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Photovoltaic (PV) Systems Output Power and Their Impact on The Distribution Network

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ABSTRACT
This project investigates the effect of large penetration of distributed photovoltaic generation systems on the quality of power especially the quality of voltage in the power distribution system. The main characteristics of PV generation are first illustrated with a general description of the main components of a practical PV system.
A model of a certain distribution network was built and validated based on a datasheet that was provided from the supervisor which matches the real UK data network.
Distributed small scale PV generators were integrated into the distribution model to study the effect on the system voltage by simulation. The effect of rapid changes in irradiance under different conditions on the distribution network was also investigated.
Finally the simulation results were used to find out ways to overcome the possible disadvantages of integrating PV generators into the distribution network.

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I. INTRODUCTION

Government around the world are now funding more and more projects to develop new more efficient ways to exploit renewable energy resources such as wind and solar energy.

The main objective of this project is to investigate the effect of using small scale distributed photovoltaic PV generators on the quality of power specially the quality of voltage in the power system. To achieve this objective the project was divided into two main chapters.

Chapter 1 investigates the characteristics of PV systems and introduces their various components and gives a general description of their advantages and disadvantages. While chapter 2 describes the steps followed to model and simulate the distribution network.

Modeling and simulation was divided into six parts. Part 1 investigates the necessity of using transformers with load tap changing capabilities in the distribution network. Part 2 investigates the effect of changing the load demand on the voltage level at each bus bar of the modelled distribution network. Part 3 models and validates the 11KV feeder and part 4 models and simulates the entire distribution network described in table 1. Part 5 integrates embedded PV generators into the complete distribution network model and part 6 investigates the effect of rapid changes in the PV generators output on the power network.

1- Photovoltaic systems overview

This part of the report investigates the characteristics of PV systems and introduces their various components and gives a general description of their advantages and disadvantages.

1.1 Introduction to PV systems

Solar energy or photovoltaic is not new; it has been used for more than 35 years to power communication satellites in outer space. People were not that much interested in using solar power to generate electricity except for rural areas located hundreds of kilometers from the nearest utility electric grid line.

Motivated by the large increase in greenhouse gases emissions and rising oil prices, governments around the world are now considering the use of distributed or embedded generation systems such as dispersed photovoltaic generators and wind turbines. These small scale renewable energy systems offer the advantage of producing electrical power near the place where it is consumed. This reduces the I^2R losses in transmission and distribution circuits and increases the overall system efficiency, and reduces the amount of power drawn from the utility power grid.

Photovoltaic “PV” systems are considered to be environmentally friendly energy source because they do not have any carbon dioxide emissions and they do not generate radioactive wastes. Another advantage of PV systems is that they do not incorporate any moving parts like the case with wind turbines; this makes PV systems durable and reliable.

There are two types of PV power systems; grid connected PV systems in which the PV generator is interconnected to the utility power grid, and stand alone PV systems (Weatherization Works 2009).

Grid connected PV systems allow the customer to cover some of his demand while still connected to the utility power grid. Any extra power needed above that generated by the PV system can be drawn from the utility power line.

The primary objective of using grid connected PV generation is to reduce the amount of electrical power drawn from the utility grid.

Grid connected PV generators do not require backup batteries because utility outages do not commonly happen, these systems are equipped with a protection device to disconnect the PV system in case of an outage to protect utility maintenance personnel. For the component and installation sequence See (***Figure**: Components of a typical PV system)* in page 13 but with removing the charge controller and backup battery bank. (Weatherization Works 2009)

PV systems that are not connected to the utility power grid are called stand alone PV systems. Normally these systems are larger than conventional grid connected systems because they are required to supply the entire demand of the customer, not just a portion of it as the case with grid connected PV systems.

Stand alone PV systems are commonly used to power small loads up to several hundred watts in remote rural areas where connection to the utility power grid is not possible or economical.

