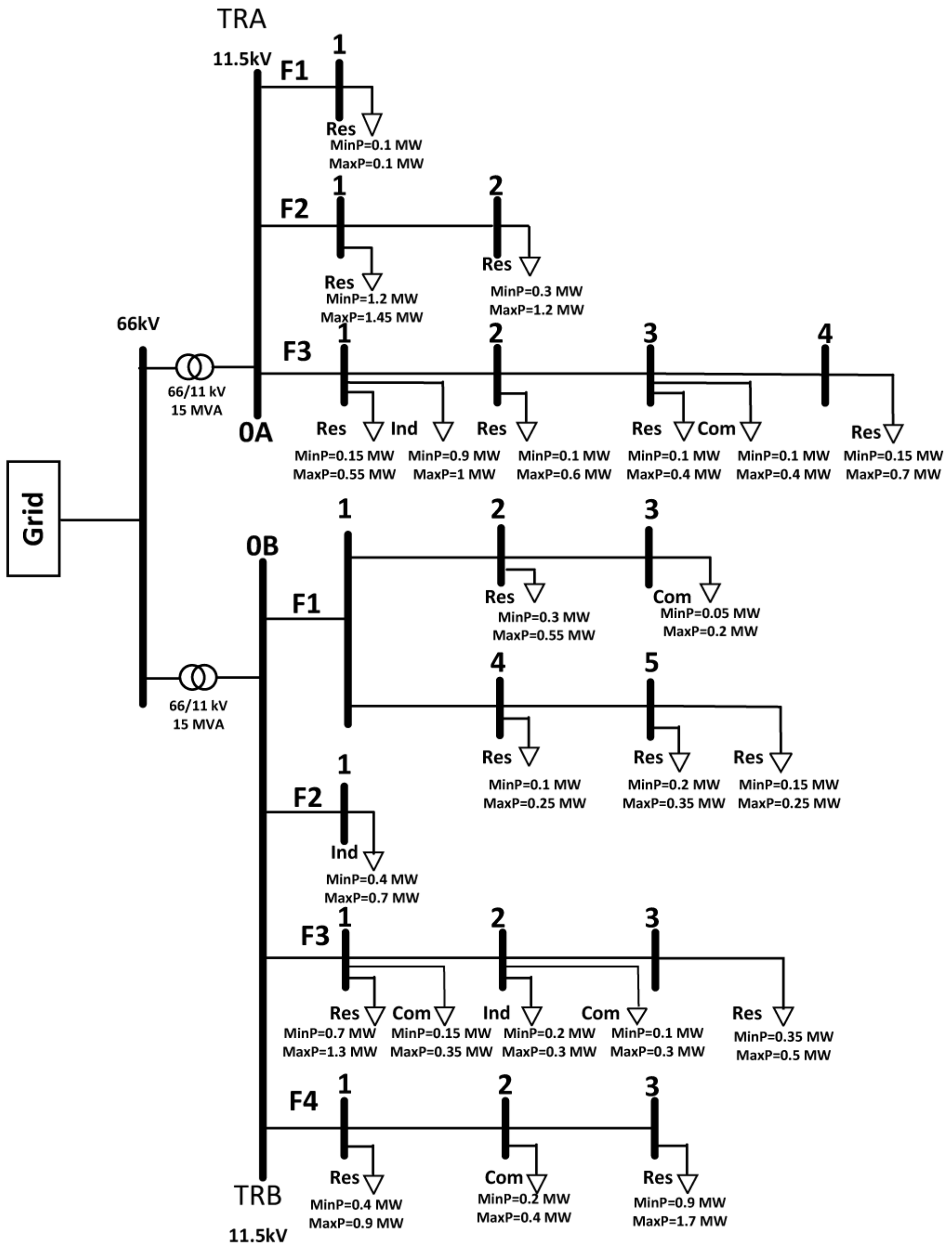
Integration of Large Capacity PV Power and Measuring PV Hosting Capacity of North Cyprus MV Grid



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EPSH4-1033

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Rifat Celiloglu

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Synopsis:

This project is aimed for developing a methodology to define PV hosting capacity of distribution substations for integration of large-capacity PV solar power. Electricity authority of North Cyprus (KIB-TEK) is about to have initial steps into renewable energy sector by integrating 30 MW of PV solar power into their MV grid. It is decided to distribute all power to whole grid and hosting capacity of substations must be known for this integration.

A model of North Cyprus grid has been developed over real data supplied by KIB-TEK and a substation has been selected for applying different scenarios by increasing power levels in incrementation of 0.5 pu to observe responses of the grid under minimum and maximum loading conditions. It has been seen that loading of transformers are the main limitation for substations to integrate more power into MV grid. Over defined limits by transformers, line loadings and voltage deviations has been also analysed to define maximum PV injection capacity of substations.

A voltage control method over reactive power support has been applied to MV nodes for obtaining desired voltage magnitudes of nodes and improvements has been seen by absorbing correct amount of reactive power from nodes. During analyses, It has been observed that initial place of absorption effects amounts of reactive power support to feeders. Over this, two strategies has been analysed by changing initial absorption point on feeders. Through results, to start support from nodes at the end of feeder and continuing by getting closer to MV bus has seen as best method for reactive power support.

Preface

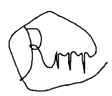
The work on this project has been carried on the 10th semester at Aalborg University as a part of the master programme in *Electrical Power Systems and High Voltage*. Prerequisites for reading the report is basic knowledge regarding electrical power systems. The project deals with developing a methodology to define PV hosting capacity of distribution substation to operate in optimal condition.

I would like to thank the supervisor, Associate Professor Florin Iov for the help and guidance offered through out the project. I would also like to thank Electricity Authority of North Cyprus (KIB-TEK) for providing necessary data for developing simulation model for this project.

Reading guide

Through the report source references in the form of the Harvard method will appear and these are all listed at the back of the report. References from books, homepages or the like will appear with the last name of the author and the year of publication in the form of [Author, Year].

Figures and tables in the report are numbered according to the respective chapter. In this way the first figure in chapter 2 has number 2.1, the second number 2.2 and so on. Explanatory text is found under the given figures and tables. Figures without references are made by me.



Rifat Celiloglu

Acronyms

Acronym	Specification
KIB-TEK	Electricity Authority of North Cyprus
NCG	North Cyprus Grid
PV	Photovoltaic
HV	High Voltage
LV	Low Voltage
MV	Medium Voltage
OHL	Overhead Line
TSO	Transmission System Operator
DSO	Distribution System Operator
DG	Diesel Generator Set
ST	Steam Turbine
EU	European Union

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Introduction 1

In this chapter, background of project will be explained and North Cyprus Grid will be introduced over production and consumption. Solar PV potential of Cyprus will be discussed and problem statement will be shared to present main motivation of project. Objectives will be pointed out to describe approach to solution. In the end, limitations will be shared with assumptions of project.

1.1 Background

Renewable energy sector is getting bigger each year and seen as the future of energy production. By the investments done on renewable energy sector, production capacity increases yearly and dependency on power produced by fossil fuels decreases. Only in 2016, renewable power capacity of world was increased by 147 GigaWatt (GW) and had the biggest annual increase. Predictions also show that renewable power capacity will increase with new records in upcoming years by the new agreements signed in national and international level. [REN21, 2016]
In Europe, countries were already set goals in order to increase share of renewable energy production and have renewable energy dependent production until 2050. These plans also encourage electricity authorities in Cyprus to integrate large capacities of renewable energy production units into their grids. South Cyprus is an European Union (EU) country and follow European standards in their power grid while North Cyprus is an Non-EU country and has their own standards to manage their own grid. South Cyprus already took a part in EU energy agreement to have 13 % share of total energy production from renewable until 2020. Now, South Cyprus has a share of 8 % (232 MW) of renewable energy capacity from biomass, wind energy and solar photovoltaic (PV) technologies and capacity increase is also on track to meet 13 % share by 2020. [Zachariadis and Hadjikyriakou, 2016] [Tomescu et al., 2016]
Electricity Authority of North Cyprus took its first step into renewable energy sector in 2011 by installing 1.2 MW PV solar power plant in Serhatkoy and now they want to create their own long term plan for having a good share of renewable energy production. As an initial step, it is planned to install a total of 30 MW PV solar power to MV nodes in 2 years time. As a continuation, addition of more PV solar power, wind power and biomass is expected in 5 years period to increase renewable energy share to 30 %. [KIB-TEK]

1.2 North Cyprus Grid

North Cyprus Grid (NCG) is under control of governmental authority called Electricity Authority of North Cyprus (KIB-TEK). KIB-TEK is the only authority responsible from production, transmission and distribution of power in North Cyprus. KIB-TEK is so called transmission and distribution system operator (TSO & DSO) of North Cyprus.

Since last year, North Cyprus is in good relations with South Cyprus and EU to be a member of EU. Over this, KIB-TEK wants to have improvements in their grid to equalize quality of power with South Cyprus. Within current plan, initial steps are seen to reduce gas emissions from production units and get into renewable energy sector with a good share. Decrease of gas emissions in generation units is seem to be difficult option to start as all production units are heavily depending on imported petroleum products (Fuel & Diesel oil). However, Cyprus has good potential of renewable energy to produce power from sun and wind. To implement second plan, studies are about to start for installing 30 MW of PV solar power into distribution grid and it is planned to be completed in two years time. After this project, a realistic plan will be prepared for increasing renewable share of North Cyprus.

As Cyprus is an island, it is electrically isolated from other countries and electricity authorities must have ability to supply all national demand. This means that energy cannot be imported from other countries during peak demand and cannot be sold during existence of excess. This shows that integration of renewable energy plants is seen as the best option to decrease dependency on fossil fuels for production.

Power Plant	Type	Power Capacity [MW]	Total[MW]
Teknecik	SteamTurbine	2x60	120
Teknecik	Diesel	8x17.5	140
Teknecik*	GasTurbine	20+10	30
Kalecik	SteamTurbine	1x8.5	8.5
Kalecik	Diesel	8x17.5	140
Dikmen*	GasTurbine	1x20	20
Serhatkoy	PVSolar	1.2	1.2
*Not Active		Total [MW]	459.7

Table 1.1. Production Units and Capacities

From table 1.1, it can be observed that NCG has a total power production capacity of 459.7 MW from steam turbine, diesel, gas turbine and solar power technologies where gas turbines are deactivated due to their low efficiency and high operational costs. Therefore, actively 409.7 MW can be produced through 3 generation plants where 99.7 % of total production depends on fossil fuel dependent generation units. Serhatkoy PV solar power plant is the first renewable energy plant of North Cyprus with 1.2 MW power capacity. [KIB-TEK]

From figure 1.1, it can be observed that 61 % of total production capacity depends on diesel generator sets where 28 % depends on steam turbine generators. Although gas turbine generators form 11 % of total production, they cannot be used due to financial considerations. Renewable power from solar forms only a small portion of total and it cannot be able to support grid as in EU countries.

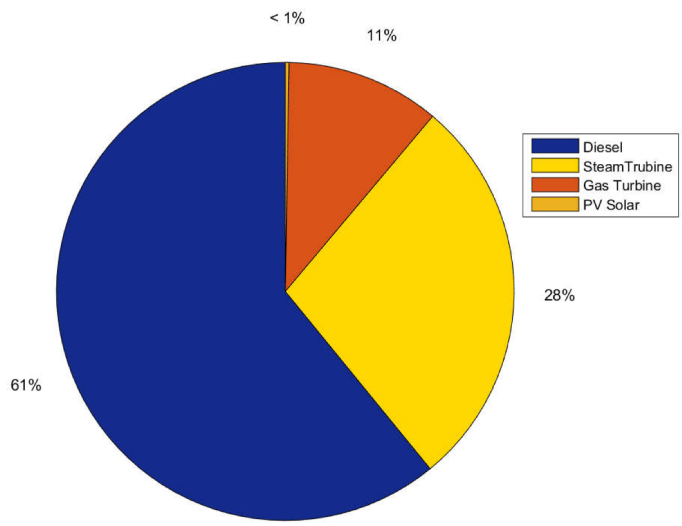

Figure 1.1. Distribution of production capacities over type of technologies

Figure 1.2 illustrates distribution of produced power into generation units for 2016. Diesel generator unit in Kalecik supplied approximately half of total power in 2016 and Diesel generation set in Teknecik followed it by 24 %. To generalize data in figure 1.2, Teknecik and Kalecik power plants shares total production capacities with 51 % and 48 % respectively and 72 % of total production depends on diesel generator sets.

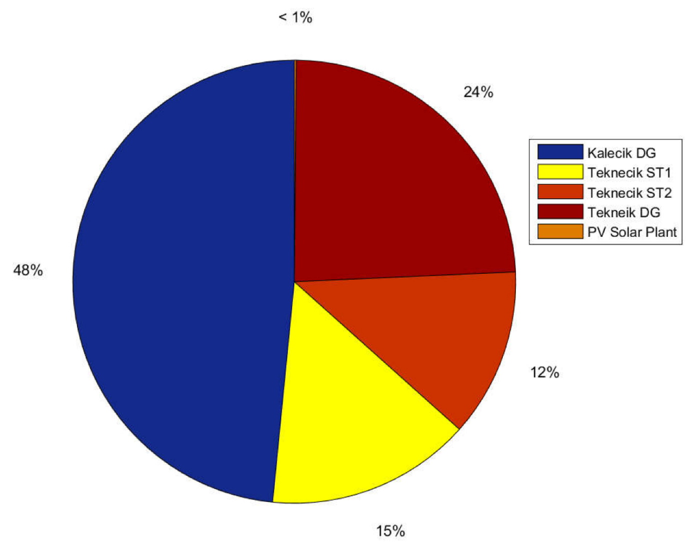

Figure 1.2. Distribution of power production into generation units in 2016

Power production and consumption curve for 2016 is given by figure 1.3. From figure 1.3, highest production points are observed during summer and winter with 158,547 and 133,348 GWh respectively. During summer time, temperatures can show up to 45 °C and air conditioners are only solution for people to decrease effects of hot weather. That is why, peak generation and loads are observed during summer. Within spring and fall, the usage of electricity decreases as balanced weather conditions appear and in winter, it shows a rise again as big portion of heating depends on electrical heaters. This shows that for peak

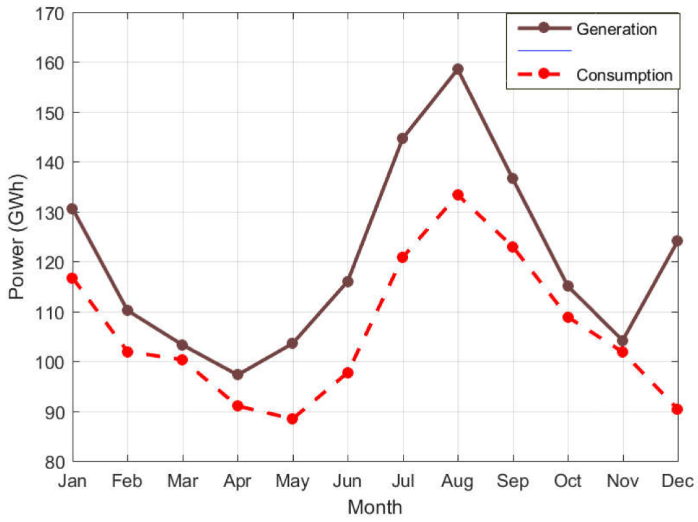

Figure 1.3. Power production and consumption of North Cyprus in 2016

loads in summer, PVs will be a good solution for producing clean energy through sun and decreasing loading on fuel based generation units. In addition, sun appears approximately 300 days in a year in Cyprus so it will also be an useful solution for winter.

