2MW Load with Grid-Connected PV

0.2MW loading without the PV generation, voltage at 415V MSB consumer bus is constant at 99.93% as shown in below Figure 4.9.

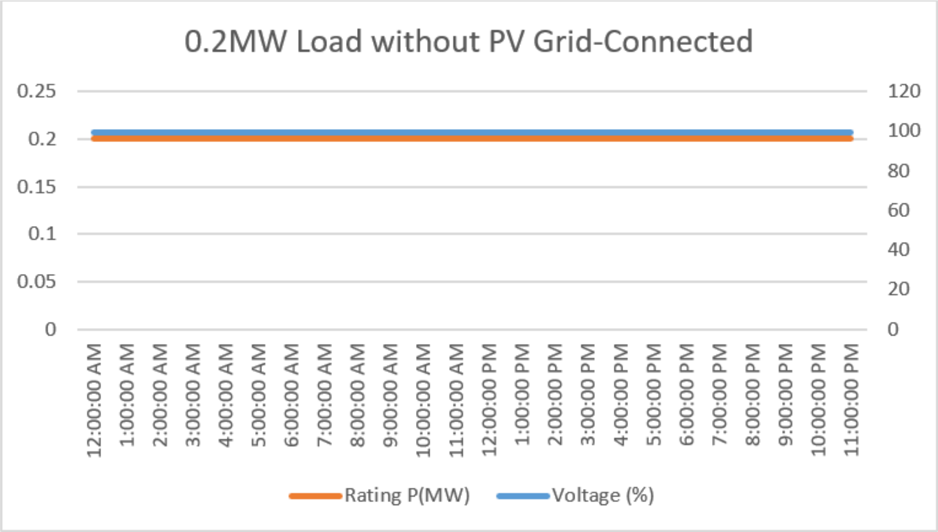


Figure 4.9. 0.2MW Load without Grid-Connected PV

Case 4:

0.4MW loading with the grid-connected PV system. The voltage level at 415V MSB consumer bus is 99.82% when no sunlight and 99.914% at the peak sun hours as shown in below Figure 4.10.

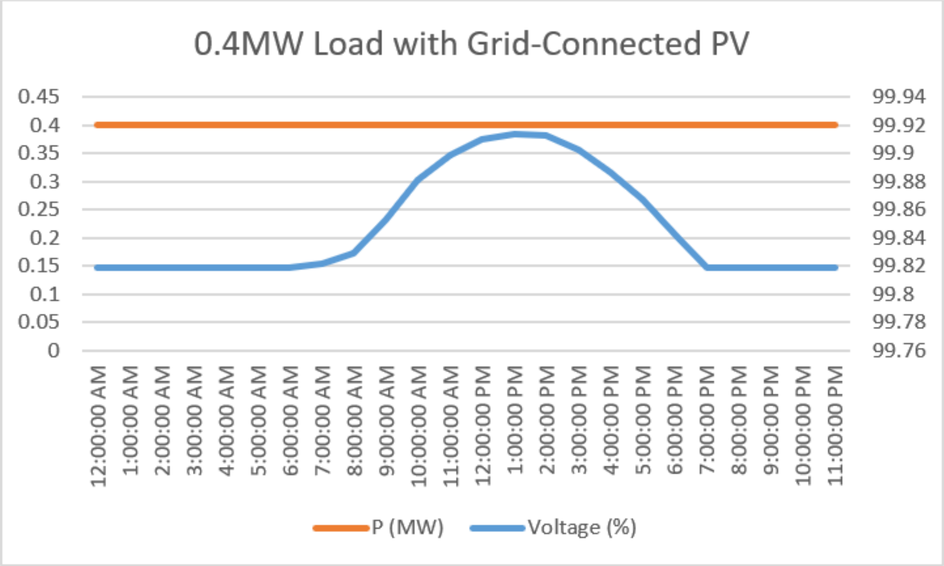


Figure 4.10. 0.4MW Load with Grid-Connected PV

0.4MW loading without the PV generation, voltage at 415V MSB consumer bus is constant at 99.82% as shown in below Figure 4.11.