A backup battery with a charge controller must be used with these systems to cover the customer’s demand when there is not enough sunlight available during the night and during cloudy days.

Stand alone PV systems are commonly incorporated with other auxiliary energy sources such as small fossil fuel generators or wind turbines to increase the overall reliability. Despite the fact that they are expensive, PV systems are the best choice for generating electricity in remote rural areas. (Enolar 2003)

1.2 Photovoltaic systems components

Typical PV system components include, PV array, combiner box, DC/AC inverter, batteries, and a balance of system hardware that includes disconnect switches, mounting racks, and protection and control circuits used for integrating the photovoltaic system into the customer’s electrical network. The components listed below are explained by (Enolar 2003).

- **PV array**

A PV array is made up of several PV modules that are composed of a collection of PV cells – the basic unit of the PV system – the PV array is responsible for converting sunlight into DC electrical power. Typically each solar cell produces between 0.5 to 2 watts. They can be connected in parallel to increase the output current or in series to increase the output voltage. The size of the PV array depends on the requirements of the system they are designed to power.

- **Combiner box**

Output wires from PV models are connected together in series on in parallel to provide the voltage level necessary to operate the DC/AC inverter. The combiner box provides the connection terminals and fusing of each PV module.

- **Disconnect switches**

A DC disconnect switch is located at the PV array output to allow for disconnecting the PV array, while an AC disconnect switch is provided at the DC/AC inverter output to allow for disconnecting the PV system from the utility power grid.

- **Mounting racks**

Steel or aluminum mounting structures are used to support the PV modules. Mounting racks could be either fixed or pole mount to give the PV system the ability to track the sun.

- **Inverter**

As we saw earlier, PV arrays produce DC voltages and currents when sunlight photons hit the solar cells. DC to AC inverters are power electronic devices that are used to convert the DC electrical power generated by the PV array into the standard 50Hz power outlet voltage to power various house held appliances.

- **Protection equipment**

Various types of protection equipments are used with PV systems such as, surge arrestors that are used to protect the PV system from high lightning and switching voltage surges, earth fault protection, and over current protection.

- **Backup storage batteries**

A backup battery bank should be incorporated with stand alone PV system to supply the load when the amount of irradiance is not enough. Batteries are the most vulnerable component of the PV system, they have the highest contribution in the life time or maintenance costs of the PV system.

- **Charge controller**

The charge controller is located between the PV array and the backup battery bank. It is used to protect the battery from being deep discharged or overcharged, and prevents overheating the battery during the charging process to extend its life time and to reduce the maintenance costs of the PV system.

Figure 1 illustrates the various components of a typical stand alone photovoltaic system and shows how they interact with each other to produce the standard 50Hz voltage from the sunlight.

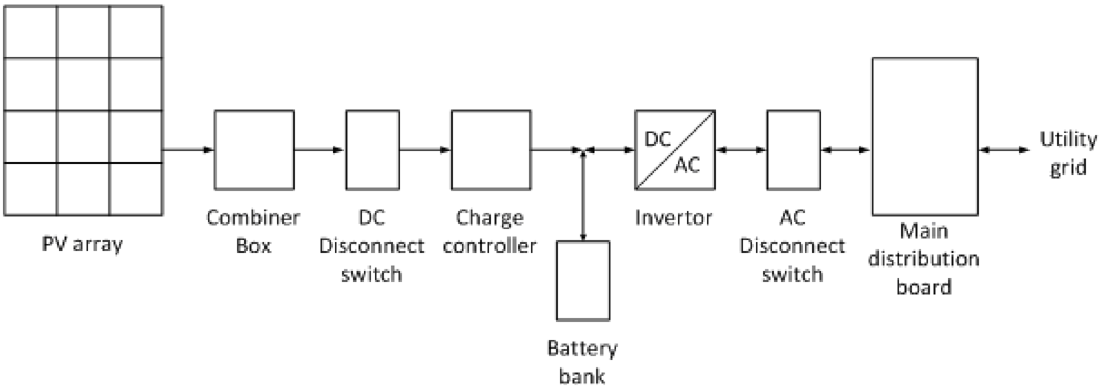


***Figure**: Components of a typical PV system*

1.3 Advantages and disadvantages of photovoltaic energy

As we have already seen, the only type of fuel used with PV systems is the sunlight; this is why they are considered to be environmentally friendly. PV systems were originally developed to power communication satellites in the outer space because they are reliable and durable without much maintenance required because they do not have any moving parts.