From 1995 to 2014, annual production was increased from 527 to 1374 GWh. Over 20

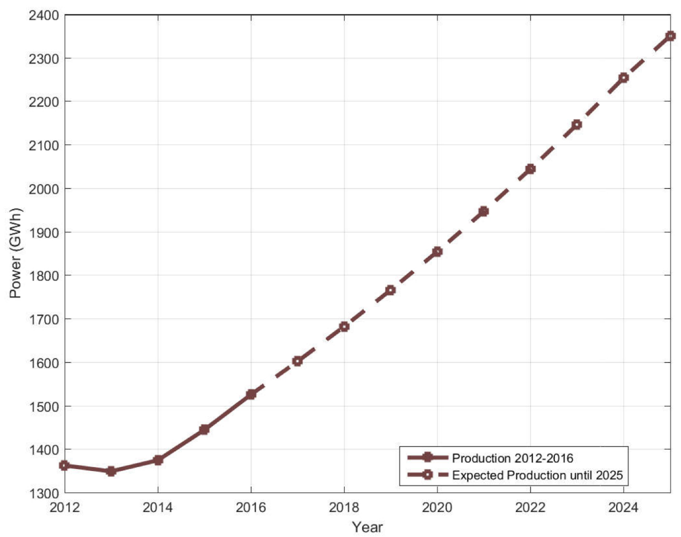

Figure 1.4. Expectations for production until 2025

years, it showed an average increase of 5.7 % yearly. In 2014, studies were done by KIB-TEK to predict annual production increase until 2025 and predictions showed that from 2015 to 2025, production will increase with 5 % in each year as shown in figure 1.4 and reach to 2350 GWh by 2025. Over this prediction, observations were done between 2014 and 2016 and it was seen that production increased by 4.85 % for 2015 and 5.32 % for 2016. This shows that predictions will match by 2025 and 2350 GWh will be observed. [KIB-TEK]

1.3 Solar Potential of Cyprus

By its locational advantage, Cyprus has one of the highest potential in Europe to convert solar energy into electricity. To start with daily sunshine durations of Cyprus, figure 1.5 can be checked. During summer and winter, average sunshine durations were calculated

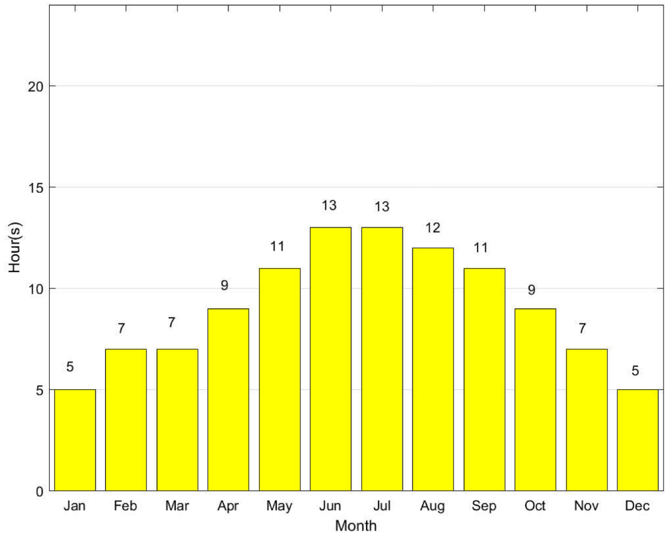

Figure 1.5. Average daily sunshine durations of Cyprus in 2016

as 13 and 6 hours respectively and yearly average as approximately 9 hours. Maximum duration of sunshine observed in December was 9.8 hours and 14.5 hours for June. In general, Cyprus accommodates sunshine for more than 300 days of a year. [CMS]

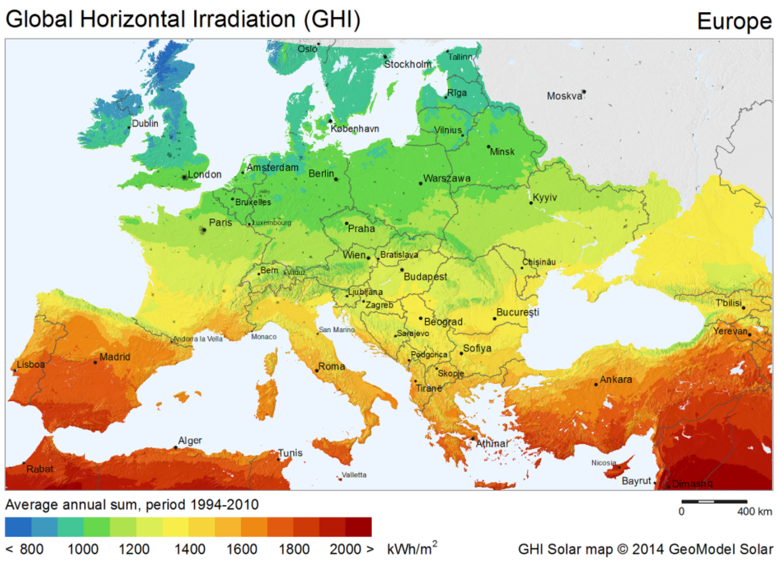

Figure 1.6. Average annual sum of GHI levels for Europe [Sol]

Cyprus has high solar irradiation levels compared to whole Europe. In figure 1.6, map shows the average annual sum of solar irradiation levels for each European country for the

period between 1994 and 2014. From map, the average of Cyprus was changing between 1700 and 2000 ($\frac{kWh}{m^2}$) place to place while big percent of European countries stayed below 1600 ($\frac{kWh}{m^2}$).
Also data obtained from North Cyprus Meteorological Service, average daily solar irradiation level on yearly base was observed as 540 ($\frac{Wh}{m^2}$) in 2014. During summer and winter, average is observed as 720 and 230 ($\frac{Wh}{m^2}$) respectively. In 2014, annual total was reached to 1730 ($\frac{kWh}{m^2}$).

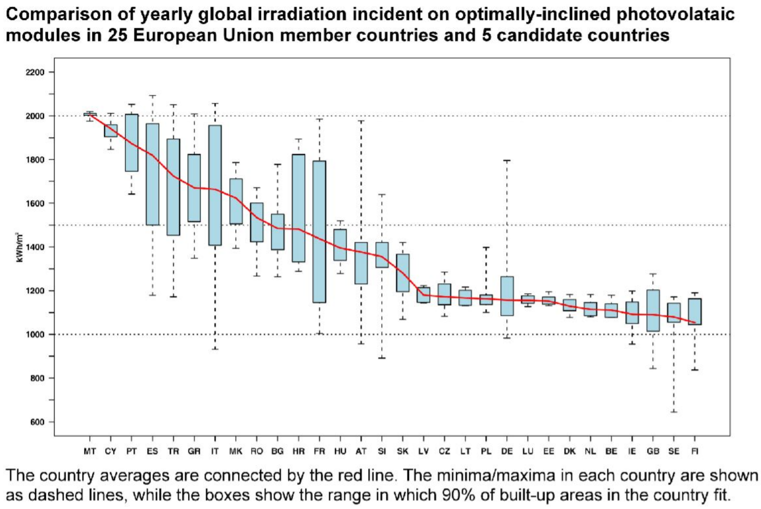

Figure 1.7. Comparison of yearly global irradiation [Suri et al., 2007]

In 2007, European commission carried out a research for comparing annual global irradiation incident with PV modules in EU member and candidate countries. Results of research shared in figure 1.7. From research, results showed that Malta has the highest amount with average of 2000 ($\frac{kWh}{m^2}$) and Cyprus follow Malta with 1930 ($\frac{kWh}{m^2}$) per year. Portugal, Spain and Turkey followed them with 1890, 1800, 1730 ($\frac{kWh}{m^2}$) per year. This also shows that Cyprus has one of the highest potential for solar irradiation. [CMS] [Suri et al., 2007]

1.4 Problem Statement

Electricity Authority of North Cyprus (KIB-TEK) is about to have initial steps into renewable energy sector by adding 30 MW of PV solar power into its grid. This project was planned in 2008 with cooperation with EU and by 2011, first PV solar plant was got in operation. However, rest of project was delayed until this year (2017) and now KIB-TEK want to add in total 30 MW of PV solar power into MV grid by 2019.

As mentioned shortly in section 1.1, EU countries were formed an Energy Union by support of EU and create a long term climate and energy policy to reach their defined goals by 2020,2030 and 2050. By 2050, energy production will be dependent on renewable energy. As a candidate of EU, North Cyprus also wants to have renewable energy dependent production by 2050 and increase their renewable share by adding new renewable energy production units into their grid.
Initial consideration of KIB-TEK was to install all 30 MW of PV solar power plant into a

single point. However, by considering changes in weather conditions and to prevent loss of all power at the same time, it is decided to distribute 30 MW power into whole grid. In a condition of loss of power from sun, generators in production units have ability to increase production by 5 MW per minute. By considering also this point, distribution of renewable production is seem as best option for controlled supply of power.
Main generation units are located in east and mid of North Cyprus. Power is supplied to west part through long transmission lines with generated losses. To prevent these losses and increase production capacity in west, it is planned to install biggest portion of PV solar power into west part of North Cyprus. By this way, produced power will be consumed locally and losses on transmission lines will be reduced.
Recently KIB-TEK had two new decisions. First of them was to stop installation of new diesel generation units and use their investments on renewable energy units. It is decided that from now on, new generator sets will be only installed if problems starts to appear on stabilization of grid. Second decision was to stop operation of Kalecik power plant by 2024. Kalecik power plant is under control of a commercial energy company called AKSA. By stopping operations of AKSA, KIB-TEK wants to take control of all generation under one unit. In order to stop operation and compensate supplied power from that plant,it is expected that installation of renewable generation units will gain speed and hold a good share of total production in upcoming years.

Addition of 30 MW into MV nodes was planned, however hosting capacity of nodes are not known to define maximum capacity of PV solar power can be injected into nodes. Apart from this, integration of large capacity of PV power into distribution grid will create problems on power quality of connection nodes.

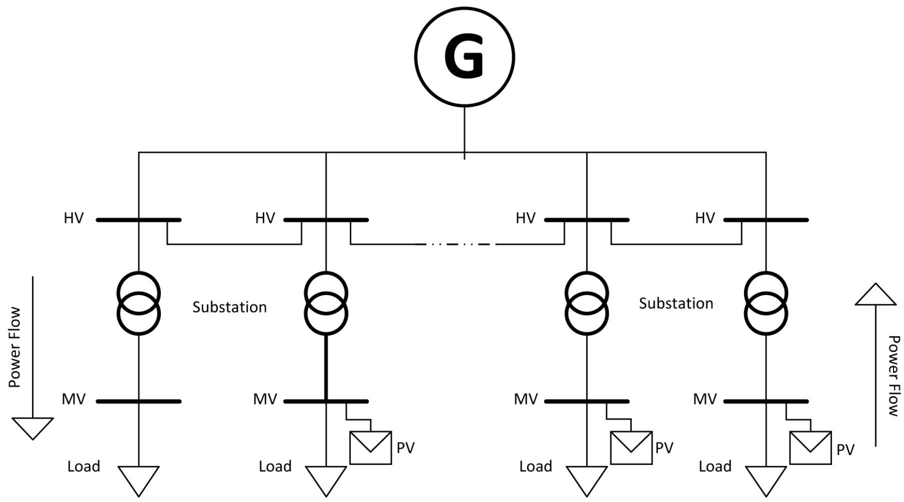

Figure 1.8. Power flow with/without PV Units

As illustrated in figure 1.8, NCG is used to produce power from centralised generation units and distribute power to loads through substations. However, by addition of PV power into distribution grid, direction of power flow will change and power will flow into grid. This create questions about quality of power on MV nodes as NCG grid didn't have two way flow of power before.

In [Farhoodnea et al., 2013] and [Ehara, 2009] , impact of grid-connected PVs on power quality was discussed. Overvoltage and voltage fluctuations were seen as two of main problems affect the power quality of connected nodes. In order to supply all collected solar energy into grid, power factor (PF) is kept close to unity factor. Due to high PF, only active power is supplied to grid and this cause lack of reactive power on connected node which will tend to increase voltage level to have overvoltage. Also, power production of PVs depend on the amount of solar irradiation reflected on panels which is purely depend on weather conditions. Changes in amount of solar irradiation due to weather conditions will cause fluctuations in power output. This will also cause voltage to fluctuate on bus.

According to entire discussion above, project will aim to develop a methodology for defining PV hosting capacity of distribution substations and propose a control scheme to control voltage and reactive power on selected substation for reducing effects of PV solar units on power quality.

Problem also can be stated as "*How to define maximum PV power capacities that can be injected into MV nodes while maintaining stability and security of power supply ?*"

1.5 Objectives

Objective 1: Developing a methodology to define PV hosting capacity of distribution substations

- Implementation of steady state model of NCG
- Selection of substation for analysis
- Addition of PV power into selected substation with increasing power levels
- Analysing of result and defining maximum PV power capacity of substation over loading conditions of transformers and lines

Objective 2: Developing a voltage control strategy to keep voltage levels within desired limits

- Implementation of a control method to mitigate voltage problems through reactive power support
- Analysis of best method for injecting reactive power into MV nodes

1.6 Assumptions and limitations

- Time varying analysis will not be carried out since data related to load profiles were not supplied by KIB-TEK
- To define PV hosting capacity of substations, only worst case scenarios will be applied to model
- Since the main consideration is to manage voltage profile, frequency support will not be investigated
- Control strategy will only be presented over voltage and reactive power
- For modelling grid, assumptions and approximations will be made for missing information

- MV nodes are all in radial and loads will be considerate as lumped for each node for reducing complexity

1.7 Summary

In this chapter, background of project was presented. North Cyprus government wants to decrease dependency (99.7 %) on fossil fuel generation units and increase their renewable energy share by 30 % within 5 years. To have an initial step, it is planned to integrate 30 MW of power PV solar power into distribution grid of North Cyprus. Cyprus has high solar potential compared to whole European countries. It accommodates sunshine for more than 300 days in a year and average annual solar irradiation is changing between 1700 - 2000 ($\frac{kWh}{m^2}$) place to place which shows that Cyprus has high potential for solar power generation. To create a method for defining maximum PV power capacity of distribution substations and maintain stability of grid, studies will start by describing current condition of NCG with the following chapter of report.

System Characterization 2

In this chapter, overview of NCG will be presented. Type of substations and transformers will be explained. Power and voltage ratings of transformers will be shared with their vector groups. Transmission lines will be explained over conductor types and sizes to give a general idea of power transmission. In the end, PV solar power capacity of North Cyprus will be given and first PV solar power plant of North Cyprus will be introduced for readers.

2.1 Overview

Grid accommodates 2 fossil fuel dependent power plants, 21 substations and a 1.2 MW solar power plant with total production capacity of 409.7 MW. Currently, 132 and 66 kV for High Voltage (HV) and 22 and 11 kV for Medium Voltage (MV) are in use. NCG has interconnection with South Cyprus over two lines. One of the line is connected to Herakles substation and operates with 66 kV. Other line is attached to OHL between Lefkosa and Guneskoy substations and operates with 132 kV. These interconnections are only used to supply power in a fault condition of a side. Daily net power flow over lines is equal to 0 MW. Through this, power flow between South and North Cyprus will not be taken into consideration for modelling.

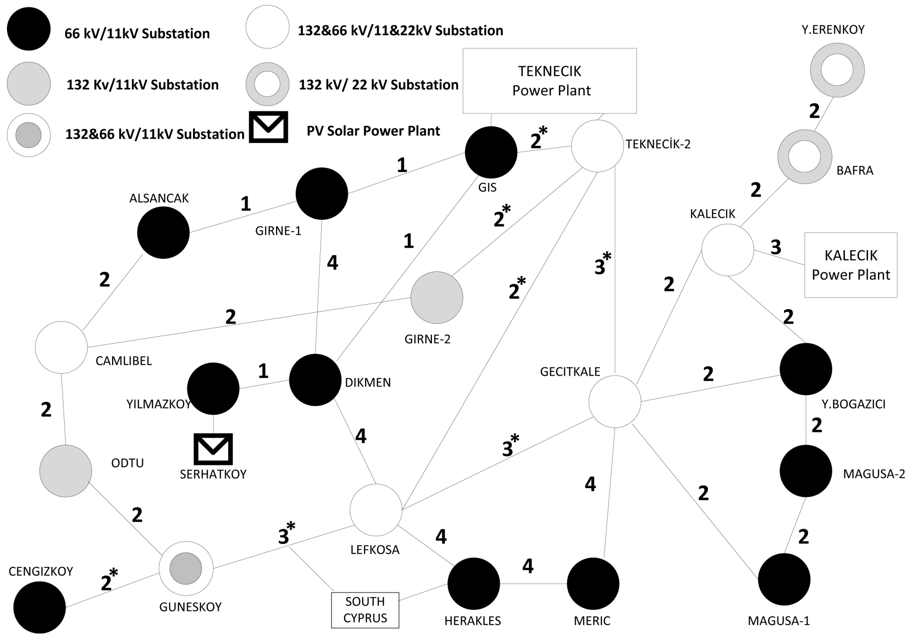

Figure 2.1. Overview of grid

From figure 2.1, overview of grid can be seen. In general, there are 5 type of substations

to convert 132 & 66 kV voltage levels into 22&11 kV levels as shown on figure 2.1. 85 % of substations in ring for HV side while all power distribution in MV voltage side is in radial. Power generation units are located in north and east of grid. Required power for loads in west are supplied through long OHL with losses. To overcome these losses and create local production units, biggest share of 30 MW PV solar power is planned to be placed in west part of grid.
Within schedule of KIB-TEK, one of the main consideration is to replace all 66 kV system with 132 kV system and use only 132 kV HV level for whole grid. 66 kV system date backs to 1960s and still in use more than half of substations and lines. Currently on going projects for this replacement are listed below as;

- To renovate 66kV Cengizkoy substation (which date backs to 1960):
  Cengizkoy substation will be demolished and new 132 kV substation will be installed its place. Currently, Cengizkoy substation has a connection to South Cyprus. However, the line was deactivated a long time before and now with new substation, this line will be activated to connect North and South side grids over 132 kV line. As a connection of this project, 66 kV side in Guneskoy will be terminated and new 132 kV feeders will be added to supply power for Cengizkoy substation. Over this, Cengizkoy substation will be only modelled as load and changes in substation will not be considered.

- To deactivate old Herakles substation:
  Currently, a new 132 kV (Haspolat) substation is about to be completed and this substation will take place of Herakles substation within 3 months. The new substation will have connection to Lefkosa, Meric substations and also to South Cyprus over 132 kV voltage level. As a continuation of this project, Meric substation will also be converted into 132 kV substation. Meric substation was already designed for 132 kV voltage level and it just waits completion of new 132 kV substation for operating in 132 kV. For modelling, Herakles and Meric substations will be modelled over current conditions and studies will be done over 66 kV.

2.2 Substations & Transformers

As mentioned in section 2.1, there are 21 substations in NCG to convert 132 & 66 kV HV level into 22 & 11 kV MV level. In figure 2.1, substations were categorized by 5 types. However, to simplify types of substation, they will be considered over their HV level. In table 2.1, type and number of substations are given.

From table 2.1, it can be observed that 11 of 21 substations are old 66 kV substations and new 132 kV substations form only 20 % of all. In grid, 6 of old 66 kV substations

HV level [kV]	No ofSubstations
132	4
66	11
132&66	6

Table 2.1. Number of Substations (Now)

HV level [kV]	No ofSubstations
132	8
66	8
132&66	5

Table 2.2. Number of substation (Will be)

were converted into 132&66 kV substation by addition of 132 kV buses. This is done for replacing these substations into 132 kV substation and deactivate 66 kV side after completion of pending projects. As also mentioned in section 2.1, Cengizkoy substation is about to be renovated and converted into 132 kV substation while Herakles substation is about to be deactivated by ending project of new 132 kV substation. Correspondingly, Meric substation will be operated as 132 kV substation. So, number of 132 kV substations will be 8 within a year. Expected number of substations according to their types are given in table 2.2.