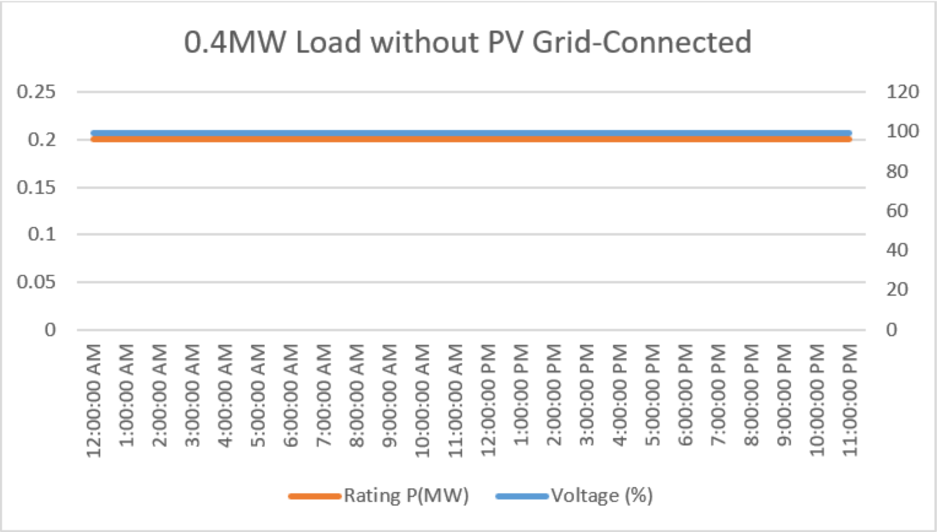


Figure 4.11. 0.4MW Load without Grid-Connected PV

Case: 5

0.7MW loading with the grid-connected PV system. The voltage level at 415V MSB consumer bus is 99.65% when no sunlight and 99.74% at the peak sun hours as shown in below Figure 4.12.

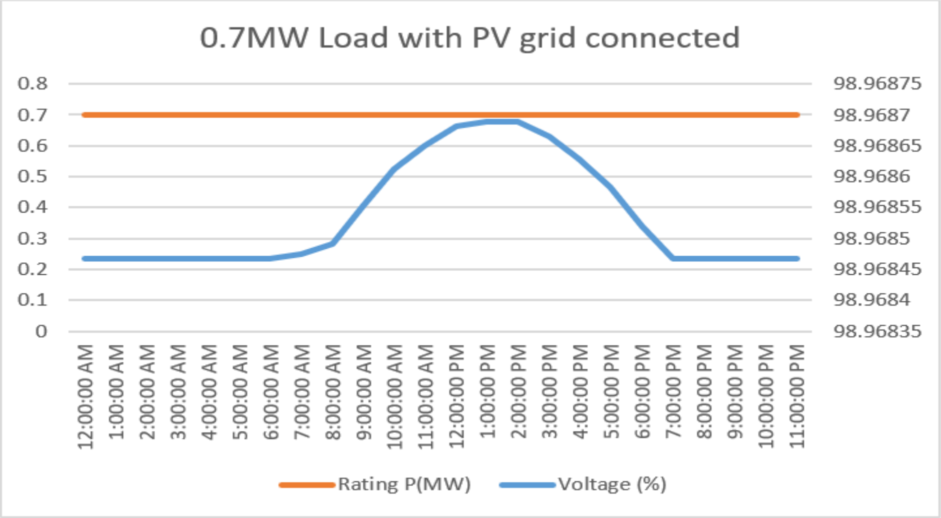


Figure 4.12. 0.7MW Load with Grid-Connected PV

0.7MW loading without the PV generation, the voltage level at 415V bus level is constant at 99.65% as shown in the below figure 4.13.