Small scale PV systems do not require much space and can be mounted on any unused spaces on the rooftops of the buildings. Another important advantage of PV energy is that they can be easily enlarged to account for any increase in the customer’s energy demand by adding more PV modules.

Having a look at all of these advantages, one might think that PV energy is the perfect solution, this is not completely true. PV systems do have some disadvantages.

The initial cost of building a PV system is considerably higher than any other conventional source of energy due to their high manufacturing costs. However, governments are spending more money on researches to increase the conversion efficiency of the PV system and to give it the ability to compete with other sources of energy.

Another important disadvantage is that PV systems require sunlight to generate electricity; therefore we cannot use them when the sun is not shining during the night or during cloudy days. This means that if you really want to stop drawing power from the utility grid, you need to have a large backup battery bank to cover your demand when it is dark.

This project will explore the effect of integrating small scale PV systems into the utility power grid by simulation, and will investigate some possible measures to mitigate the negative effects.

2- Power Distribution network modeling and simulation

The main objective of all power systems is to provide a continuous high quality supply to the customer. To achieve this objective all power systems are composed of the following main components

- Power generators.
- Power and distribution transformers.
- Transmission lines.
- Protection and voltage regulation circuits.

Large sized coal or nuclear power plants are used to generate electricity at a relatively low voltage level of approximately 25KV to reduce the level of insulation required for equipment used in the power plant. Large power transformers are used to step up the voltage level to reduce the I^2R loses in transmission lines and to increase the load handling capability of the power system. Transformers in various distribution substations are then used to step down the voltage to a level suitable for use by the customer, typically 0.4KV for residential and commercial customers, and 11KV for industrial customers.

Various control and protection circuits are used to protect generators, feeder lines, and transformers from any possible fault condition in the power system such as earth fault protection, overload and over current protection. On load tap changers (OLTC) are used with transformers rated at 11KV and above to keep the voltage level at the secondary winding of the transformer within a prescribed limit regardless of variations in the loading level.

As shown in table 1, the modeled distribution network consists of a balanced three phase 33KV 50Hz source, whose three phase fault level is 500MVA that is connected to two parallel 33/11.5KV 15MVA power transformers that are equipped with on load tap changing mechanism on their primary windings.

The 11KV substation supplies six 11KV feeders, each 11KV feeder cable comprise 1.5 Km of 185 mm^2 3 core cable and 1.5Km of 95 mm^2 3 core cable. Eight 11/0.433KV 500KVA distribution transformers are equally distributed along each 3Km 11KV feeder cable.

Each 0.4KV substation supplies four 400V 0.3Km feeders with a total of 96 residential customers evenly distributed along each 0.4KV feeder. Figure 1 shows a detailed single line diagram of the modeled distribution network.

At first we are going to model the 0.4KV detailed feeder and then the 11Kv feeder. Both models will be used to build the complete distribution network model. All models will be simulated and verified by making sure that the voltage level at each bus bar does not exceed the -6/+10% standard limits.