Currently, 132/66 kV auto transformers are in use in 132&66 kV substations to transfer power between 132 and 66 kV buses. After renovations, all of these auto transformers will be deactivated with 66 kv power transformers to use only 132 kV buses of substations.

Transformers used in NCG can be divided into three category as substation transformer, generator transformer and auto transformer. From table 2.3 , all substation transformers can be observed with their ratings and types.

Rated Power[MVA]	RatedVoltage[kV]	Vector Group	Tap Changer
25	132/11 51	Dyn11	On-Load
25	132/23	Dyn11	On-Load
25	66/23	Dyn11	On-Load
20	66/11 5	Dyn11	On-Load
15	66/11 5	Dyn11	On-Load
12.5	66/11 5	Dyn11	On-Load
6.25	66/11 51	Dyn11	On-Load
5	66/11 51	Dyn11	On-Load

Table 2.3. Substation Transformers

All substation transformers are two winding transformers and have vector group of Dyn11 and On-Load tap changers. Their power rating are changing between 5 to 25 MVA. 25 MVA transformers are in use at new 132 kV substations and 2 of 66 kV substations.
Generator transformers are located at Teknecik and Kalecik power plants. Each power plant has two type of transformer for 66 and 132 kV HV levels. Their ratings and types can be observed from table 2.4.

Rated Power[MVA]	RatedVoltage[kV]	Vector Group	Tap Changer
140 - Kalecik	15/15/132	YNd11d11	On-Load
100 - Teknecik	15/132	YNd11	On-Load
71 - Teknecik	11/66	YNd1	Off-Load
62.5 - Kalecik	15/66	YNd11	On-Load

Table 2.4. Generator Transformers

Teknecik power plant has 4 two-winding transformers. 100 MVA ones are step-up transformer of Diesel generation set with vector group of YNd11 while 71 MVA ones are step-up transformer of Steam turbine generation units with vector group of YNd1. Kalecik power plant has one three-winding transformer with vector group of YNd11d11 and two two-winding transformer with vector group of YNd11. Three-winding transformer has power rating of 140 MVA and connected to both steam turbine and disel generation units. 62.5 MVA and two-winding generator transformers are connected to another diesel generation set in Kalecik by keeping one of the transformers at stand-by condition. Tap changers of all generator transformer are type of on-load except 71 MVA transformers.

Auto transformers are used in all 132&66 kV substations to supply power from 132 kV bus to 66 kV bus of substation. Auto transformers at substations are all same kind and have three-winding with power rating of 62.5 MVA. Only YN (132 kV) and yn (66 kV) windings of transformers are in use and d1 windings are not connected to any load. Details of auto transformer can be seen by table 2.5.

Rated Power[MVA]	RatedVoltage[kV]	Vector Group	Tap Changer
62.5	132/66	YN0d1	On-Load

Table 2.5. Auto Transformer

In general, tap changing time is changing between 4 to 10 seconds for all given transformers and 5 seconds will be used as fixed time changing duration for all types.

2.3 Transmission Lines

In NCG, all power transfer between substations is provided by Over Head Lines (OHL). In total, 4 different OHLs are in use in NCG and they are illustrated with numbers from 1 to 4 in figure 2.1. Each number defines the type of line over their conductor size. Relation is given as below;

1. 266.8 MCM
2. 477 MCM
3. 954 MCM
4. 3/0 AWG

Double lines are indicated with a star (⋆).
Ratings, types and lengths of OHLs are given in table 2.6.

Conductor Size	266.8MCM	477 MCM	954 MCM	3/0AWG
Rated Voltage [kV]	66	132&66	132&66	66
Rated Current [A]	313	455	681	241
Type	ACSR	ACSR	ACSR	ACSR
Length for 66kV [km]	63.37	141.75	2.1	61.71
Length for 132kV [km]	0	177.59	223.48	0
Total Length	63.37	319.34	235.58	61.71

Table 2.6. Over Head Lines

All conductors are type of Aluminium conductor steel-reinforced (ACSR) cable. 266.8 MCM and 3/0 AWG conductors are old conductors that only used between old 66 kV substations. 477 MCM is used widely in 66 and 132 kV level while 954 MCM is just used for 132 kV HV level. From table 2.6, total length of all conductors is calculated as 680 km. 82% of total length is captured by 477 and 954 MCM conductors and 60% of total installed cables are used for 132 kV transmission. As they have higher current carrying capacity than 3/0 AWG and 266.8 MCM conductor, KIB-TEK prefers to use 477 and 954 MCM for new installations.

2.4 Solar PV Power

Solar PV power capacity in North Cyprus can be divided into 3 categories as;

1. **Residential:** As name indicates, this category is for installed PV units for residences. Total power capacity is 3.1 MW.
2. **Commercial:** This category covers large scale installation of PV units for hotels, universities and industrial companies which are not connected to distribution grid. Power capacity of this category is reached to 4.2 MW and it is expected to increase by the support of government in upcoming years.
3. **Governmental:**Governmental installations and distribution grid connected PV units are placed in this category. Until now, only Serhatkoy solar PV plant is placed for this category with 1.2 MW capacity but capacity tends to increase by addition of new solar plants by government.

In total, 8.5 MW of PV solar power is in use in North Cyprus.

From figure 2.2, overview of Serhatkoy power plant can be seen. Serhatkoy power plant has 6192 panels with power rating of 206 W each. 12 panels forms an array and each 6 array is connected to an inverter. There are 86 inverter in total and they distributed into 22 and 21 groups to get in connection with 4 junction boxes. Each junction box is also connected to 0.433 kV node to supply produced power from PVs. To supply produced power into grid a step-up transformer is used to increase voltage level to 11 kV and supply to grid connected node in Yilmazkoy substation.

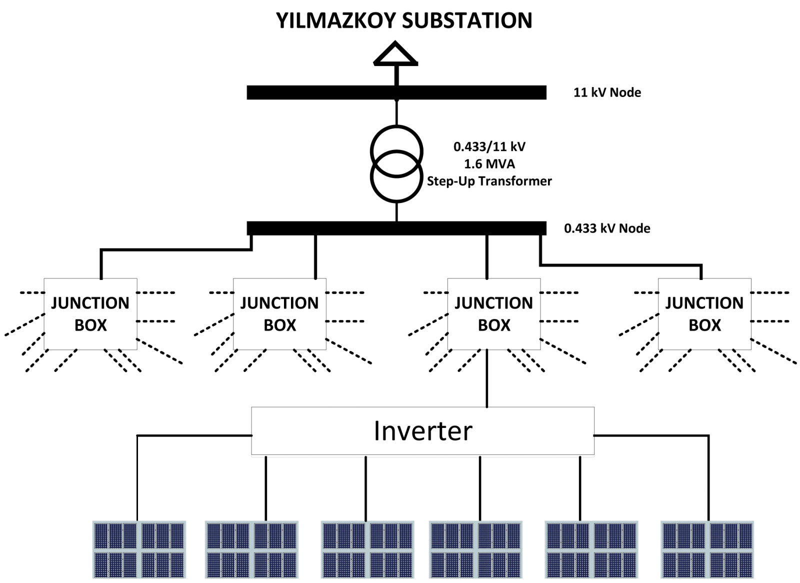

Figure 2.2. Overview of Serhatkoy solar PV plant

Plant's operational power factor is close to power unity and changing between 0.99 to 1. [KIB-TEK]

2.5 Summary

In this chapter, overview of North Cyprus power grid has been shared. Grid has been introduced and necessary information about substations, transformers and transmission lines has been explained. First PV solar power plant of North Cyprus has been also introduced with total PV solar power capacity of North Cyprus. The given details will be used for further analysis in upcoming chapters.

System Modelling 3

In this chapter, modelling of grid components will be presented. By the data obtained from KIB-TEK, transmission lines and transformers will be modelled with assumptions and simplifications. A description of models will be given shortly and with a summary, chapter will be completed.

3.1 Transmission Lines

To model transmission lines, nominal π model will be used as represented in figure 3.1. π model is used for lines below 250 km and it is formed by series resistance (R) and inductance (X_L) paralleled with half shunt capacitances ($\frac{C}{2}$) lumped at the end (receiving and sending end) of each line. Sending end (V_s) and receiving end (V_r) voltages are also indicated on the same figure. Longest transmission line in NCG is 40.477 km so π model is preferred to use.

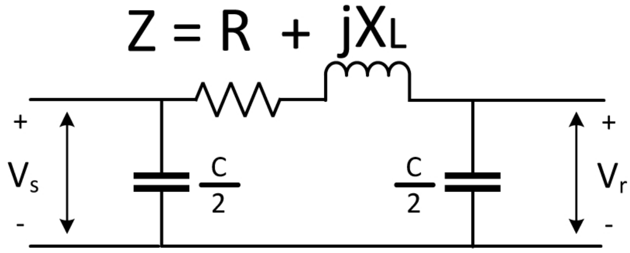

Figure 3.1. Nominal π model

R,X_L and C parameters used for modelling lines are given in table A.1.(Appendix A)

3.2 Transformers

Modelling of transformers will be based on information provided by KIB-TEK. As section 2.2, modelling of transformer will be also analysed over three categories. To model two-winding and three-winding transformers, equivalent circuits to be used are given in figure 3.2 and figure 3.3 respectively.

Number 1, 2 and 3 on figures 3.2 and 3.3 stands for primary, secondary and tertiary side of the transformer. The notations seen on the figure represent the following:

R_1, R_2 and R_3 - winding resistance
X_1, X_2 and X_3 - leakage reactance
R_m - magnetizing resistance
X_m - magnetizing reactance

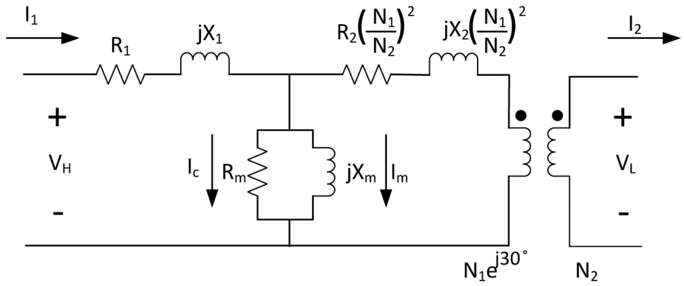

Figure 3.2. Transformer equivalent T circuit

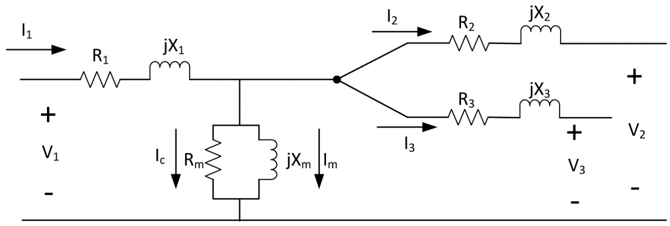

Figure 3.3. 3-Winding Transformer equivalent circuit

$\frac{N_1}{N_2}$ - Turns ratio

3.2.1 Substation Transformers

For substation transformers, power ratings, voltage ratings and vector groups were shared in table 2.3. All substation transformers have Dy connection with 30° of phase shift between primary and secondary side. To model transformers with given data, equivalent T-model circuit will be used as shown in figure 3.2.

To obtain accurate model, parameters of equivalent circuit model must be known. These parameters were not provided directly but they can be obtained by data supplied by KIB-TEK. Apart from data shown on table 2.3, KIB-TEK also provided open and short circuit test results of each transformer which are enough to calculate shunt branch and equivalent series impedances. Explanation of open and short circuit test are given in section B.1. By using those tests and equations given in section B.1, magnetizing branch and equivalent series impedances are calculated and their parameters are shared in table A.2 for each transformer.

3.2.2 Generator Transformers

For modelling two-winding generator transformers, data is provided by KIB-TEK. However 3-winding transformer is under operation of AKSA and data is not provided for that transformer. Open and short circuit test results of a typical 3-winding transformer with similar ratings is used for modelling. This data is obtained through ***DIgSILENT PowerFactory 2017*** program library.
For modelling two-winding generator transformers, same pattern is used as in substation transformers by using open and short circuit tests shown in section B.1. Calculated equivalent circuit parameters of two-winding generator transformers are given in table

A.3.
For modelling 3-winding transformer, equivalent circuit is given in figure 3.3. To model 3-winding transformer, Z_1 , Z_2 and Z_3 must be known with Z_m. To obtain them, open and short circuit test will be applied for the transformer as explained in section B.2.

Calculated parameters of 3-winding generator transformer are given in table A.4.

3.2.3 Auto Transformer

Auto transformers in NCG are all in YN0d1 vector group. Primary and secondary windings are YNyn connected with an internal tertiary winding of d1. However, the tertiary windings of auto transformers are not in use and only first two windings are in operation. That is why, autotransformer will be modelled as two-winding auto transformers for simplification. Auto transformers in NCG are grounded without grounding impedance so it will be neglected for modelling. Through this, the equivalent model is same as two-winding transformers as shown in figure 3.2 without phase shift. To obtain equivalent series and magnetizing branch impedances, same steps and tests were applied as shown in section B.1. The calculated parameters are given in table A.5.

3.3 Summary

In this chapter, major components of NCG has been modelled. π model has been used to model transmission lines with data provided by KIB-TEK. Equivalent T-circuit model has been used to model transformers. To obtain equivalent circuit parameters, open and short circuit test results of transformers has been used for calculations.

Steady State Analysis 4

In this chapter, a method will be generated to examine maximum PV power capacity of selected substation. System will be analysed over 3 case scenarios to observe limits of PV power injection over loading conditions of transformers and lines. In the end, results of cases will be discussed and optimum operational limits will be defined

To initialize studies for measuring maximum PV capacity of MV nodes, a method is going to be applied by considering loading (lines & transformer) and node voltages of substations. This reason, several scenarios will be applied for MV nodes within this chapter and their results will be used to obtain information for loading conditions and node voltages of chosen substation. As mentioned in problem statement, big share of PV power integration will be integrated into substations in the west part of NCG. By considering this, Guneskoy substation is selected as pilot substation to carry out studies.

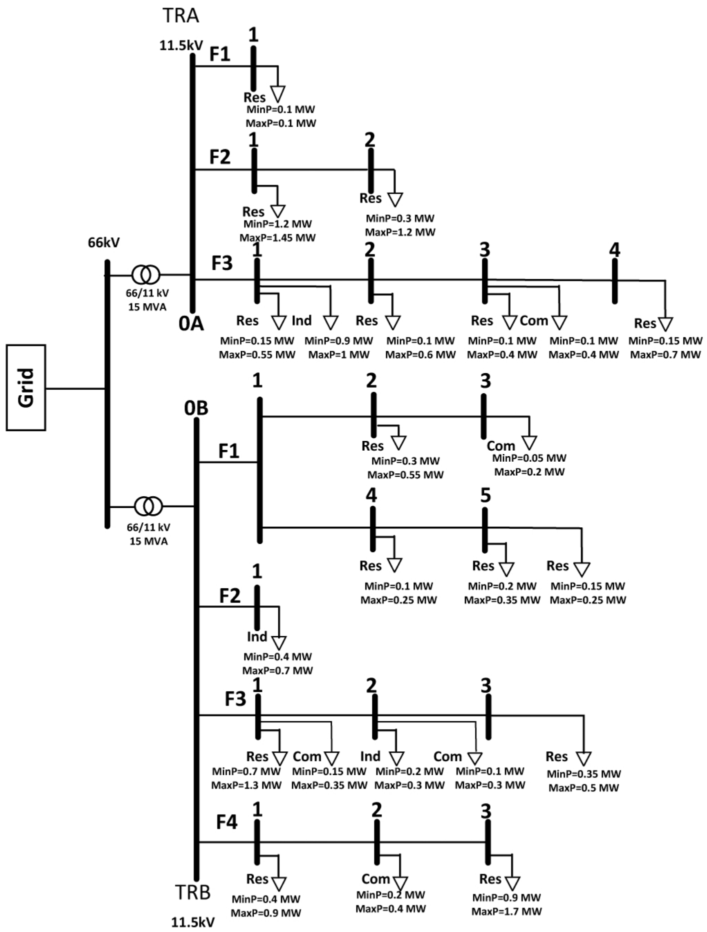

Figure 4.1. 66 kV side of Guneskoy substation

The method is going to be applied for this substation will be used as a template to carry out studies for other substations. Guneskoy substation accommodates 2 HV levels and has two 66/11 kV (15 MVA) transformers for transforming power to supply MV grid. All MV feeders and loads are in radial and their structure can be seen by in figure 4.1. Maximum and minimum loads of nodes are also given on figure 4.1 with the type of loading. Loads are categorised in 3 types in NCG and their power factor (PF) are kept within same ranges as given in table 4.1 .

Type of Load	Residential	Commercial	Industrial
Power Factor	0 93	0.96	0.89

Table 4.1. Type of Loads

To carry out analysis, 3 main scenarios will be applied to grid for observing responses.

1. **Max Load - No PV power:** In this case, current situation of voltage levels of nodes and loading condition of transformers and lines will be observed under maximum loading condition of the grid.

2. **Max Load - Max PV power:** In this case, maximum PV power will be applied to each feeder node and loading conditions will be analysed with node voltages under maximum loading condition of the grid.

3. **Min Load - Max PV Power:**In this case, maximum PV power will be applied to each feeder node and loading conditions will be analysed with node voltages under minimum loading condition of the grid.