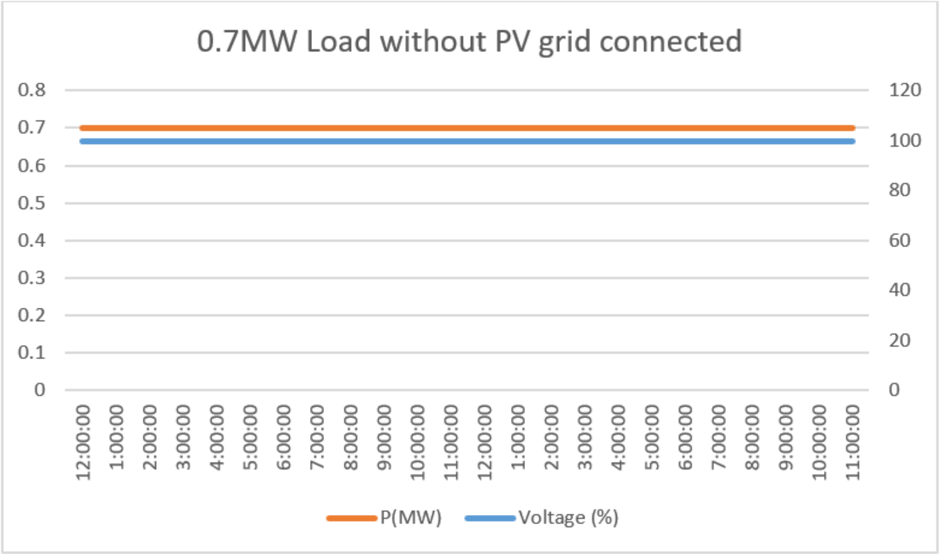


Figure 4.13. 0.7MW Load without Grid-Connected PV

Power consumption rating (kW)	Consumer 415V MSB Voltage level variation (V%)		Different voltage (V%)
	Without PV	Peak Sun hour	
0	100%	100.13%	0.13%
200	99.93%	100.024%	0.094%
400	99.82%	99.914%	0.094%
700	99.65%	99.743%	0.093%

Table 4.5 Simulation Results in Different Load Patterns in PV Solar System

4.4 Chapter Conclusions

4.4.1 ETAP Simulation for Load Flow Analysis

The PV solar system grid connects the system to the commercial or industrial using ETAP load flow analysis and time domain for the assessment of voltage stability to ensure that the results are in the acceptable value. The simulation of load flow analysis results shows in the system loading with grid connected to PV and without grid connected to the PV as shown in Tables 4.1 and 4.2.

The low power factor is present during the grid-connected to PV.

4.4.2 ETAP Simulation for Loaf Flow Time Domain

This assessment grid integration of photovoltaic systems in a factory distribution network using a PV system with 545kWp connected the 415V consumer MSB. The load flow time domain analysis in different cases has been carried out with results shown in Figures 4.. and Table 4.3.

4.4.3 Case No1. Low Power Factor Solution

This assessment grid integration of photovoltaic systems for the above was simulated with double sizes of the PV connected on the consumer 415V MSB No.1. The results show that the low power factor will be experienced at both sides, and consumer 415V MSB No.1 is more significant compared to consumer 415V MSB No.2, The improvement of low power factor can be based on the methods of power factor regulator to cut-in with capacitors bank or reactive power compensation through PV inverter.

4.4.4 Case No.2. No Loading Condition

When no load and no sunlight irradiance condition the 415V Consumer MSB voltage incoming supply from the grid is 100%. When the sunlight irradiance increased, the voltage level increased to 100.13% at peak sun hour (PSH)..

4.4.5 Case No.3 200kW Loading Condition

When the system carried is 200kW without sunlight irradiance, the 415 Consumer MSB voltage incoming supply from the grid is slightly decreased from 100% to 99.93%. During the sunlight irradiance increased, the voltage level increased to 100.024% at peak sun hour (PSH).

4.4.6 Case No.4 400kW Loading Condition

When the system carried is 400kW without sunlight irradiance, the 415 Consumer MSB voltage incoming supply from the grid is slightly decreased from 100% to 99.82%. During the sunlight irradiance increased, the voltage level increased to 99.914% at peak sun hour (PSH).