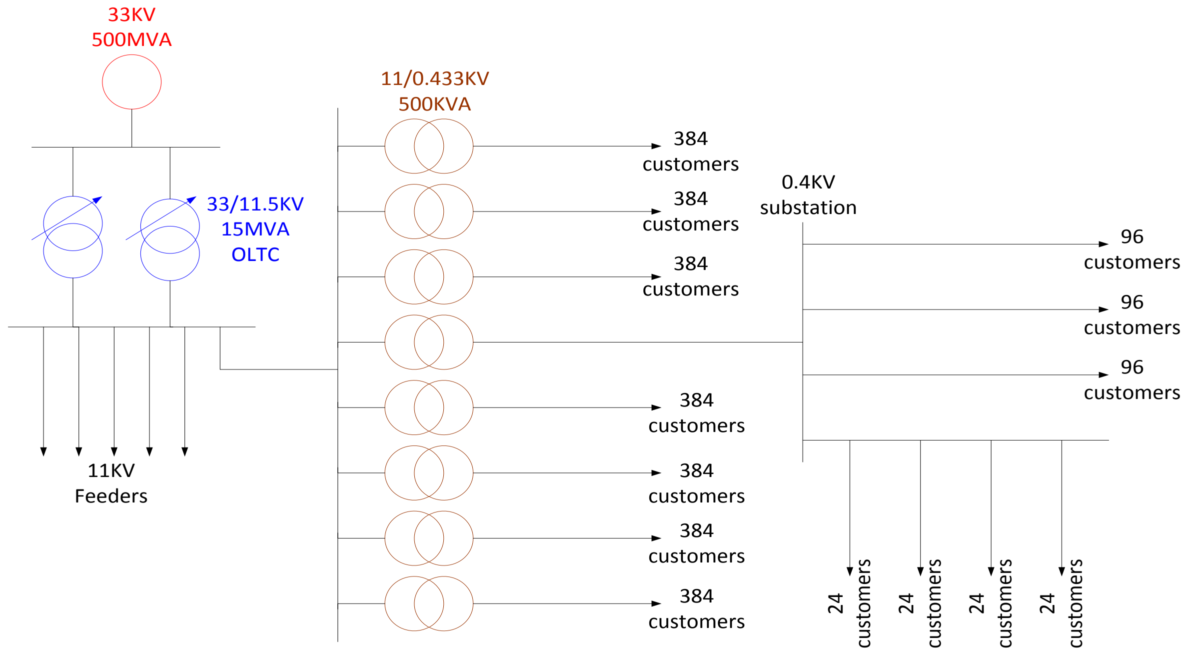


***Figure 1**: Modeled distribution network single line diagram*

***Table 1:** Modeled distribution network data. (provided by the supervisor)*

Component	**Description**	**Comments**
33kV Source	• 33kV source with 500MVA symmetrical break fault level	
33/11.5kV Transformer	• 7.5/15MVA • 18% impedance on 30MVA base • YY0 windings • X/R ratio 15	11kV 3 phase fault level of 125MVA Neutral earthing resistor

	• Tow transformers in parallel, one NER in service • -20/+10% tap changer with 1.67% tap steps • AVC scheme with 2.5% bandwidth • Voltage setpoint between 11.0kV and 11.1kV • Off load ratio 33/11.5kV	gives a single phase fault level of 1200A
11kV Feeder Circuits	• Six 400A circuit breakers, three per bus section • Five feeders modelled with lumped 11kV 3 phase load of 2MVA. Power factor will be the same as the sixth detailed feeder	Each feeder loaded at 2MVA
11kV detailed Feeder Circuit	• Sixth feeder circuit comprising 8 x 500kVA substations. • Feeder cable comprises 1.5km of 185mm^2 3 core PICAS plus 1.5km of 95mm^2 3 core PICAS • 500kVA substations distributed equally along 3km feeder	185mm^2 Cable parameters: - 0.164+j0.080Ω/km 95mm^2 Cable parameters:- 0.32+j0.087Ω/km
11/0.433kV Substation	• Comprises one 500kVA transformer • Four outgoing 400V 3 phase feeders • ADMD of each feeder is 125kVA • No load volts < = 253V • Full load volts >= 220V • Load factor = 0.5 (MD on sub is 250kVA) • 384 customers supplied • ADMD = 1.3kVA per customer	Three feeders modelled as lumped loads and generators
11/0.433kV Transformer	• 500kVA • 5% impedance • Dy11 windings • X/R ratio of 15	
400V Detailed Feeder	• Feeder comprise two segments of cable 150m of 185mm^2 CNE and 150m of 95mm^2 CNE cable • 96 customers distributed evenly along feeder • customers distributed evenly across three phases • service joints distributed evenly along feeder cable segments • up to four customers per service joint	185mm^2 Cable parameters: 0.164+j0.074Ω/km (phase) 0.164+j0.014Ω/km (neutral) 95mm^2 Cable parameters: 0.32+j0.075Ω/km (phase) 0.32+j0.016Ω/km (neutral)
Individual customers	• ADMD of 1.3kVA, 1.0pf • Minimum demand of 0.16kVA, 1.0pf • SSEG of 1.1kVA, 0.95pf • 30m of service cable, 35 mm^2 CNE • G74 motor load fault infeed	