Max Load - Max Power and Min Load - Max Power cases are also going to have sub-cases by increasing PV power in levels with increments of 0.5 pu and loading of transformer will be considerate to limit this incrementation. When both transformers loading exceeds 95 %, incrementation of PV power will be interrupted. For injection of PV power to each MV node, 1 pu of PV power will be equal to total maximum load power of each feeder node. To evaluate all cases over node voltages and loading of transformers and lines, tables are generated for each transformer based on number of feeders and nodes to simply analysis with given color codes. To start from evaluation showed in figure 4.2, it is going to be used for illustrating voltage levels in each case to have easier comparison between different cases. Initial big cell will illustrate voltage level of 11.5 kV bus of transformers. Each feeder is named with 'F' and each node is showed with an 'N'. Their common cell will illustrate related feeder node's voltage level by given color codes. For all cases, maximum voltage deviations are desired to be in range of ± 0.05 % and deviation more that value will not be wanted.

Figure 4.3 will be used to illustrate loading of lines and transformers. Initial big cell will be used to show transformer loadings with given color codes and rest of them will be used for line loading matching with feeder and node axis. For NCG, 80 % loading is not exceed normally and it is seen as safety region for lines and transformers. However, there are few lines and transformers in NCG that operates between 80 % and 95 % during peak loading

TRB

N0B				
	F1	F2	F3	F4
N1				
N2				
N3				
N4				
N5				

TRA

N0A			
	F1	F2	F3
N1			
N2			
N3			
N4			

Node Voltage (pu)	
< 0.95	(blue)
[0.95, 1]	(yellow)
[1.01, 1.05]	(orange)
> 1.05	(red)

Figure 4.2. Evaluation criteria for node voltages of transformer A and B

of grid. That is why, above 80% is seen as operational case for our criteria and over 95 % will not be acceptable for operation.

TRB

TRB				
	F1	F2	F3	F4
0B-1				
1-2				
2-3				
1-4				
4-5				

TRA

TRA			
	F1	F2	F3
0A-1			
1-2			
2-3			
3-4			

Loading (%)	
< 80	(yellow)
[80 , 95]	(orange)
> 95	(red)

Figure 4.3. Evaluation criteria for transformer and line loading

4.1 Max Load - No PV Power

This case will be used as base case scenario of NCG to have comparison between other cases, to discuss changes and effects of PV power injection into nodes. From figure 4.4, all nodes have voltage level within range of 1±0.05 pu except TRB-F4-N3, TRA-F3-N3 and TRA-F3-N4. Their voltage levels remain below the desired limits.

TRB

N0B	1.01			
	F1	F2	F3	F4
N1	0.99	0.99	0.99	0.96
N2	0.98		0.96	0.95
N3	0.98		0.95	0.94
N4	0.98			
N5	0.97			

TRA

N0A	1.01		
	F1	F2	F3
N1	1.01	0.98	0.97
N2		0.96	0.95
N3			0.94
N4			0.93

Node Voltage (pu)	
< 0.95	(blue)
[0.95, 1]	(yellow)
[1.01, 1.05]	(orange)
> 1.05	(red)

Figure 4.4. Node voltages for maximum load - no PV power condition

From figure 4.5, loading of all transformers and lines are within safety regions. Only TRA-F3-0A-1 line is 86.4% loaded and it is also acceptable for operation.

TRB

TRB	61			
	F1	F2	F3	F4
0B-1	36	17	63	71
1-2	17		26	50
2-3	4		12	41
1-4	20			
4-5	14			

TRA

TRA	50		
	F1	F2	F3
0A-1	2	63	86
1-2		28	50
2-3			36
3-4			17

Loading (%)	
< 80	
[80 , 95]	
> 95	

Figure 4.5. Loadings for maximum load - no PV power condition

4.2 Max Load - Max PV Power

For this case, PV power will be injected with incrementation of 0.5pu to observe effects of injection on loading of transformers and lines while also examining changes in voltage of nodes under maximum loading condition of the grid.

4.2.1 0.5 pu

0.5 pu of PV power injection wiil be applied to all feeder nodes and deviations will be compared with Max Power - No PV power condition over figure 4.6 and figure 4.7. Injection of 0.5 pu PV power increased voltage levels in all feeder nodes and voltage levels of TRB-F4-N3, TRA-F3-N3 and TRA-F3-N4 are also improved and get into desired ranges.

TRB

N0B	1.02			
	F1	F2	F3	F4
N1	1.01	1.01	1.01	0.99
N2	1.01		0.99	0.99
N3	1		0.99	0.98
N4	1			
N5	1			

TRA

N0A	1.02		
	F1	F2	F3
N1	1.02	1	1
N2		0.99	0.99
N3			0.98
N4			0.97

Node Voltage (pu)	
< 0.95	
[0.95, 1]	
[1.01, 1.05]	
> 1.05	

Figure 4.6. Node voltages for maximum load - maximum PV power condition (0.5 pu)

Loading of all transformers and lines are decreased by the injected PV power as the produced power consumed locally by loads. Loading map of 0.5 pu case can be seen by figure 4.7.

TRB

TRB	35			
	F1	F2	F3	F4
0B-1	20	10	36	40
1-2	10		15	28
2-3	2		7	23
1-4	11			
4-5	8			

TRA

TRA	29		
	F1	F2	F3
0A-1	1	38	50
1-2		16	28
2-3			20
3-4			10

Loading (%)	
< 80	
[80 , 95]	
> 95	

Figure 4.7. Loading condition for maximum load - maximum PV power case (0.5 pu)

4.2.2 1 & 1.5 pu

For 1 pu of PV power injection, all node voltages had an increase and get into range of [1.01, 1.05]. Loading of lines and transformers are decreased compared to 0.5pu case and stayed below 80% range as previous case.

TRB

N0B	1.03			
	F1	F2	F3	F4
N1	1.02	1.02	1.02	1.01
N2	1.02		1.01	1.01
N3	1.02		1.01	1.01
N4	1.02			
N5	1.02			

TRA

N0A	1.03		
	F1	F2	F3
N1	1.03	1.02	1.02
N2		1.01	1.01
N3			1.01
N4			1.01

Node Voltage (pu)	
< 0.95	
[0.95, 1]	
[1.01, 1.05]	
> 1.05	

Figure 4.8. Node voltages for maximum load - maximum PV power condition (1 pu)

For 1.5 pu case, slight rises in node voltages are observed compared to 1 pu case. However color map for node voltages is remained same with 1 pu case and showed as in figure 4.8. Increasing power injection tends to increase loading of lines and transformers slightly and active power start to flow into MV buses of substation as produced power exceeded load power.However, color map of loading is remained same as 1 pu case and can be seen through figure 4.7.

4.2.3 2 pu

For this case, voltage levels are increased considerably in 3^{rd} and 4^{th} nodes of feeders. This tend to TRA-F3-N3 to exceed desired limits and get into red area as shown in figure 4.9. For other nodes, color map is remained in orange region as in figure 4.8.

Loading of lines and transformers are increased by 1.5 to 2 times of previous case but stayed in safe (yellow) region for this case.

TRB				
N0B	1.03			
	F1	F2	F3	F4
N1	1.04	1.03	1.04	1.04
N2	1.04		1.04	1.05
N3	1.04		1.05	1.05
N4	1.04			
N5	1.04			

TRA			
N0A	1.03		
	F1	F2	F3
N1	1.03	1.04	1.04
N2		1.05	1.05
N3			1.05
N4			1.06

Node Voltage (pu)	
< 0.95	
[0.95, 1]	
[1.01, 1.05]	
> 1.05	

Figure 4.9. Node voltages for maximum load - maximum PV power condition (2 pu)

TRB				
TRB	57			
	F1	F2	F3	F4
0B-1	34	16	59	64
1-2	16		24	45
2-3	4		11	36
1-4	18			
4-5	13			

TRA			
TRA	46		
	F1	F2	F3
0A-1	2	58	79
1-2		26	44
2-3			32
3-4			15

Loading (%)	
< 80	
[80 , 95]	
> 95	

Figure 4.10. Loading condition for maximum load - maximum PV power case (2 pu)

4.2.4 2.5 pu

For this case, voltage levels are remained almost same with slight increases for all the nodes except the ones shown with red in figure 4.11. Compared to 2 pu case, 4 more feeder nodes are marked as red on the map as they exceeded the 1.05 pu voltage level.

TRB				
N0B	1.02			
	F1	F2	F3	F4
N1	1.04	1.03	1.04	1.05
N2	1.04		1.05	1.06
N3	1.04		1.06	1.06
N4	1.04			
N5	1.04			

TRA			
N0A	1.03		
	F1	F2	F3
N1	1.03	1.04	1.05
N2		1.05	1.05
N3			1.07
N4			1.07

Node Voltage (pu)	
< 0.95	
[0.95, 1]	
[1.01, 1.05]	
> 1.05	

Figure 4.11. Node voltages for maximum load - maximum PV power condition (2.5 pu)

Loading of transformer A and B are increased by injected PV power and transformer B get into orange region with F3-0B-1 and F4-0B-1 lines compared to 2 pu case. For transformer A, loading is also increased but it remained below 80% level. However, increase on PV power cause to TRA-F3-0A-1 line to overload and exceed limits to reach 112%. The loading of TRA-F2-0A-1 line is also increased significantly (24.3%). However, loading of

TRB

TRB	82 (orange)			
	F1	F2	F3	F4
0B-1	50	22	85	91
1-2	23		34	64
2-3	6		15	52
1-4	26			
4-5	19			

TRA

TRA	65		
	F1	F2	F3
0A-1	3	83	112
1-2		37	63
2-3			45
3-4			21

Loading (%)	
< 80	(yellow)
[80 , 95]	(orange)
> 95	(red)

Figure 4.12. Loading condition for maximum load - maximum PV power case (2.5 pu)

line stayed between range of [80, 95] and it is acceptable for operation.

4.2.5 3 pu

By applying 3 pu PV power, 3 more nodes are exceeded desired voltage levels and marked as red on the map while other nodes remained almost same as 2.5 pu case.

TRB

N0B	1.01			
	F1	F2	F3	F4
N1	1.03	1.02	1.03	1.05
N2	1.04		1.06	1.06
N3	1.04		1.06	1.07
N4	1.04			
N5	1.04			

TRA

N0A	1.02		
	F1	F2	F3
N1	1.02	1.04	1.05
N2		1.06	1.07
N3			1.07
N4			1.08

Node Voltage (pu)	
< 0.95	(blue)
[0.95, 1]	(yellow)
[1.01, 1.05]	(orange)
> 1.05	(red)

Figure 4.13. Node voltages for maximum load - maximum PV power condition (3 pu)

From figure 4.14, significant loading of transformer B is observed with 107% and transformer cannot be operated with this loading. Transformer A loading is also increased significantly by 20% and reach to 85%. To check line loadings, orange layers from 2.5 pu case turned into red and cause overloading for operation.

TRB

TRB	107			
	F1	F2	F3	F4
0B-1	65	29	112	120
1-2	31		44	83
2-3	8		20	68
1-4	35			
4-5	24			

TRA

TRA	85		
	F1	F2	F3
0A-1	4	108	146
1-2		48	83
2-3			59
3-4			27

Loading (%)	
< 80	(yellow)
[80 , 95]	(orange)
> 95	(red)

Figure 4.14. Loading condition for maximum load - maximum PV power case (3 pu)

4.2.6 3.5 pu

Voltage levels are not changed significantly for this case. However, voltage levels are decreased on big percentage of nodes compared to 3 pu case and 3 of them marked as yellow .

TRB

	F1	F2	F3	F4
N0B	1			
N1	1.02	1.01	1.02	1.05
N2	1.03		1.06	1.06
N3	1.03		1.06	1.07
N4	1.03			
N5	1.04			

TRA

	F1	F2	F3
N0A	1		
N1	1	1.03	1.05
N2		1.06	1.07
N3			1.08
N4			1.09

Node Voltage (pu)
< 0.95
[0.95, 1]
[1.01, 1.05]
> 1.05

Figure 4.15. Node voltages for maximum load - maximum PV power condition (3.5 pu)

Transformer A is also overloaded with 105% and incrementation of increasing power injection is interrupted by 3.5 pu case as both transformers are over 95% level. Apart from transformers, TRA-F3-1-2 and TRB-F4-1-2 lines are also turned from orange to red as loading of lines exceeded 95%.

TRB

	F1	F2	F3	F4
TRB	134			
0B-1	82	37	140	149
1-2	38		55	103
2-3	10		25	84
1-4	43			
4-5	30			

TRA

	F1	F2	F3
TRA	105		
0A-1	5	134	181
1-2		59	103
2-3			73
3-4			34

Loading (%)
< 80
[80 , 95]
> 95

Figure 4.16. Loading condition for maximum load - maximum PV power case (3.5 pu)

4.2.7 Conclusion

To start from Max Load - No PV Power case, system was operating within desired voltage levels and loadings except 3 nodes that appeared as under-voltage for desired limits. By injection of PV power, system loading and node voltages were all get into desired ranges as under-voltage nodes also had increase on their voltage levels. Until 2 pu case, system operation was within desired ranges. However, red cells start to appear and tend to increase by increasing power injection until 3.5 pu case. By 3.5 pu case, both TRA and TRB were overloaded and incrementation of power levels were interrupted.

4.3 Min Load - Max PV Power

For this case, PV power will be injected with incrementation of 0.5pu to observe effects of injection on loading of transformers and lines while also examining changes in voltage of nodes under minimum loading condition of the grid.

4.3.1 0.5 pu

With injection of 0.5 pu PV power, transformers' MV bus voltages get into range of [1, 1.01]. For transformer A, most of the feeder nodes are remained as 1.01 pu while 2 of the feeder nodes for transformer A are remained 1 pu as shown in figure 4.17.

TRB

N0B	1.01			
	F1	F2	F3	F4
N1	1.01	1.01	1	1
N2	1		1	1
N3	1.01		1	1
N4	1			
N5	1			

TRA

N0A	1.01		
	F1	F2	F3
N1	1.01	1	1.01
N2		1	1.01
N3			1.01
N4			1.01

Node Voltage (pu)	
< 0.95	
[0.95, 1]	
[1.01, 1.05]	
> 1.05	

Figure 4.17. Node voltages for minimum load - maximum PV power condition (0.5 pu)

Loading of transformers and lines stayed below 16% and all of them marked with yellow on the map.

TRB

TRB	11			
	F1	F2	F3	F4
0B-1	6	4	13	12
1-2	3		6	9
2-3	1		4	8
1-4	4			
4-5	3			

TRA

TRA	10		
	F1	F2	F3
0A-1	1	16	16
1-2		7	13
2-3			9
3-4			4

Loading (%)	
< 80	
[80 , 95]	
> 95	

Figure 4.18. Loading condition for minimum load - maximum PV power case (0.5 pu)

4.3.2 1 pu

By increasing PV power from 0.5pu to 1 pu, voltage levels of feeder nodes tends to increase and get all into orange region. The increase in TRA-F3-N2, N3 and N4 are seen significant and they are so close to exceed desired limit.

TRB

NOB	1.01			
	F1	F2	F3	F4
N1	1.01	1.01	1.01	1.02
N2	1.01		1.01	1.02
N3	1.02		1.01	1.02
N4	1.01			
N5	1.02			

TRA

NOA	1.01		
	F1	F2	F3
N1	1.01	1.01	1.02
N2		1.02	1.03
N3			1.03
N4			1.04

Node Voltage (pu)	
< 0.95	(blue)
[0.95, 1]	(yellow)
[1.01, 1.05]	(orange)
> 1.05	(red)

Figure 4.19. Node voltages for minimum load - maximum PV power condition (1 pu)

Loading of transformers and lines are increased by additional power. However, they remained in the safe region of loading as 0.5 pu case and color map can be shown as in figure 4.20

TRB

TRB	28			
	F1	F2	F3	F4
0B-1	18	8	28	33
1-2	9		11	22
2-3	3		4	18
1-4	9			
4-5	6			

TRA

TRA	24		
	F1	F2	F3
0A-1	1	28	46
1-2		19	34
2-3			23
3-4			11

Loading (%)	
< 80	(yellow)
[80 , 95]	(orange)
> 95	(red)

Figure 4.20. Loading condition for minimum load - maximum PV power case (1 pu)

4.3.3 1.5 pu

For this case, node voltages are also tend to increase compared to 1 pu case and TRA-F3-N4 exceeded the desired limits and reached to 1.06 pu.

TRB

NOB	1.01			
	F1	F2	F3	F4
N1	1.02	1.01	1.02	1.03
N2	1.02		1.03	1.03
N3	1.02		1.03	1.04
N4	1.02			
N5	1.02			

TRA

NOA	1.01		
	F1	F2	F3
N1	1.01	1.02	1.03
N2		1.04	1.05
N3			1.05
N4			1.06

Node Voltage (pu)	
< 0.95	(blue)
[0.95, 1]	(yellow)
[1.01, 1.05]	(orange)
> 1.05	(red)

Figure 4.21. Node voltages for minimum load - maximum PV power condition (1.5 pu)

Lines and transformers are loaded 1.5 to 2 times of 1pu case and TRA-F3-0A-1 line is loaded with 92 % which is considerably high loading for the line. Loading map of 1.5 pu case can be seen by figure 4.22.

TRB

TRB	52			
	F1	F2	F3	F4
0B-1	33	14	55	62
1-2	16		21	42
2-3	5		9	34
1-4	17			
4-5	12			

TRA

TRA	47		
	F1	F2	F3
0A-1	1	52	92
1-2		30	65
2-3			38
3-4			18

Loading (%)	
< 80	
[80 , 95]	
> 95	

Figure 4.22. Loading condition for minimum load - maximum PV power case (1.5 pu)

4.3.4 2 pu

Increasing injection of PV power into grid cause MV bus voltage level to decrease and voltage levels become 1 pu by 2 pu case. TRA-F1-N1 is also had a decline in voltage magnitude as almost all the flowing power is active power and ratio of reactive power is so less. Opposite to them, voltage levels are increased for feeders of 2 and 3 and TRA-F3-N3 also passover 1.05 pu level.