4.4.7 Case No.5 700kW Loading Condition

When the system carried is 400kW without sunlight irradiance, the 415 Consumer MSB voltage incoming supply from the grid is slightly decreased from 100% to 99.65%. During the sunlight irradiance increased, the voltage level increased to 99.743% at peak sun hour (PSH).

4.4.8 Load Profile with Time Domain Load Flow Analysis in Time Series

The load profile of this studied cases of the factory by using the ETAP simulation software with incorporating a details time domain load profile and solar generation pattern into the simulation of time series load flow analysis enable a bigger data and accurate assessment of the interactions between PV generation and commercial electricity demand throughout the day.

Load profile cases simulated results in Table xx show that the voltage level slightly varies with the load and PV solar energy generation. When the power loading increases the voltage will slightly be decreased. In no solar irradiation conditions, maximum load demand of 700kW loading causes a voltage drop of 0.35% compared to a 200kW loading voltage drop of only 0.07%. During the period of high solar irradiation, with a maximum load demand of 700kW, the grid-connected PV system at 415V Consumer MSB improved the voltage level from 99.65% to 99.743%.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Referring to the results obtained from the simulation of load flow analysis and time domain series, during the peak sun hour (PSH) grid-connected PV generated around 300kW. The load flow analysis results show power factor value reading affected at Consumer 415V MSB1 and MSB2.

- Consumer 415V MSB1 PF = 47.89%.
- Consumer 415V MSB2 PF = 87.7%

The 415V Consumer MSB1 power factor reading 47.89% which is less than the utility minimum requirement of 85%.

The plotted graphs and Table 5.1 of time domain load flow analysis hourly for the load profile demonstrated different loading patterns at the Consumer 415V MSB. The voltage slightly increases from 100% to 100.13% during no-load conditions. The full load maximum demand at 700kW without the grid-connected PV or off-peak hours the voltage drop from 100% to 99.65%. and during the peak sun hours, the voltage improves from 99.65% to 99.743%.

Power consumption rating (kW)	Consumer 415V MSB Voltage level variation (V%)		Different voltage (V%)
	Without PV	Peak Sun hour	
0	100%	100.13%	0.13%
200	99.93%	100.024%	0.094%
400	99.82%	99.914%	0.094%
700	99.65%	99.743%	0.093%

Table 5.1 Simulation Results in Different Load Patterns in PV Solar System

It can be seen that the comparison of the load flow analysis in the time domain series for the grid-connected PV system during the high irradiation slightly change in voltage levels does not impact the voltage profile. Instead, during full load conditions, the grid-connected PV generates energy to improve the voltage profile across the buses, and during no load conditions exports power to the grid.

5.2 Recommendations

The impact of the low power factor during the grid-connected PV in high irradiation shall be looked into the improvement methods by adding reactive load (capacitor bank) or a signal given to the PV inverter to generate reactive power export to the Consumer 415V MSB bus. However, sufficient information related to the existing types of equipment of the grid-connected PV system and a power system study will help to come out with the most suitable solution.

REFERENCES

1.) Al-Shetwi, A. Q., Hannan, M. A., Jern, K. P., Alkahtani, A. A., & Abas, A. E. P. G. (2020). Power quality assessment of grid-connected PV system in compliance with the recent integration requirements. *Electronics (Switzerland)*, *9*(2). https://doi.org/10.3390/electronics9020366

2.) (Tobnaghi, 2016)*A-review-on-impacts-of-grid-connected-pv-system-on-distribution-networks-ok*. (n.d.).

3.) Blooming, T. M., Asheville, E. E., Carolina, N., & Carnovale, D. J. (n.d.). *APPLICATION OF IEEE STD 519-1992 HARMONIC LIMITS*.