2.1 - Line Impedance Calculation

Based on the given data sheet of the modeled network, cable impedances were calculated as follows.

- **11KV feeders**

For 185 mm^2 cable / 1.5 Km

$R+j(2*\pi*f) = 0.164 + j0.08\ \Omega/Km$

$R \Rightarrow 1.5 * 0.164 = 0.246\ \Omega$

$X \Rightarrow 1.5 * 0.08 = 0.12\ \Omega$

$L = X / (2*\pi*f) = 3.81 \times 10^{-4}\ H$

For 95 mm^2 cable / 1.5 Km

$R+j(2*\pi*f) = 0.32 + j0.087\ \Omega/Km$

$R \Rightarrow 1.5 * 0.32 = 0.48\ \Omega$

$X \Rightarrow 1.5 * 0.087 = 0.1305\ \Omega$

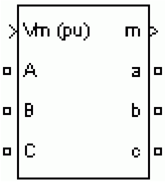
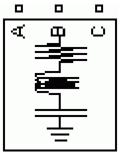
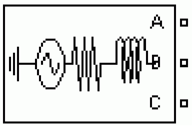
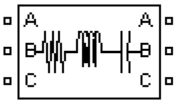
$L = X / (2*\pi*f) = 4.16 \times 10^{-4}\ H$

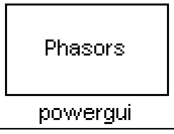
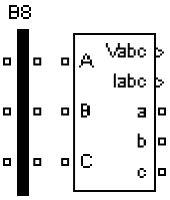
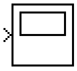
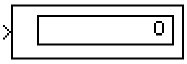
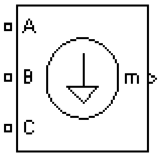
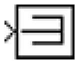
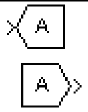
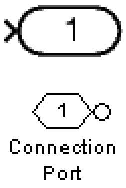
- **400v feeders**

For 185 mm^2 cable / 0.15 Km
R+j(2*π*f) = 0.164 + j0.074 Ω/Km (phase)
R ⇨ 0.15 * 0.164 = 0.0246 Ω
X ⇨ 0.15 * 0.074 = 0.011 Ω
L = X / (2*π*f) = 3.5 x 10^{-5} H
R+j(2*π*f) = 0.164 + j0.014 Ω/Km (neutral)
R ⇨ 0.15 * 0.164 = 0.024 Ω
X ⇨ 0.15 * 0.014 = 0.0021 Ω
L = X / (2*π*f) = 6.69 x 10^{-6} H
For 95 mm^2 cable / 0.15 Km
R+j(2*π*f) = 0.32 + j0.075 Ω/Km (phase)
R ⇨ 0.15 * 0.32 = 0.048 Ω
X ⇨ 0.15 * 0.075 = 0.01125 Ω
L = X / (2*π*f) = 3.58 x 10^{-5} H
For 95 mm^2 cable / 0.15 Km
R+j(2*π*f) = 0.32 + j0.016 Ω/Km (neutral)
R ⇨ 0.15 * 0.32 = 0.048 Ω
X ⇨ 0.15 * 0.016 = 0.0024 Ω
L = X / (2*π*f) = 7.64 x 10^{-6} H
Calculated line impedance values are to be used in the distribution network model shown below.