TRB

N0B	1			
	F1	F2	F3	F4
N1	1.02	1.01	1.02	1.04
N2	1.02		1.04	1.04
N3	1.03		1.04	1.05
N4	1.02			
N5	1.03			

TRA

N0A	1		
	F1	F2	F3
N1	1	1.02	1.04
N2		1.05	1.05
N3			1.06
N4			1.07

Node Voltage (pu)	
< 0.95	
[0.95, 1]	
[1.01, 1.05]	
> 1.05	

Figure 4.23. Node voltages for minimum load - maximum PV power condition (2 pu)

TRA-F3-0A-N1 line loading is increased by 24% from 1.5 pu case to 2 pu case and become overloaded for operation. Significant increases are also seen in TRB-F3-0B-1 and TRB-

TRB

TRB	78			
	F1	F2	F3	F4
0B-1	49	21	82	90
1-2	24		32	62
2-3	7		13	50
1-4	26			
4-5	17			

TRA

TRA	63		
	F1	F2	F3
0A-1	2	78	116
1-2		42	74
2-3			52
3-4			24

Loading (%)	
< 80	
[80 , 95]	
> 95	

Figure 4.24. Loading condition for minimum load - maximum PV power case (2 pu)

F4-0B-1 lines and their loadings are reached to 82% and 90% respectively and get into orange region.

4.3.5 2.5 pu

TRA-F3-N2 and TRB-F4-N3 are turned into red by the increasing voltage on those nodes. Compared to them, other nodes are remained in the same voltage ranges and not change their color on the map

TRB

NOB	0.99			
	F1	F2	F3	F4
N1	1.01	1	1.01	1.04
N2	1.02		1.04	1.05
N3	1.02		1.04	1.06
N4	1.02			
N5	1.03			

TRA

N0A	0.99		
	F1	F2	F3
N1	0.99	1.02	1.04
N2		1.05	1.06
N3			1.07
N4			1.09

Node Voltage (pu)	
< 0.95	
[0.95, 1]	
[1.01, 1.05]	
> 1.05	

Figure 4.25. Node voltages for minimum load - maximum PV power condition (2.5 pu)

By increasing power form 2 pu to 2.5 pu, transformer B is overloaded by 103%. Transformer A is also loaded 20% more than previous case. However, it stayed within orange region. 3 new lines are turned into red on the map and overloaded. TRA-F2-0A-1 line had a huge increase by 26% and reached to 104%. TRA-F3-1-2 is also so close to exceed 95% level and got orange color by increase of 19% from 2 pu case.

TRB

TRB	103			
	F1	F2	F3	F4
0B-1	65	28	110	119
1-2	31		42	82
2-3	9		18	66
1-4	34			
4-5	24			

TRA

TRA	83		
	F1	F2	F3
0A-1	3	104	151
1-2		54	93
2-3			66
3-4			31

Loading (%)	
< 80	
[80 , 95]	
> 95	

Figure 4.26. Loading condition for minimum load - maximum PV power case (2.5 pu)

4.3.6 3 pu

From 2.5pu to 3pu case, node voltage levels are remained same as shown in figure 4.25. However, both transformers become overloaded by 3 pu case and system cannot be operated. Apart from transformers, 2 new line turned into red while 2 other get orange color by the increasing loading as shown in figure 4.27.

TRB

TRB	130			
	F1	F2	F3	F4
0B-1	82	36	138	149
1-2	39		53	103
2-3	11		23	83
1-4	43			
4-5	30			

TRA

TRA	103		
	F1	F2	F3
0A-1	4	131	187
1-2		65	113
2-3			79
3-4			37

Loading (%)	
< 80	
[80 , 95]	
> 95	

Figure 4.27. Loading condition for minimum load - maximum PV power case (3 pu)

4.3.7 Conclusion

To compare Max load and Min load cases, system was operating also within desired ranges for minimum load case until 1 pu. However, problems started to appear earlier than Max load condition and by 1.5 pu, red colors start to appear on map of voltage levels as first feeder node voltage level exceeded 1.05 pu. As maximum load case, problems tend to increase by increasing PV power injection and by 2.5 case, TRB became overloaded. By increasing injected power from 2.5 pu to 3 pu, TRA was also overloaded and incrementation interrupted.

To sum up, as load is getting less, more active power is injected into grid. This tends to observe problems earlier than maximum load case compared to minimum load case. That is why, injection of PV power must be compatible with both cases to keep loading and voltage levels within desired limits. From results, it is so obvious that maximum power will be injected to MV nodes are limited by the loading of transformers and lines. Loading conditions and voltage levels will be main consideration in upcoming section to define maximum PV power capacity of nodes.

4.4 Discussion

In previous sections, different case scenarios were analysed to observe responses of grid for increasing injection of PV power. In this section, results will be assessed and important points will be examined in detail. Analysis will be carried over transformers' loading with problematic nodes and lines that are marked as red. As defined before, transformers are the main limitation for injection of PV power for this substation. Below, loading conditions of transformers over increasing injection of PV power are given for each case in figure 4.28 (Max Load) and figure 4.29 (Min Load). From figure 4.28, initial point of overloading for transformer B is observed at 3 pu case while transformer A had initial overloading at 3.5 pu case for maximum load condition. Under minimum load condition of grid, transformers are overloaded earlier at 2.5 pu for TRB and 3 pu for TRA as more PV power is injected into MV bus. Initial overloading points of transformers for each case are summarised in table 4.2 .

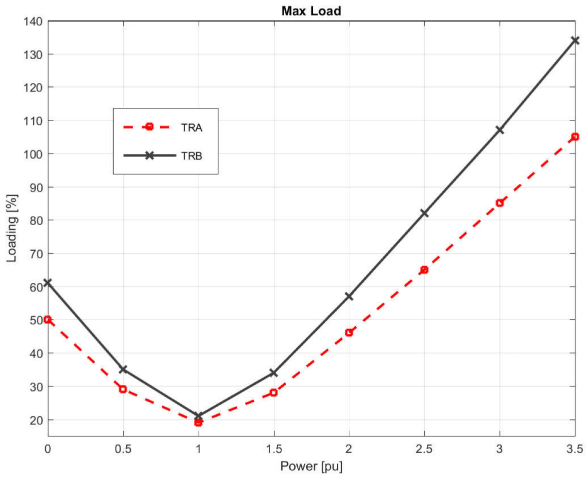

Figure 4.28. Transformers' loading at maximum loading condition

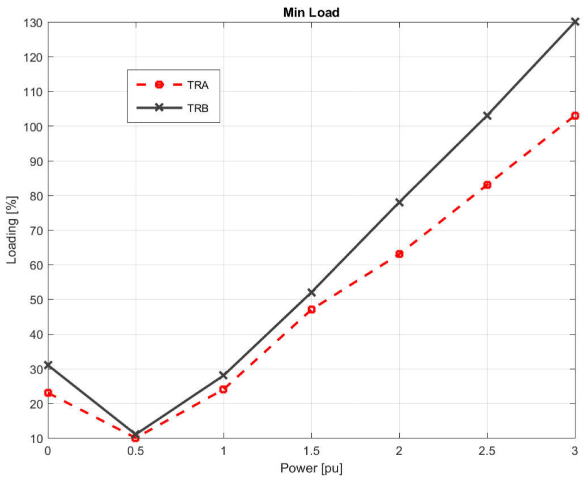

Figure 4.29. Transformers' loading at minimum loading condition

	TRA		TRB	
	NC	OPC	NC	OPC
Max Load	3 5pu	3 pu	3 pu	2.5 pu
Min Load	3pu	2.5 pu	2.5 pu	2 pu

Table 4.2. Operational and non-operational cases of transformers

In table 4.2, operational (OPC) and non-operational (NC) cases for transformers are indicated. To check transformers loading for maximum loading and minimum loading conditions together, transformer A can be operated safely at 2.5 pu. For transformer B, this limit is defined at 2 pu. Over this, transformer A and B allows 2.5 pu and 2 pu respectively injection of PV power. By considering these limits and to observe other limitations over lines and nodes, substation will be analysed over 2 pu case for B side of substation and 2.5 pu for A side. At 2 pu PV power injection, nodes and lines that are marked as red are shown in figure 4.11 and figure 4.12 for A side of substation. For B side, there is no problem with lines and nodes considering both Max load and Min Load conditions of the grid at 2 pu. However, by checking both cases for A side at 2.5 pu, most problems appears at min load condition of the grid as shown in figure 4.25 and figure 4.26 with overloaded lines (TRA-OA-1 F2 and F3) and nodes that exceeded desired limits (TRA-F3-N2, N3 and N4). For both overloaded lines, loading condition from 0 to 2.5 case for minimum load condition is showed on figure 4.30. Only minimum load condition is illustrated by figure 4.30 as it is observed as worst case scenario for those lines.

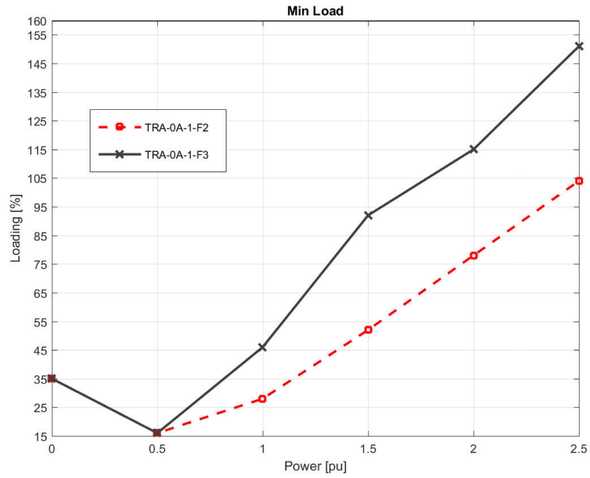

Figure 4.30. Loading of lines under minimum load condition

From figure 4.30, TRA-0A-1-F2 line can operate within acceptable conditions until 2 pu case while TRA-0A-1-F3 line could operate until 1.5 pu case. This shows that, if we decrease power on those feeders and inject same amount of power into feeder 1 which is loaded only with 2 %, system will operate within desired limits. Over this a case is generated by applying 1.5 pu power into feeder 3 and 2 pu power into feeder 2 while adding all difference power into feeder 1 which has only one node. Results are shown in figure 4.31 .

TRA

NOA	1		
	F1	F2	F3
N1	1.02	1.02	1.02
N2		1.05	1.03
N3			1.04
N4			1.05

TRA

TRA	80		
	F1	F2	F3
0A-1	94	78	78
1-2		42	51
2-3			38
3-4			18

Figure 4.31. Transformer A loading and node voltages for selected case

From figure 4.31, it can be observed that decreasing power in feeders 2 and 3 and adding difference into feeder 1, eliminate all problems on loading of lines. Also, node voltages got into desired limits by this application. Only TRA-0A-1F1 is loaded by 94% and it can be decreased by distributing extra amount of power into other feeders.

From overall, in total of 2 pu (14.7 MW) for B side of substation and 2.5 pu (16 MW) for A side are observed as maximum power can be injected into Guneskoy substation (total of 30.7 MW) to be able to operate system within desired limits and conditions while having maximum loading for each transformer approximately 80 % which is a desired value for electricity authorities.

4.5 Summary

From overall, system was analysed over 3 base scenarios with several sub-cases to observe responses of grid to injected PV power. From results, main problem to limit injection of PV power was seen as power capacity of transformers. Transformers are 15 MVA transformers and limit MV nodes to inject more PV power into grid. Over this, acceptable injection amounts of power defined in discussion section and problems associated with lines and nodes were indicated. By analysing line loadings over increasing power cases, optimal loading for feeder lines of transformer A are obtained 2 pu for TRA-0A-1-F2 and 1.5 pu for TRA-0A-1-F3 to allow acceptable operation of lines. By decreasing power on those feeders and adding to feeder 1, voltage levels of all TRA nodes remained within acceptable ranges to operate system. Over all, main consideration of studies must be concentrated on power capacity of transformers and lines for injection of PV power. For this substation, problems were not arise for voltage levels. However, it is possible to appear for other substations and a method will be discussed in upcoming chapter to keep voltage levels within desired limits.

Voltage Profile Management 5

In this chapter, a control strategy will be applied over voltage sensitivity analysis and reactive power to regulate MV nodes of substations. Necessary reactive power will be calculated and injected into nodes and results will be shared. In the end, two injection strategies will be presented and best option will be selected over active power loss calculation.

Over last chapter, Guneskoy substation was analysed under several cases and optimal PV power injection capacity was revealed out. Main limitation for further injection of PV power was seen as limited power capacity of transformers. From studies, injection of 14.7 MW power for B side and 16 MW power for A side of Guneskoy substation were seen as optimal cases for keeping loading of transformers under 95%. By selected optimal cases, voltage levels of all nodes were remained within desired limits and there is no need for grid support for regulation of voltage. However, Guneskoy substation is only one substation of NCG and by considering other substations, problems related to node voltages will appear. To overcome those problems and allow stable operation of substations, a control strategy over reactive power will be developed by aiming to keep voltage levels in all nodes within operational limits. For analyses, Guneskoy substation will be used with optimal power injection scenario of PVs (2 pu for TRB and 2.5 pu for TRA). For this case, voltage levels were already within defined ranges. That is why, to improve stability and reduce difference of measured voltage from reference voltage (1 pu), it is going to be aimed for keeping all node voltage as shown in figure 5.1. As nodes are getting away from MV bus, nodes become more sensitive to additional power and loads while more power is lost during distribution of power to those nodes. That reason, starting from level 1, initial nodes will be aimed to have voltage level below or equal to 1.01 pu. For second level nodes, aim will be to achieve 1.02 pu while for level 3 nodes, it will be 1.03 pu.

5.1 Voltage Sensitivity Analysis

Voltage sensitivity analysis (VSA) is widely used for power system studies to analyse relation of voltage deviations with respect to changes in active and reactive power. This analysis studies how variations in active and reactive power will affect voltage magnitude and gives a general knowledge of selected points of the grid. VSA is originating from Jacobian matrix (J) which holds all related information of power system studies over 4 variables (P,Q,V & θ). Jacobian matrix is formed by partial derivatives of P and Q over

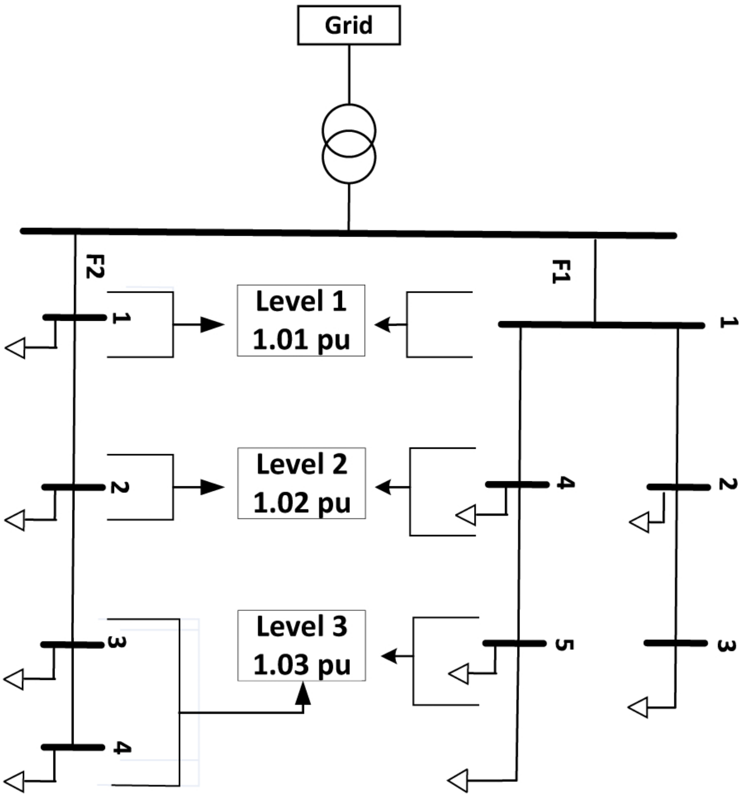

Figure 5.1. Desired voltage levels for nodes

V and θ and given in matrix form as below.

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} \frac{\partial P}{\partial \delta} & \frac{\partial P}{\partial V} \\ \frac{\partial Q}{\partial \delta} & \frac{\partial Q}{\partial V} \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta V \end{bmatrix}$$

To obtain sensitivity analysis, inverse of Jacobian matrix is used as follows,

$$\begin{bmatrix} \Delta \delta \\ \Delta V \end{bmatrix} = \begin{bmatrix} [S_{\delta p}] & [S_{\delta q}] \\ [S_{vp}] & [S_{vq}] \end{bmatrix} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix}$$

By taking into consideration of variables related to voltage, deviation of voltage is concluded as in equation 5.1.

$$\Delta V = S_{vp} \Delta P + S_{vq} \Delta Q \tag{5.1}$$

From equation 5.1, deviation of voltage depends on both active and reactive power with their sensitivity variables related to voltage. Injection of active power is defined as fixed for operation of PV power plants and to regulate voltage magnitude of nodes over high penetration of active PV power, reactive power is selected as changing variable for regulation. S_{vq} is the part of the matrix that holds information to show how the voltage is influenced by deviating reactive power. Over this, matrix related to selected sensitivity is given below;

$$\begin{bmatrix} \Delta V_1 \\ \vdots \\ \Delta V_{12} \end{bmatrix} = \begin{bmatrix} \frac{\partial V_1}{\partial Q_1} & \cdots & \frac{\partial V_1}{\partial Q_{12}} \\ \vdots & \ddots & \vdots \\ \frac{\partial V_{12}}{\partial Q_1} & \cdots & \frac{\partial V_{12}}{\partial Q_{12}} \end{bmatrix} \cdot \begin{bmatrix} \Delta Q_1 \\ \vdots \\ \Delta Q_{12} \end{bmatrix}$$

Transformer A has 7 and transformer B has 12 nodes in total. To analyse voltage sensitivity of nodes over reactive power, only diagonal elements of matrix will be used to analyse variations at the same point of injection. As only diagonal elements are going to be used, they will be illustrated by tables instead of matrix forms.