4.) da Silva Benedito, R., Zilles, R., & Pinho, J. T. (2021). Overcoming the power factor apparent degradation of loads fed by photovoltaic distributed generators. *Renewable Energy*, *164*, 1364–1375. https://doi.org/10.1016/j.renene.2020.10.146

5.) Fani, B., Bisheh, H., & Sadeghkhani, I. (2018). Protection coordination scheme for distribution networks with high penetration of photovoltaic generators. *IET Generation, Transmission and Distribution*, *12*(8), 1802–1814. https://doi.org/10.1049/iet-gtd.2017.1229

6.) Farhoodnea, M., Mohamed, A., Shareef, H., & Zayandehroodi, H. (2012). Power quality impact of grid-connected photovoltaic generation system in distribution networks. *SCOReD 2012 - 2012 IEEE Student Conference on Research and Development*, 1–6. https://doi.org/10.1109/SCOReD.2012.6518600

7.) Jacob Marsh. (2023). *Monocrystalline vs. Polycrystalline solar panels*. https://www.energysage.com/solar/monocrystalline-vs-polycrystalline-solar/

8.) Jo, S. H., Son, S., & Park, J. W. (2013). On improving distortion power quality index in distributed power grids. *IEEE Transactions on Smart Grid*, *4*(1), 586–595. https://doi.org/10.1109/TSG.2012.2222943

9.) Kar, S., Jati, D., & Samantaray, S. R. (2016, October 5). Overcurrent relay coordination for micro-grid with different operating conditions. *2016 IEEE 6th International Conference on Power Systems, ICPS 2016*. https://doi.org/10.1109/ICPES.2016.7584205

10.) KoohiKamali, S., Yusof, S., Selvaraj, J., & Esa, M. N. Bin. (2010). Impacts of grid-connected PV system on the steady-state operation of a Malaysian grid. *PECon2010 - 2010 IEEE International Conference on Power and Energy*, 858–863. https://doi.org/10.1109/PECON.2010.5697699

11.) Laveyne, J. I., Bozalakov, D., Van Eetvelde, G., & Vandevelde, L. (2020). Impact of Solar Panel Orientation on the Integration of Solar Energy in Low-Voltage Distribution Grids. *International Journal of Photoenergy*, *2020*. https://doi.org/10.1155/2020/2412780

12.) Mahela, O. P., & Ola, S. R. (2016, July 11). Impact of grid disturbances on the output of grid-connected solar photovoltaic system. *2016 IEEE Students' Conference on Electrical, Electronics and Computer Science, SCEECS 2016*. https://doi.org/10.1109/SCEECS.2016.7509319

13.) Makram, E. B., Subramaniam, E. V., Girgis, A. A., & Catoe, R. (1993). Harmonic filter design using actual recorded data. *IEEE Transactions on Industry Applications*, *29*(6), 1176–1183. https://doi.org/10.1109/28.259730

14.) MATTHEW SABAS. (2016, February 18). *History of Solar Power*. https://www.instituteforenergyresearch.org/renewable/solar/history-of-solar-power/

15.) Saad, S. M., El Naily, N., & Mohamed, F. A. (2018). Investigating the effect of DG infeed on the effective cover of distance protection scheme in mixed-MV distribution network. *International Journal of Renewable Energy Development*, *7*(3), 223–231. https://doi.org/10.14710/ijred.7.3.223-231

16.) Smith, J. W., Sunderman, W., Dugan, R., & Seal, B. (2011). Smart inverter volt/var control functions for high penetration of PV on distribution systems. *2011 IEEE/PES Power Systems Conference and Exposition, PSCE 2011*. https://doi.org/10.1109/PSCE.2011.5772598

17.) Transformer Handbook. (n.d.). Retrieved April 5, 2024, from https://library.e.abb.com/public/c1256b3c00492da6c1256fdd0053c4c2/1LAC000010-A_introTbl.pdf

18.) Zobaa, A. F., & Abdel Aleem, S. H. E. (2014). A new approach for harmonic distortion minimization in power systems supplying nonlinear loads. *IEEE Transactions on Industrial Informatics*, *10*(2), 1401–1412. https://doi.org/10.1109/TII.2014.2307196

19.) Dr. Lim Boon Boon Han, (2022). Photovoltaic system design. Wind and solar engineering, retrieved April 6. 2024 from lecture notes.