2.2- Introduction to Simulink (Matlap Help)
Simulink is a powerful modeling and simulation tool developed by the MathWorks Inc. as a part of the Matlab environment. Simulink is generally used for molding and simulating dynamic system. Table 2 summarizes the various block used for molding the distribution network in table 1.

***Table 2**: Description of the Simulink blocks used for modeling the distribution network*

Block name	*Description*	
Three phase OLTC regulating transformer		Used to model a two winding three phase transformer with an On Load Tap Changer on its primary winding that is used to keep the voltage at the secondary winding within a prescribed level.
Three phase series RLC load		Used to model a balanced three phase load as a series combination of R,L, and C elements at the specified frequency and power ratings.
Three phase source		Used to model a balanced three phase voltage source at the given frequency and voltage ratings. The internal R and L values are determined using the source three phase fault level and X/R ratio.
Three phase series RLC branch		Used to model the feeder cables as a series combination of R,L, and C elements. The values of these elements are calculated later on this section.

Powergui		Used with every Simulink model containing SimPowerSys blocks and provides a graphical user interface for analysis of the simulated model.
Three phase VI measurement		Used to measure the three phase voltages and currents in the modeled circuit. In our model this block is used to represent the various bus bars within the network.
Scope		Used to display the signal on its input port. In our case the p.u. voltages and tap position variations of the OLTC with the simulation time.
Display		Used to display the current OLTC tap position.
Three phase dynamic load		Used to model a balanced three phase variable load whose active and reactive power are controlled by an external [P,Q] vector.
Terminator		Used to cap unused output ports of any block to avoid error messages during simulation.
Goto and From		Used to route signals between different blocks within the model without the need to actually connect them. This makes the model look less complex.
Outport and connection port		The outport is used to create an output port for a subsystem. While the connection port is used to connect different SimPowerSys subsystems to SimPowerSys blocks.

2.3 Part 1: On load tap changer regulating transformers

In this part we will investigate the necessity of using transformers with load tap changing capabilities in the distribution network. First we are going to use the data provided in the network datasheet to model a small power system in which 96 customers are evenly distributed along a 300m 400v feeder that is supplied from a 500KVA 11/0.433KV three phase two winding transformer.

Simulation is carried out using two different models; the first model uses a 33/11.5KV 15MVA two winding transformer, and the second uses a three phase power transformer with OLTC on its primary winding. Both models are shown in figures 4 and 5 below.

For the load tap changer, the datasheet says that the 33/11.5KV transformer is equipped with a -20/+10% tap changer with 1.67% tap steps. So the Maximum tap position is $10 \big/ 1.67 = 5.99$, and the minimum tap position is $-20 \big/ 1.67 = 11.98$. This means that the maximum and minimum tap positions are +6 and -12 respectively.

Load tap changers are composed of a control circuit that measures the voltage level at the transformer's secondary winding and operates a motorized make before break switch to add or remove portions of the primary winding to change the transformation ratio.

For the tap changers to change its position, the condition $\left|(Vm - Vref)\right| > \text{dead band}/2$, should be satisfied where V_m is the measured voltage at the secondary winding of the OLTC transformer, and V_{ref} is the reference voltage, in our case 1 p.u.

The OLTC transformer dead band parameter is set to 2.5%, i.e. the measured voltage should be at least 1.25% above or below the reference voltage in order for the LTC to change its position.