Feeder	Node	$V_{measured}$ [pu]	$\frac{\delta V}{\delta Q}$ $[\frac{pu}{Mvar}]$
1	1	1.017	0.02023
	2	1.022	0.02565
	3	1.025	0.03830
	4	1.023	0.02717
	5	1.027	0.03470
2	1	1.010	0.02370
3	1	1.017	0.01656
	2	1.035	0.03497
	3	1.038	0.04185
4	1	1.036	0.02257
	2	1.042	0.02492
	3	1.050	0.02987

Table 5.1. V-Q sensitivity analysis of TRB nodes

Table 5.1 and table 5.2 illustrates measured voltage (V_{mea}) and $\frac{\delta V}{\delta Q}$ of all the nodes in Guneskoy substation without any voltage control/reactive power support. These information will be compared with results of cases after injection of reactive power. 3 decimals are used for voltage to obtain closer reference reactive power (Q_{ref}) for regulation of voltage.

Feeder	Node	$V_{measured}$ [pu]	$\frac{\delta V}{\delta Q}$ $[\frac{pu}{Mvar}]$
1	1	1.021	0.01543
2	1	1.022	0.01935
	2	1.047	0.03394
3	1	1.024	0.01931
	2	1.036	0.02489
	3	1.043	0.02984
	4	1.050	0.04149

Table 5.2. V-Q sensitivity analysis of TRA nodes

From table 5.1 and table 5.2, V-Q sensitivity is increasing while the distance between analysed node and MV bus increases. Increasing sensitivity cause higher voltage deviations with small deviations in reactive power. Voltage levels are also increasing with the same manner and had higher voltage deviations at the end node of feeders. Over this, analyses over different levels of nodes (figure 5.1) will give out better understanding of behaviour of nodes in upcoming sections

5.2 Capability Curves of Renewable Generation Units

Renewable generation units (ReGen) have capability curves to define limits of active and reactive power that the plant can supply. This limitation is related to power capacity of plants as well as grid codes of electricity authorities. Currently, limitations for reactive power supply of PV units were not limited by authorities according to size of plants and maximum reactive power supply for each of them seen as 1 pu of total power as shown in figure 5.2 A. For wind turbines, there are valid limitations for operational reactive power defined over size of Wind Turbines (WT). In chapter 4, the injected PV power was assumed at unity power factor for the applied cases, however to assume that generation plants will also supply 1 pu of reactive power is not realistic. That is why, similar power capability curves from Danish grid codes (as KIB-TEK has not valid grid codes) for WTs will be used to define reactive power capability of PV generation units with related power ranges. Size of power plants are changing from 0.4 to 4.7 MW for the cases and grid code selected for wind turbines that have power output range between 1.5 to 25 MW. Capability curve is given in figure 5.2 B for selected grid code. WT within these power ranges have reactive power limit of ±0.228 pu and this limit will be applied to PV generation units.

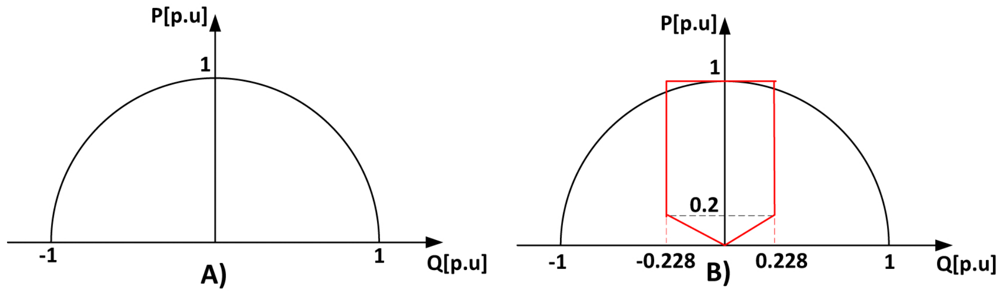

Figure 5.2. Power Curves A)1 pu B)0.228 pu

Active and reactive power limits of each PV power plant is given in table 5.3 and table 5.4 with corresponding feeder and node of both buses. Maximum reactive power (Q_{max}) of PV power plants are given in 4 decimals as the nodes at the end feeder will be so sensitive to deviations of reactive power and small changes in reactive power will result with significant deviations of voltage magnitudes. To also observe those deviations, more decimals are used for maximum reactive power capability of plants.

Feeder	Node	$P_{max}[MW]$	$Q_{max}[Mvar]$
1	1	-	-
	2	1.10	0.2508
	3	0.40	0.0912
	4	0.50	0.1140
	5	1.20	0.2736
2	1	1.40	0.3192
3	1	3.30	0.7524
	2	1.20	0.2736
	3	1.00	0.2280
4	1	1.80	0.4104
	2	0.80	0.1824
	3	3.40	0.7752

Table 5.3. Power capabilities of PV units of TRB nodes

In table 5.3, power of all PV units corresponds 2 pu of total power load on each node. Over this, table 5.3 also gives idea about the distribution of high and low loads on feeders and nodes. For A side of substation, power is distributed separately (F3-1.5 pu, F2-2 pu and rest of power on F1) and it can also give idea only over load difference of nodes for each feeder and can be seen from table 5.4.

Feeder	Node	$P_{max}[MW]$	$Q_{max}[Mvar]$
1	1	4.70	1.0716
2	1	2.90	0.6612
	2	2.40	0.5472
3	1	2.33	0.5301
	2	0.90	0.2052
	3	1.20	0.2736
	4	1.05	0.2394

Table 5.4. Power capabilities of PV units of TRA nodes

5.3 Voltage Control

Renewable generation plants have capability to inject/absorb reactive power within defined limits of each plant. By using this ability, a reactive power based control method will be applied to nodes for regulating voltage level. Main aim of this application to observe benefits of reactive power support and affects on nodes for improving voltage levels for the selected substation. In figure 5.1, goals for voltage levels were set and necessary reactive power will be calculated for achieving given voltage levels. To apply control method, VSA related to reactive power ($\frac{\delta V}{\delta Q}$) will be used with difference (V_{diff}) between measured voltage (V_{meas}) and reference voltage (V_{ref}) of nodes. Over this, an approximation is going to be made for setted voltage level to calculate necessary reactive power support of node. To have an example, method will be applied to TRB-F4-N3. Node is a 3^{rd} level node (figure 5.1) and node voltage must be reached to 1.03 pu at the end of analysis. Necessary variables ($V_{measured}$ & $\frac{\delta V}{\delta Q}$) of the calculation were calculated in section 5.1 and results were given as 1.050 pu and 0.02987 $\frac{pu}{Mvar}$ for the selected node in table 5.1. From results, 0.05 pu (5%) deviation of voltage cause 1.6739 Mvar of reactive power difference on node. To approximate this to desired 1.03 pu level of the node, 0.6696 Mvar reactive power must be absorbed by the power plant to reach the desired voltage level. Node voltages before and after application are given in figure 5.3 and figure 5.4 respectively.

TRB

	F1	F2	F3	F4
N1	1.017	1.010	1.017	1.036
N2	1.022		1.035	1.042
N3	1.025		1.038	1.050
N4	1.023			
N5	1.027			

TRA

	F1	F2	F3
N1	1.021	1.022	1.024
N2		1.047	1.036
N3			1.043
N4			1.05

Node Voltage (pu)	
≤ Desired Limit	
> Desired Limit	

Figure 5.3. Node voltages before absorption

TRB

	F1	F2	F3	F4
N1	1.010	1.002	1.009	1.021
N2	1.014		1.028	1.024
N3	1.018		1.031	1.030
N4	1.016			
N5	1.020			

TRA

	F1	F2	F3
N1	1.019	1.020	1.021
N2		1.044	1.033
N3			1.040
N4			1.049

Node Voltage (pu)	
≤ Desired Limit	
> Desired Limit	

Figure 5.4. Node voltages after absorption

By applying the calculated reactive power to model, improvements are observed in all nodes of substation. From results, significant improvements are observed on feeders that are connected to same MV bus of regulated feeder. Although transformer A feeders were not connected to same bus, improvements were also seen on those feeders. Over this, absorption of reactive power from a single node not only improves voltage level on the same node, also improve all other nodes. This also changes the necessary amount of reactive power to be absorbed from other nodes. That is why, reactive power will be calculated step by step for each node to achieve desired voltage levels. VSA will also be made step by step for each node. From initial results, absorption of reactive power didn't have impact on $\frac{\delta V}{\delta Q}$ of nodes and they remained same for both cases. However, the change will be analysed after total injection of reactive power to nodes to achieve all setted goals. As a result, only effect of reactive power support is seen on node voltages. It is also clear that point of initial support is important for total reactive power absorption from buses. That is why, 2 absorption strategies will be applied to observe changes over strategies. In the end power loss calculations will be made for them to give decision of best absorption method of reactive power. For strategy 1, analysis will start from level 3 nodes to level 1 nodes while it will start from level 1 nodes to level 3 nodes for strategy 2. Steps to be followed for strategy 1 and 2 are given in figure 5.5.

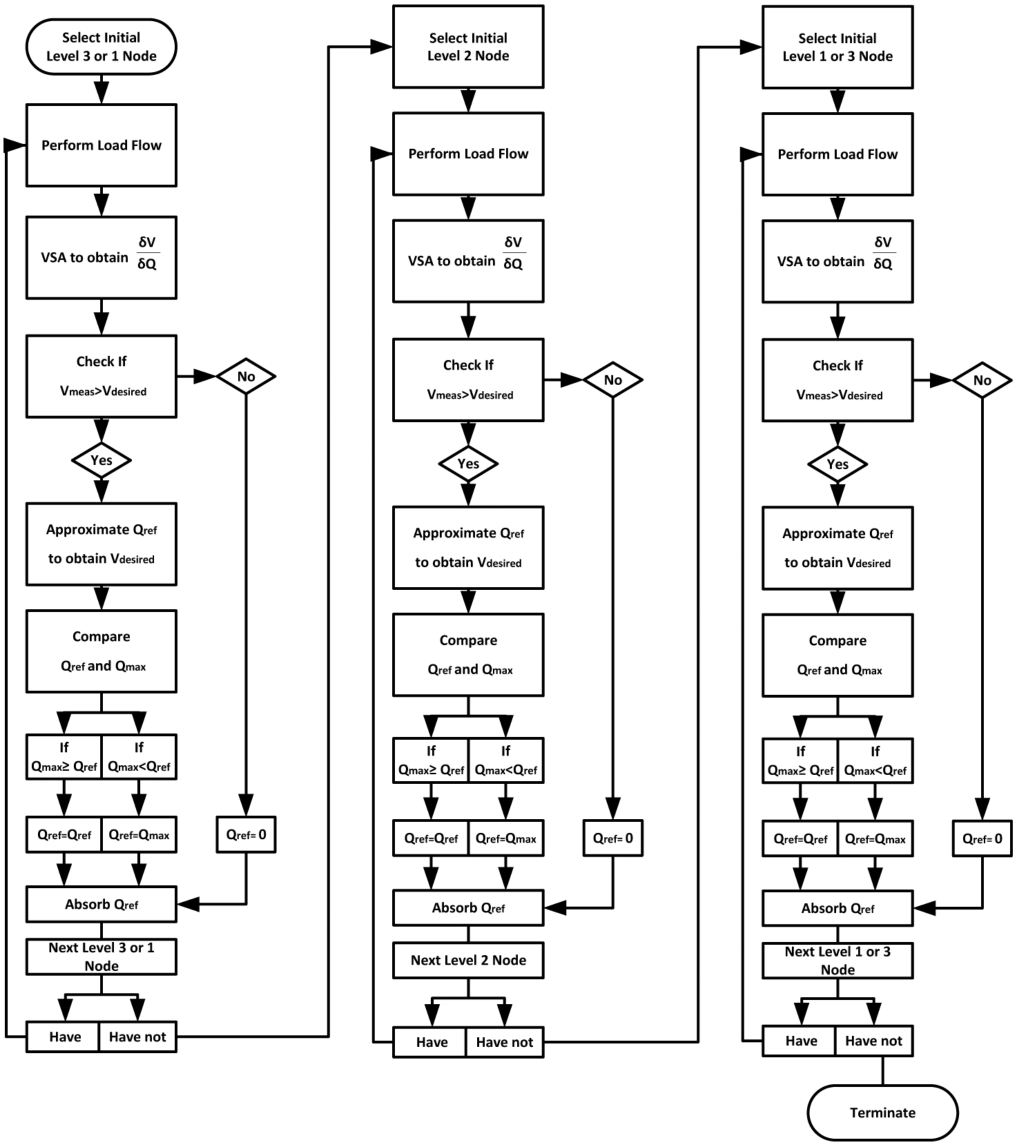

Figure 5.5. Flow chart of strategies

Strategy 1

Initial strategy will be based on level 3 nodes. Starting from level 3 nodes, support for each node will be calculated and injected into nodes to improve voltage levels according to defined goals. TR-F4-N3 will be used as initial node for injection and this will be followed by other feeders. After completion of level 3 nodes, same process will applied to level 2 and level 1 nodes. From table 5.5, initial calculations for reference reactive power (Q_{ref}) can be seen with achieved (V_{ach}) voltage level after injection. For level 3 nodes, it is desired to have 1.03 pu of voltage. To achieve this, relation between measured voltage and $\frac{\delta V}{\delta Q}$ is used to approximate Q_{ref} forV_{diff} between desired and V_{mea}. In section 5.2, maximum reactive power (Q_{max}) of PV units was calculated and they will be compared with calculated Q_{ref} for defining amount of reactive power injection/absorption. If calculated Q_{ref} is less than Q_{max}, calculated value will be used for injection/absorption. Otherwise,Q_{max} will be injected/absorbed into/from node for regulation. On table 5.5, absorbed power is shown with bold. For TRB-F4-N3 and TRB-F3-N3, necessary reactive power is calculated less than Q_{max} of PV unit and 1.03 pu is achieved by absorbing reference reactive power. However, for TRA-F3-N4, Q_{ref} was higher than Q_{max}. So, Q_{max} was applied for the node. As less amount of reactive power is absorbed by PV unit, desired voltage level is not achieved. For the nodes that have voltage magnitude equal or below to desired level, Q_{ref} is defined as 0 Mvar.

TR-Feeder	Node	V_{mea} [pu]	V_{diff} [pu]	$\frac{\delta V}{\delta Q}$ [$\frac{pu}{Mvar}$]	$Q_{ref}[Mvar]$	$Q_{max}[Mvar]$	V_{ach} [pu]
B-4	3	1.050	+0.02	0.02987	**0.6696**	0.7752	1.030
B-3	3	1.031	+0.001	0.04226	**0.0237**	0.2280	1.030
A-3	4	1.049	+0.019	0.04162	0.4565	**0.2394**	1.038
A-3	3	1.033	+0.003	0.03043	**0.0985**	0.2736	1.030

Table 5.5. Level 3 analysis for strategy 1

From results in figure 5.6, absorption of reactive power in level 3 nodes improved voltage levels of nodes compared to figure 5.3. All level 3 nodes got less than or equal to desired limits except TRA-F3-N3 that requests more reactive power absorption than Q_{max} of PV unit. Improvements are also seen on level 2 and level 1 nodes of TRB feeders. This proves that supply of reactive power to a node also affects all other nodes on the same bus.

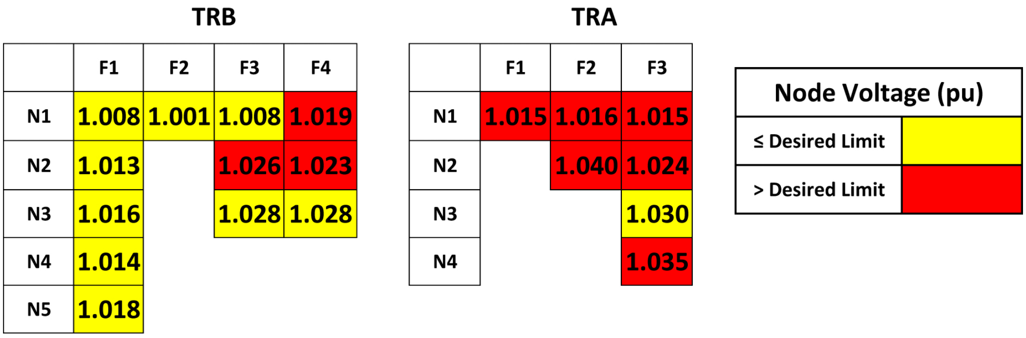

Figure 5.6. Node voltages after level 3 reactive power supply for strategy 1

Table 5.6 shows the variables that used for level 2 calculations. All calculated Q_{ref} of level 2 nodes are lower than Q_{max}. That is why all necessary reactive power is absorbed by nodes and desired 1.2 pu is achieved at all level 2 nodes.

TR-Feeder	Node	V_{mea} [pu]	V_{diff} [pu]	$\frac{\delta V}{\delta Q}$ [$\frac{pu}{Mvar}$]	$Q_{ref}[Mvar]$	$Q_{max}[Mvar]$	V_{ach} [pu]
B-4	2	1.023	+0.003	0.02596	**0.1156**	0.1824	1.020
B-3	2	1.025	+0.005	0.03552	**0.1410**	0.2736	1.020
A-3	2	1.023	+0.003	0.02550	**0.1176**	0.2052	1.020
A-2	2	1.038	+0.018	0.03433	**0.5243**	0.5472	1.020

Table 5.6. Level 2 analysis for strategy 1

From results given in figure 5.7, voltage levels of all nodes were improved and get into desired limits except TRB-F4-N1 which needs more reactive power support to achieve 1.01 pu level.

TRB

	F1	F2	F3	F4
N1	1.003	0.995	1.001	1.012
N2	1.007		1.017	1.016
N3	1.011		1.020	1.021
N4	1.009			
N5	1.013			

TRA

	F1	F2	F3
N1	1.007	1.003	1.005
N2		1.020	1.014
N3			1.020
N4			1.026

Node Voltage (pu)	
≤ Desired Limit	
> Desired Limit	

Figure 5.7. Node voltages after level 2 reactive power supply for strategy 1

To achieve 1.01 pu for TRB-F4-N1, necessary Q_{ref} is calculated over table 5.7 and results were shared in figure 5.8.

TR-Feeder	Node	V_{mea} [pu]	V_{diff} [pu]	$\frac{\delta V}{\delta Q}$ $[\frac{pu}{Mvar}]$	$Q_{ref}[Mvar]$	$Q_{max}[Mvar]$	V_{ach} [pu]
B-4	1	1.012	+0.002	0.02373	**0.0843**	0.4104	1.010

Table 5.7. Level 1 analysis for strategy 1

From results, all nodes are got into desired voltage levels and voltage map of all nodes turned into yellow.

TRB

	F1	F2	F3	F4
N1	1.002	0.994	1.000	1.010
N2	1.006		1.016	1.014
N3	1.010		1.019	1.019
N4	1.008			
N5	1.012			

TRA

	F1	F2	F3
N1	1.007	1.003	1.005
N2		1.019	1.014
N3			1.020
N4			1.026

Node Voltage (pu)	
≤ Desired Limit	
> Desired Limit	

Figure 5.8. Node voltages after level 1 reactive power supply for strategy 1

Table 5.8 and table 5.9 illustrates measured voltage levels and V-Q sensitivity analysis with (WS) and without (WOS) reactive power support . It is clearly seen that all voltage levels are improved by absorbed reactive power and voltage become more sensitive for changing reactive power in all nodes. This proves that absorption of reactive power have effect on both voltage level and $\frac{\delta V}{\delta Q}$ of all nodes. Absorption of reactive power decreases voltage magnitudes while increasing sensitivity of nodes.

Feeder	Node	V_{mea} [pu] (WOS)	V_{mea} [pu] (WS)	$\frac{\delta V}{\delta Q}$ [$\frac{pu}{Mvar}$](WOS)	$\frac{\delta V}{\delta Q}$ [$\frac{pu}{Mvar}$](WS)
1	1	1.017	1.002	0.02023	0.02073
	2	1.022	1.006	0.02565	0.02624
	3	1.025	1.010	0.03830	0.03907
	4	1.023	1.008	0.02717	0.02779
	5	1.027	1.012	0.03470	0.03543
2	1	1.010	0.994	0.02370	0.02428
3	1	1.017	1.000	0.01656	0.01706
	2	1.035	1.016	0.03497	0.03610
	3	1.038	1.019	0.04185	0.04314
4	1	1.036	1.010	0.02257	0.02384
	2	1.042	1.014	0.02492	0.02642
	3	1.050	1.019	0.02987	0.03188

Table 5.8. Sensitivity analysis of Transformer B nodes (ST1)

Feeder	Node	V_{mea} [pu] (WOI)	V_{mea} [pu] (WI)	$\frac{\delta V}{\delta Q}$ [$\frac{pu}{Mvar}$](WOI)	$\frac{\delta V}{\delta Q}$ [$\frac{pu}{Mvar}$](WI)
1	1	1.021	1.007	0.01543	0.01583
2	1	1.022	1.003	0.01935	0.02010
	2	1.047	1.019	0.03394	0.03583
3	1	1.024	1.005	0.01931	0.02000
	2	1.036	1.014	0.02489	0.02592
	3	1.043	1.020	0.02984	0.03115
	4	1.050	1.026	0.04149	0.04348

Table 5.9. Sensitivity analysis of Transformer A nodes (ST1)

Strategy 2

Second strategy will be based on level 1 nodes. Starting from level 1 nodes, injection for each node will be calculated and injected into nodes to improve voltage levels according to defined goals. TR-F4-N1 will be used as initial node for injection and this will be followed by other feeders. After completion of level 1 nodes, same process will applied to level 2 and level 3 nodes. For level 1 nodes, it is desired to achieve 1.01 pu. To achieve this value, initial calculations are shared in table 5.10. For TRB-F3-N1 and TRA-F2-N1, calculated Q_{ref} is less than Q_{max} of PV units. So, calculated reactive power is absorbed from nodes to achieve 1.01 pu level. For TRB-F4-N1 and TRA-F3-N1, calculated Q_{ref} is higher than reactive power limits. This reason, Q_{max} of PV units were applied to nodes. However, desired voltage levels for those level 1 nodes couldn't achieved.

TR-Feeder	Node	V_{mea} [pu]	V_{diff} [pu]	$\frac{\delta V}{\delta Q}$ [$\frac{pu}{Mvar}$]	$Q_{ref}[Mvar]$	$Q_{max}[Mvar]$	V_{ach} [pu]
B-4	1	1.036	+0.026	0.02257	1.152	**0.4104**	1.027
B-3	1	1.012	+0.002	0.01669	**0.1198**	0.7524	1.010
A-3	1	1.022	+0.012	0.01937	0.6195	**0.5301**	1.012
A-2	1	1.015	+0.005	0.01960	**0.2550**	0.6612	1.010

Table 5.10. Level 1 analysis for strategy 2

From figure 5.9, improvements on node voltages can be seen clearly after absorption of reactive power on nodes. By having comparison between figure 5.9 and figure 5.3, all level 1 nodes got into desired levels (except TRB-F4-N1) and also improved voltage levels of level 2 and level 3 nodes.

TRB

	F1	F2	F3	F4
N1	1.008	1.001	1.007	1.023
N2	1.013		1.026	1.028
N3	1.016		1.029	1.037
N4	1.014			
N5	1.019			

TRA

	F1	F2	F3
N1	1.011	1.001	1.009
N2		1.034	1.021
N3			1.028
N4			1.036

Node Voltage (pu)	
≤ Desired Limit	(yellow)
> Desired Limit	(red)

Figure 5.9. Node voltages after level 1 reactive power supply for strategy 2

For level 2 calculations, variables are given in table 5.12. TRB-F4-N2 requests more reactive power support than Q_{max} of PV unit on the same node. That reason, 1.02 pu level couldn't achieved by initial absorption. However, by absorption of reactive power on TRB-F3-N2, voltage levels of feeder 4 also improved and get into desired ranges as shown in figure 5.10.

TR-Feeder	Node	V_{mea} [pu]	V_{diff} [pu]	$\frac{\delta V}{\delta Q}$ $[\frac{pu}{Mvar}]$	$Q_{ref}[Mvar]$	$Q_{max}[Mvar]$	V_{ach} [pu]
B-4	2	1.028	+0.008	0.02557	0.3130	**0.1824**	1.023
B-3	2	1.024	+0.004	0.03552	**0.1126**	0.2736	1.020
A-2	2	1.033	+0.013	0.03463	**0.3754**	0.5472	1.020

Table 5.11. Level 2 analysis for strategy 2

Absorption of reactive power from level 2 nodes, improved all node voltages and turned all map into yellow except for TRA-F3-N4 and TRB-F4-N1. To achieve also desired limits for them, level 3 reactive power support is necessary to implement. Over level 3 nodes,

TRB

	F1	F2	F3	F4
N1	1.003	0.996	1.002	1.016
N2	1.008		1.018	1.020
N3	1.012		1.021	1.029
N4	1.009			
N5	1.014			

TRA

	F1	F2	F3
N1	1.005	1.001	1.003
N2		1.020	1.015
N3			1.023
N4			1.031

Node Voltage (pu)	
≤ Desired Limit	(yellow)
> Desired Limit	(red)

Figure 5.10. Node voltages after level 2 reactive power supply for strategy 2

only the node out of desired limits is TRA-F3-N4 and Q_{ref} is calculated and applied for it to achieve 1.03 pu.

TR-Feeder	Node	$V_{measured}$ [pu]	$V_{difference}$ [pu]	$\frac{\delta V}{\delta Q}$ $[\frac{pu}{Mvar}]$	$Q_{ref}[Mvar]$	$Q_{max}[Mvar]$	V_{ach} [pu]
A-3	4	1.031	+0.001	0.04269	**0.0234**	0.2394	1.030

Table 5.12. Level 3 analysis for strategy 2

From figure 5.11, voltage level in TRA-F3-N4 got into desired limits and goal is achieved. For node TRB-F4-N1 reactive power support is done over node TRB-F4-N3 as Q_{max} of the node was already applied

TRB

	F1	F2	F3	F4
N1	1.001	0.995	1.000	1.010
N2	1.005		1.016	1.015
N3	1.009		1.019	1.022
N4	1.007			
N5	1.011			

TRA

	F1	F2	F3
N1	1.004	1.000	1.002
N2		1.018	1.014
N3			1.021
N4			1.029

Node Voltage (pu)	
≤ Desired Limit	(yellow)
> Desired Limit	(red)

Figure 5.11. Node voltages after level 3 reactive power supply for strategy 2

As mentioned in first strategy section, $\frac{\delta V}{\delta Q}$ is getting bigger and cause node voltages become more sensitive to changes in reactive power. For second strategy, same condition is valid V-Q sensitivities of node higher than no reactive power support condition. By comparing strategy 1 and 2, they have approximately same V-Q sensitivities.

Feeder	Node	$V_{measured}$ [pu] (WOI)	$V_{measured}$ [pu] (WI)	$\frac{\delta V}{\delta Q}$ $[\frac{pu}{Mvar}]$(WOI)	$\frac{\delta V}{\delta Q}$ $[\frac{pu}{Mvar}]$(WI)
1	1	1.017	1.001	0.02023	0.02075
	2	1.022	1.005	0.02565	0.02627
	3	1.025	1.009	0.03830	0.03911
	4	1.023	1.007	0.02717	0.02781
	5	1.027	1.011	0.03470	0.03546
2	1	1.010	0.995	0.02370	0.02430
3	1	1.017	1.000	0.01656	0.01710
	2	1.035	1.016	0.03497	0.03605
	3	1.038	1.019	0.04185	0.04307
4	1	1.036	1.010	0.02257	0.02380
	2	1.042	1.015	0.02492	0.02630
	3	1.050	1.022	0.02987	0.03150

Table 5.13. Sensitivity analysis of Transformer B nodes (ST2)

Feeder	Node	$V_{measured}$ [pu] (WOI)	$V_{measured}$ [pu] (WI)	$\frac{\delta V}{\delta Q}$ [$\frac{pu}{Mvar}$](WOI)	$\frac{\delta V}{\delta Q}$ [$\frac{pu}{Mvar}$](WI)
1	1	1.021	1.004	0.01543	0.01590
2	1	1.022	1.000	0.01935	0.02023
	2	1.047	1.018	0.03394	0.03576
3	1	1.024	1.002	0.01931	0.02015
	2	1.036	1.014	0.02489	0.02584
	3	1.043	1.021	0.02984	0.03090
	4	1.050	1.029	0.04149	0.04284

Table 5.14. Sensitivity analysis of Transformer A nodes (ST2)

5.4 Conclusion

Over all chapter, analysis were carried out to analyse effects of reactive power injection/absorption to nodes. It is observed that nodes are becoming more sensitive as moving away from MV bus. That is why, voltage levels are higher compared to nodes close to MV bus. From results, with correct amount of reactive power support to nodes, desired voltage levels can be achieved depending on Q_{max} ability of PV units. If Q_{max} is lower than needed reactive power support, this support will also be obtained from other nodes of feeders to improve voltage level. To compare analysed strategies, table 5.15, 5.16 and 5.17 will be used for carrying analyses over active power losses on feeders of buses.

Feeder	P_{loss} [MW](WO)	Q_{ref} [Mvar](ST1)	P_{loss} [MW]	Q_{ref} [Mvar](ST2)	P_{loss} [MW]
1	0.045	0	0.047	0	0.047
2	0.011	0	0.012	0	0.012
3	0.077	0.1647	0.081	0.2324	0.082
4	0.193	0.8695	0.221	0.8124	0.219
Total	0.326	1.0342	0.361	1.0448	0.360

Table 5.15. P_{loss} and Q_{ref} of TRB feeders over strategies

From table 5.15 and table 5.16, power losses are analysed over without reactive power support (WO), strategy 1 (ST1) and strategy 2 (ST2) cases with absorbed reactive power amounts of feeders in total. Power losses are increased by injected reactive power as more power requested to transfer over lines. For ST1 and ST2 cases, active power losses is approximately same. However for transformer A, ST2 has higher losses than ST1 case. For TRA and TRB, more reactive power is absorbed with ST2.

Feeder	P_{loss} [MW](WO)	Q_{ref} [Mvar](ST1)	P_{loss} [MW]	Q_{ref} [Mvar](ST2)	P_{loss} [MW]
1	0.085	0	0.088	0	0.088
2	0.103	0.5243	0.115	0.6304	0.118
3	0.111	0.4555	0.122	0.5546	0.125
Total	0.299	0.9798	0.325	1.1850	0.331

Table 5.16. P_{loss} and Q_{ref} of TRA feeders over strategies

Total losses and absorbed reactive power of transformers for each case is given in table

5.17. From total, system has higher active power losses with ST2 as more reactive power absorption was requested by grid.

TR	P_{loss} [MW](WO)	Q_{ref} [Mvar](ST1)	P_{loss} [MW]	Q_{ref} [Mvar](ST2)	P_{loss} [MW]
B	0.326	1.0342	0.361	1.0448	0.360
A	0.299	0.9798	0.325	1.1850	0.331
Total	0.625	2.014	0.686	2.230	0.691

Table 5.17. Total P_{loss} and Q_{ref} of transformers' feeders over strategies

To calculate percentage active power losses for each case following equation will be used.

$$\Delta P_{loss} = \frac{|\Delta P_{lossWO} - \Delta P_{lossST}|}{\Delta P_{lossWO}} \cdot 100 \tag{5.2}$$

By using equation 5.2, percentage of power losses are calculated and summarised in figure 5.12. By analysing given results on figure 5.12, higher losses for TRB is seen with strategy 1 while TRA had higher losses with strategy 2. Reactive power support is not requested by feeder 1 and 2 of TRB and feeder 1 of TRA as node voltages were within desired limits. Total percentage loss for ST1 and ST2 are calculated over equation 5.2 as 9.76 % and 10.56% respectively. From results, to start injection from level 1 nodes cause higher losses to system than starting from level 3 nodes. The loss difference is not so big. However, flowing of more reactive power cause node voltages become more sensitive to changes in reactive power. Over this, strategy 1 is observed as better solution for supporting reactive power to nodes.