The simulation results are shown in figures 2 and 3 below. Figure 2 shows the voltage level in p.u. for each bus bar in the modeled network without using the OLTC transformer, and figure 3 shows the simulation results when a 33/11.5KV OLTC transformer is used.

For both cases we see that the loading level has an obvious effect on the power grid voltage. The voltage drops smoothly for the maximum and minimum loading conditions as we move toward the far end of the distribution network, but the drop is higher when the load is maximum.

Another thing to notice is that without using the OLTC transformer, the voltage variation is higher than 10% of the nominal voltage level, which is not acceptable. When a LTC is used, the voltage level on the high voltage side of the network is kept close to 1 p.u. but on the 0.4KV side we can still see the smooth voltage drop because the 11/0.433KV is not equipped with a tap changing mechanism, but the voltage level remains below 1.1p.u.

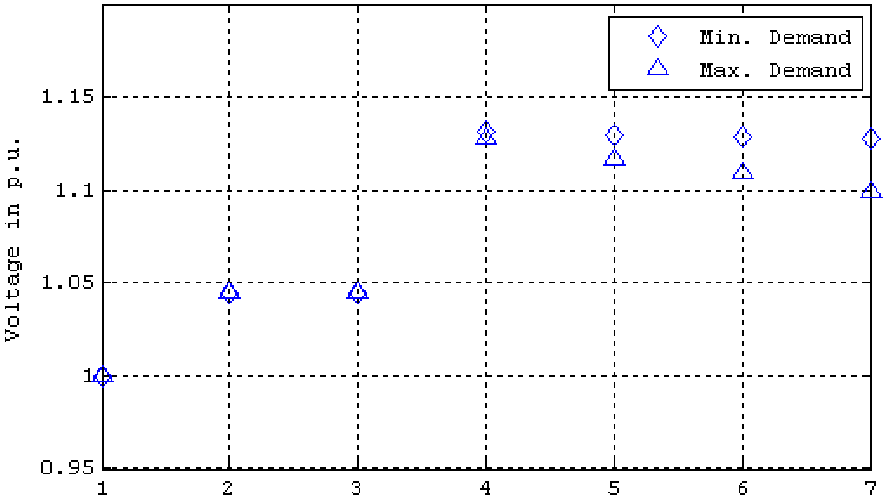


Figure 2: *Power system voltages without OLTC for maximum and minimum loading conditions*

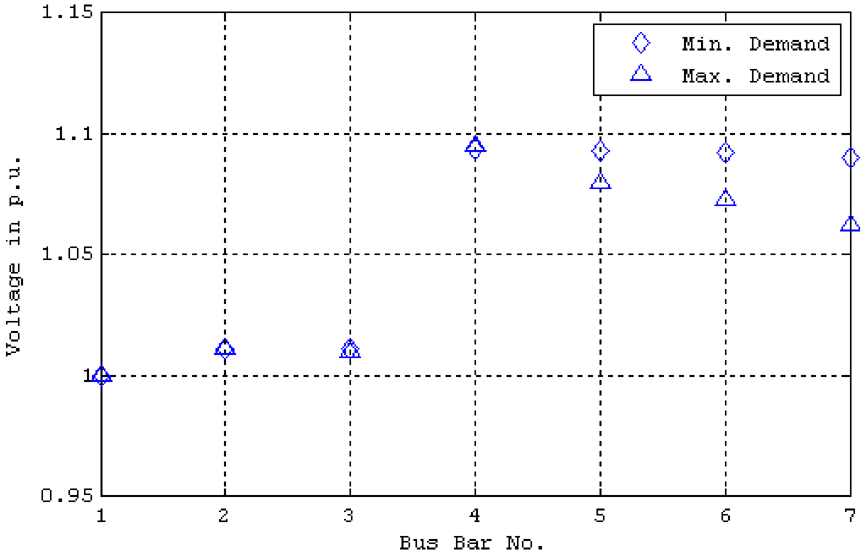


Figure 3: *Power system voltages with OLTC for the maximum and minimum loading conditions.*

This part illustrates why OLTC regulating transformers are considered to be the most important component of the power system. OLTC switching devices are commonly fitted to high voltage side of the transformer where the current level is low, to reduce the insulation class and cost.