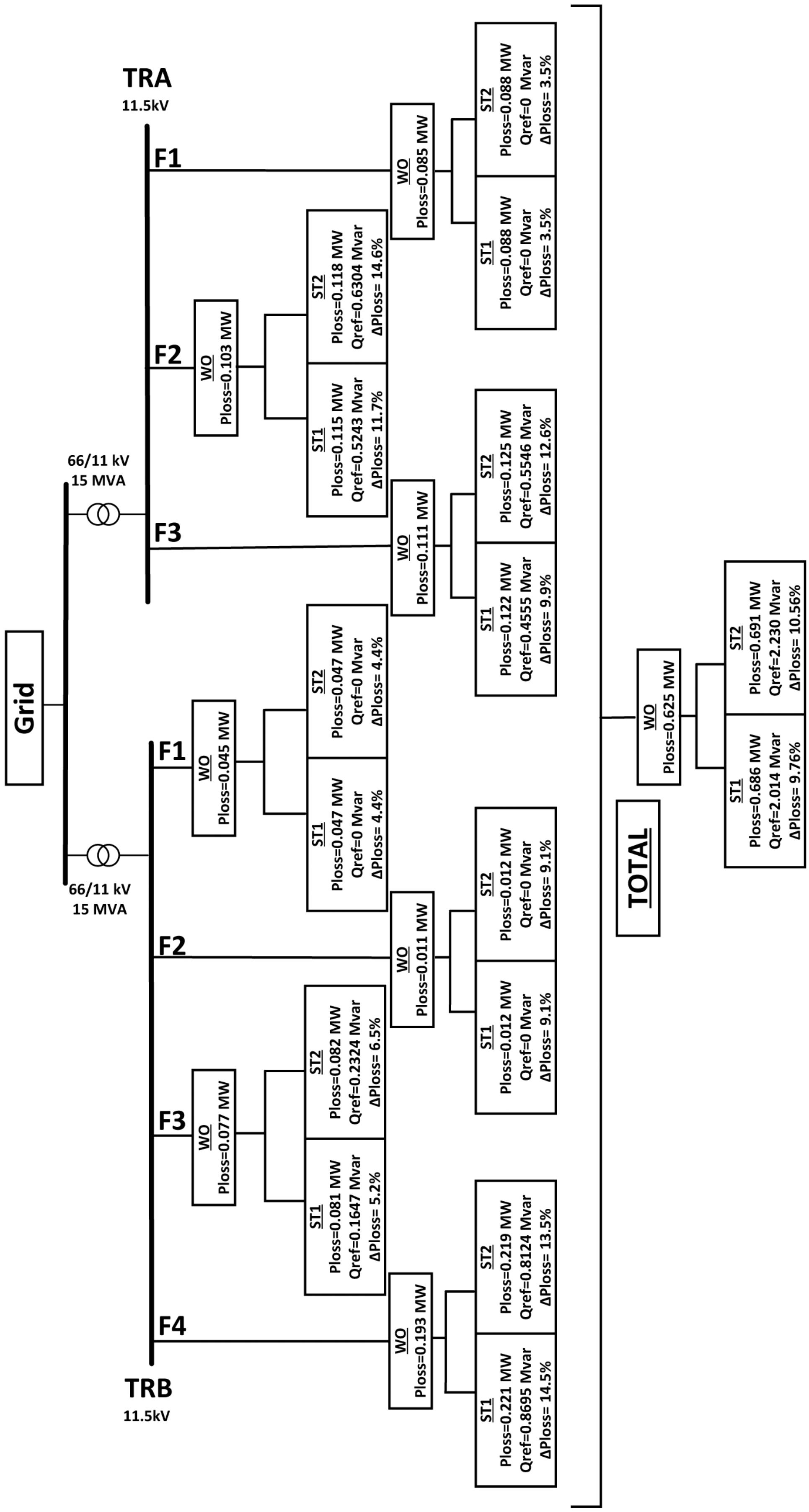

Figure 5.12. Summary over strategies

Conclusion & Discussion 6

Studies are about to start for integration of large-capacity renewable energy sources into NCG. As an initial step, it is planned to integrate a total of 30 MW of PV solar power into MV grid of North Cyprus. Biggest share of this integration is planned to be had in west part of grid to create a local generation. The rest of total power will be distributed into whole grid. Amount of initial integration is known as 30 MW. However, PV hosting capacity of substations are not known for injection. In order to estimate PV hosting capacity of distribution substations and initiate studies for further PV power integration, a method was developed over loading conditions (lines & transformers) and voltage levels of nodes. As an initial step, a substation was selected from west part of grid and analysis were carried over three cases to investigate optimum power injection for selected substation. Over studies, main limitation of injection was seen as power capacity of transformers. For cases, power was increased in levels until both transformers got overloaded. From results, 2 pu for TRB and 2.5 pu for TRA were seem as optimum points for operation of transformers with 80% maximum loading. Over this, overloaded lines under optimum conditions of transformers were examined. For TRB side, lines were operating within desired conditions and no overload was seen. However, for TRA side, TRA-0A-1-F2 and TRA-0A-1-F3 lines were overloaded under minimum loading condition of the grid. From observations, optimum operation conditions were analysed and founded as 1.5 pu for TRA-0A-1-F3 and 2 pu for TRA-0A-1-F2 lines. This optimum conditions of lines were applied to model while integrating difference power of 2.5 pu case into feeder 1 which was only loaded by 2%. After application, lines worked within desired loadings. Over-voltage problems on red marked nodes were also cleared by this application and nodes got into orange area which is acceptable for operation. Over all, optimum PV power injection capacity was finalised as 2 pu (14.7 MW) for B side and 2.5 pu (16 MW) for A side of Guneskoy substation with 1.5 pu injection to feeder 3 and 2 pu injection to feeder 2 of TRA. In total, Guneskoy substation has 30.7 MW of PV hosting capacity to operate within optimal conditions of transformers and lines while keeping voltage levels within 1±0.05 pu as desired.

Guneskoy substation is only one substation of NCG and possible problems related to voltage deviations will arise in other substation nodes. To overcome possible problems and create a method to regulate voltage level, an analysis was carried out by injection of reactive power. For operation, injection of active power was fixed and the only variable that can regulate voltage deviations was reactive power. To regulate node voltages, amount of necessary reactive power was calculated by help of VSA. From analysis, it is observed that injection of reactive power into one node also affects voltage levels of all other nodes. By considering this, analysis were carried out step by step for calculating each node Q_{ref} and injecting into node to regulate voltage level within defined limits. From results, Q_{max} of

PV units were seen as an important consideration to get node voltage into desired limits. When calculated Q_{ref} was higher than Q_{max} of PV units, desired voltage level couldn't achieved by support to that node. However, by having support to other nodes, voltage levels of those can be regulated by extra reactive power supplied from other nodes.

By considering effect of one node to other, two different strategies were applied for absorption of reactive power to obtain best method by having lower active power losses. Over studies, absorption of reactive power starting from bottom nodes and moving to upper nodes step by step was seen as best strategy for having reactive power support as less active power losses seen by lower absorption of reactive power.

Developed methodology for defining PV hosting capacity of substations are summarised in figure 6.1 step by step. By following given steps, PV hosting capacity of other substations can be defined. Voltage control step is marked with a star (*) and sub-cases can be seen by figure 5.5. In figure 5.5, steps were applied over 3 levels as three different voltage levels were desired to be achieved. However, to obtain voltage levels only below 1.05 pu, $V_{desired}$ will be equalise to 1.05 pu and one level application will be applied to regulate voltage.

To sum up, by injecting 2 pu for B and 2.5 for A side of substation, system was operated in optimum conditions after integration of PV power. And also adjusting power distribution on feeders, line loading were kept below desired limits. To regulate voltage levels and take them into desired ones, an analysis was carried out over reactive power support. From results, it was a valid solution for nodes to regulate voltage by having reactive power support from PV units. By also defining the initial point of absorption from level 3 nodes, losses related to reactive power absorption can be reduced.

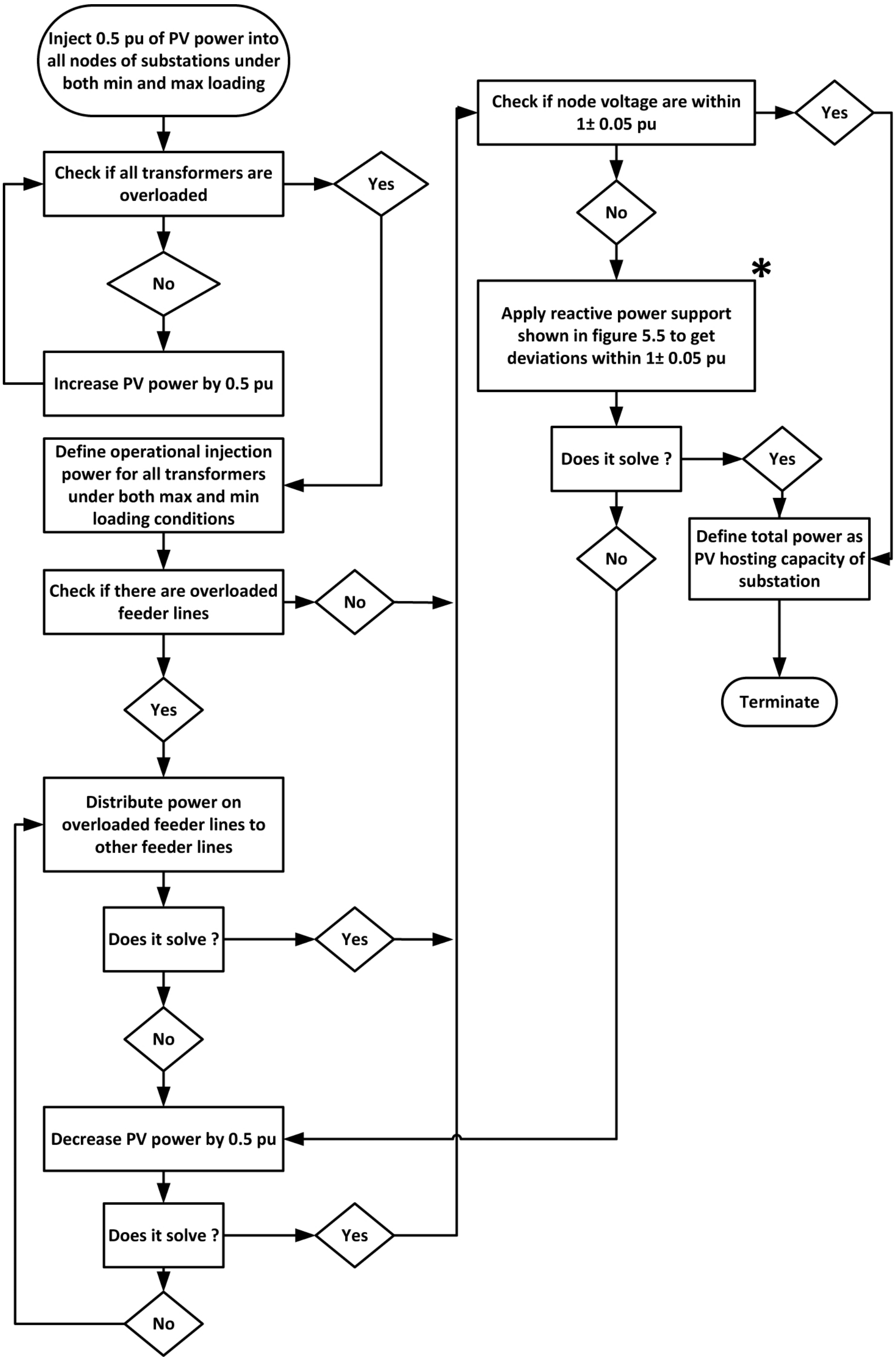

Figure 6.1. Summary of method

7 Future Works

In this report, a methodology was developed to define PV hosting capacity of substations in NCG. Static analysis were carried out and results indicated that method is working and PV hosting capacity can be measured. However, the analysis were carried over only static condition of selected substation and further studies are necessary to obtain results for showing defined values are correct. Further analysis can be listed as follows;

Expansion of Study: The study is applied over only one substation of NCG. To obtain PV hosting capacities of all other substations, studies must be expanded and proposed methodology must be applied to all other substations.

Time Varying Analysis: Load profiles of selected substation couldn't supplied by KIB-TEK. However, a time varying analysis over real data is necessary to observe behaviour of grid for 24 hour over injected PV power. Different scenarios must be also applied to analyse grid under different conditions (Max load and min load). By this way, operational condition of substations can be analysed and problems that will appear over time can be seen. Through this, correctness of defined hosting capacities can be observed.

Control Mechanism: For the project, Q_{ref} of nodes were calculated for a single moment of grid. However, for time varying analysis, a control mechanism must be used to regulate voltage over reactive power for given responses of the grid. Droop control is widely used method for those analysis and can be an option. Over this, droops related to each PV unit must be calculated to define correct support of reactive power and applied for time varying analysis. Through this, efficiency of control mechanism can be examined.

The listed items are seen as future works of the study done in this report.

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Modelling Parameters A

A.1 Transmission line parameters

Conductor Size	R $[\frac{\Omega}{km}]$	X_L $[\frac{\Omega}{km}]$	C$[\frac{nF}{km}]$
266.8 MCM	0.2250	0.4005	9.10
3/0AWG	0.3466	0.4103	8.88
477 MCM (132 kV)	0.1220	0.3942	9.26
477 MCM (66 kV)	0.1220	0.3766	9.71
954 MCM (132 kV)	0.0614	0.3733	9.81

Table A.1. Parameters of OHLs

A.2 Substation Transformers

Transformer Ratings	R_m [Ω]	X_m [Ω]	R_{eq} [Ω]	X_{eq} [Ω]
25 MVA- 132/11.51 kV	7360.0	1346.8	3.7547	83.551
25 MVA- 132/23 kV	29389	12826	3.7547	83.551
25 MVA- 66/23 kV	35830	5348.6	0.8364	20.892
20 MVA- 66/11.5 kV	8944.9	8868.0	1.1543	26.117
15 MVA- 66/11.5 kV	8960.0	16482	1.6262	29.384
12.5 MVA- 66/11.5 kV	14312	14189	2.1466	41.413
6.25 MVA- 66/11.51 kV	15383	9038.6	3.4569	49.345
5 MVA- 66/11.51 kV	15383	12586	4.3212	61.681

Table A.2. Substation Transformers equivalent circuit parameters

A.3 Generator Transformers

A.3.1 Two-Winding

Transformer Ratings	R_m [Ω]	X_m [Ω]	R_{eq} [Ω]	X_{eq} [Ω]
100 MVA - 15/132 kV	5281.7	732.76	0.4844	27.8393
71 MVA - 11/66 kV	3666.7	2617.3	0.2048	7.3592
62.5 MVA - 15/66 kV	7500.0	2075.1	0.2453	8.2032

Table A.3. Generator transformers equivalent circuit parameters

A.3.2 Three-Winding

R_1 [Ω]	X_1 [Ω]	R_2 [Ω]	X_2 [Ω]	R_3 [Ω]	X_3 [Ω]	R_m [Ω]	X_m [Ω]
0.12446	0.00158	0.00482	0.00510	0.00482	0.00533	62229	62229

Table A.4. 3-Winding generator transformers equivalent circuit parameters

A.4 Auto transformer

Transformer Rating	R_m [Ω]	X_m [Ω]	R_{eq} [Ω]	X_{eq} [Ω]
62.5 MVA - 132/66 kV	62000	62000	1.0170	33.437

Table A.5. Auto transformer equivalent circuit parameters

Transformer Tests B

B.1 Two-winding transformers

Open Circuit Test is performed to obtain shunt branch resistance and reactance of transformer. This test is also known as no-load test of transformer used to obtain no-load losses (core losses). The test is conducted with LV side and the circuit model for open-circuit test is given in figure B.1. For the test, HV side is kept open-circuit and LV side is

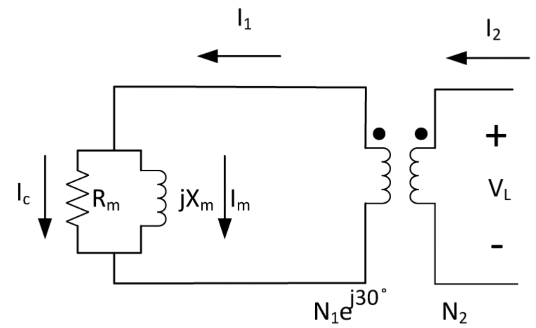

Figure B.1. Open circuit test model

energized at nominal voltage. With this test model, current only flows through magnetizing branch resistance and reactance. Three measuring devices (Ammeter, Voltmeter and Wattmeter) are used to measure open-circuit current I_{oc}, voltage V_{oc} and power loss P_{oc} on circuit. To calculate each branch element parameter, equation B.1, B.2 and B.3 are used.

$$R_m = \frac{V_{oc}^2}{P_{oc}} \tag{B.1}$$

$$|Z_m| = \frac{V_{oc}}{I_{oc}} \tag{B.2}$$

$$X_m = \frac{1}{\sqrt{(1/|Z_m|)^2 - (1/R_m)^2}} \tag{B.3}$$

Short circuit test is performed to obtain series resistance and ractance of equivalent circuit of transformer with copper losses. The test is conducted with HV side and the circuit model for short-circuit test is given in figure B.2. For the test, LV side is short-circuited

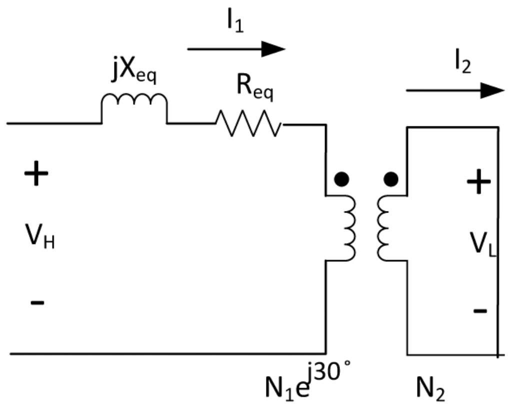

Figure B.2. Short circuit test model

and full-load current is applied to HV side of transformer. Due to behavioural flow of current, all current will flow through equivalent series impedances which is smaller than shunt branch impedances of transformer. By measurement devices, short circuit current I_{sc} , voltage V_{sc} and power losses P_{sc} are obtained. These parameters are applied to equations B.4, B.5 and B.6 to obtain equivalent series resistance and reactance of transformers.

$$|Z_{eq}| = \frac{V_{sc}}{I_{sc}} \tag{B.4}$$

$$R_{eq} = \frac{P_{sc}}{I_{sc}^2} \tag{B.5}$$

$$X_eq = \sqrt{|Z_{eq}|^2 - R_{eq}^2} \tag{B.6}$$

B.2 Three-winding transformers

Open Circuit Test of 3 winding transformer is same with 2 winding transformers and it is applied by energizing LV side at nominal voltage while keeping HV side open circuit. With the same manner of two-winding transformers, shunt branch resistance and reactance will be obtained.

For **Short circuit test**, application of test is not same as model has 3 windings. To obtain short circuit test values, 3 test must be applied to obtain Z_{12} , Z_{23} and Z_{13} parameters of transformers. Initially, short circuit voltage is applied to primary winding with short circuited secondary winding while tertiary winding is open circuit to find Z_{12}. Then, voltage is applied to primary winding again with short circuited tertiary winding while secondary winding is open circuit to find Z_{13}. In the end, voltage is applied to secondary winding with shorted tertiary winding while primary winding is short circuited to find Z_{23}. By using obtained parameters, impedances for each winding are calculated by equations B.7, B.8 and B.9.

$$Z_1 = \frac{Z_{12} + Z_{13} - Z_{23}}{2} \tag{B.7}$$

$$Z_2 = \frac{Z_{23} + Z_{12} - Z_{13}}{2} \tag{B.8}$$

$$Z_3 = \frac{Z_{13} + Z_{23} - Z_{12}}{2} \tag{B.9}$$