Figure 4 shows a distribution network model with a 33/11.5 KV two winding transformer. And figure 5 shows only the high voltage side of the distribution network with a 33/11.5 KV OLTC regulating transformer, the 0.4KV side is similar to that shown in figure 4.

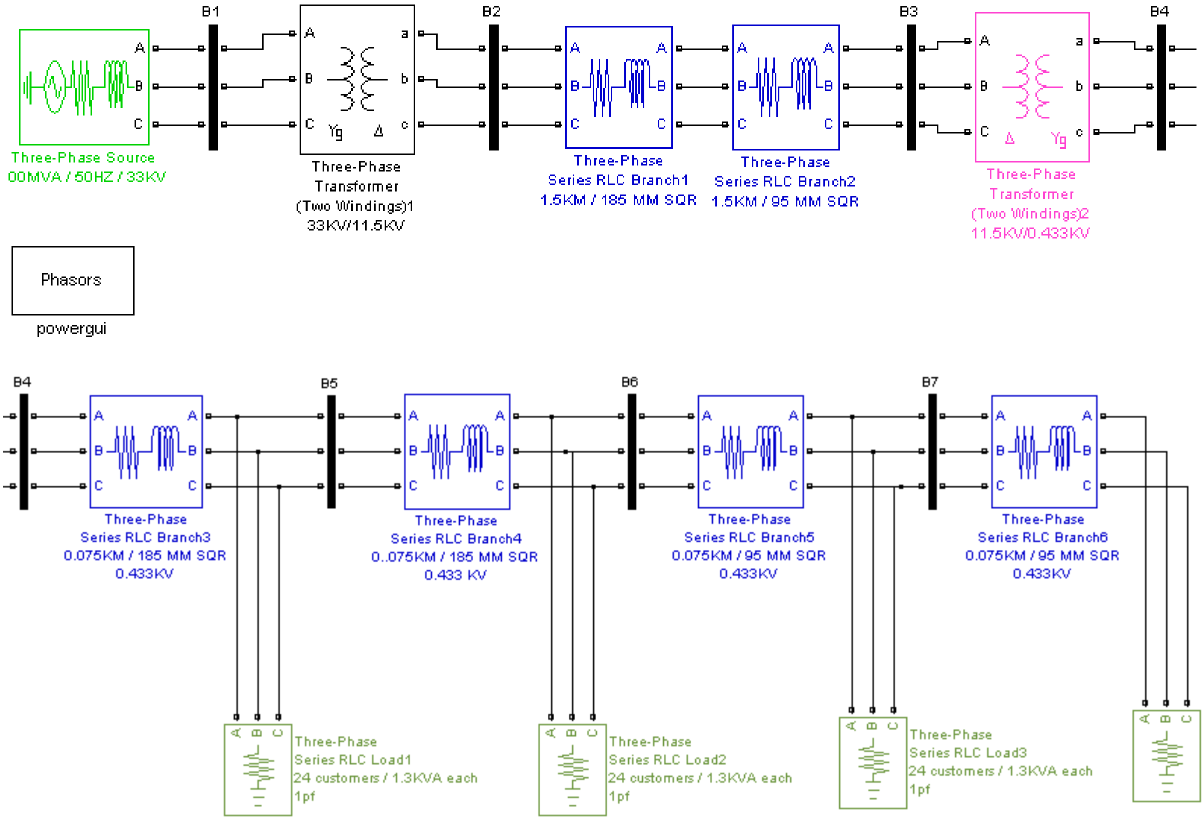


Figure 4: *Power network model without OLTC regulating transformer.*

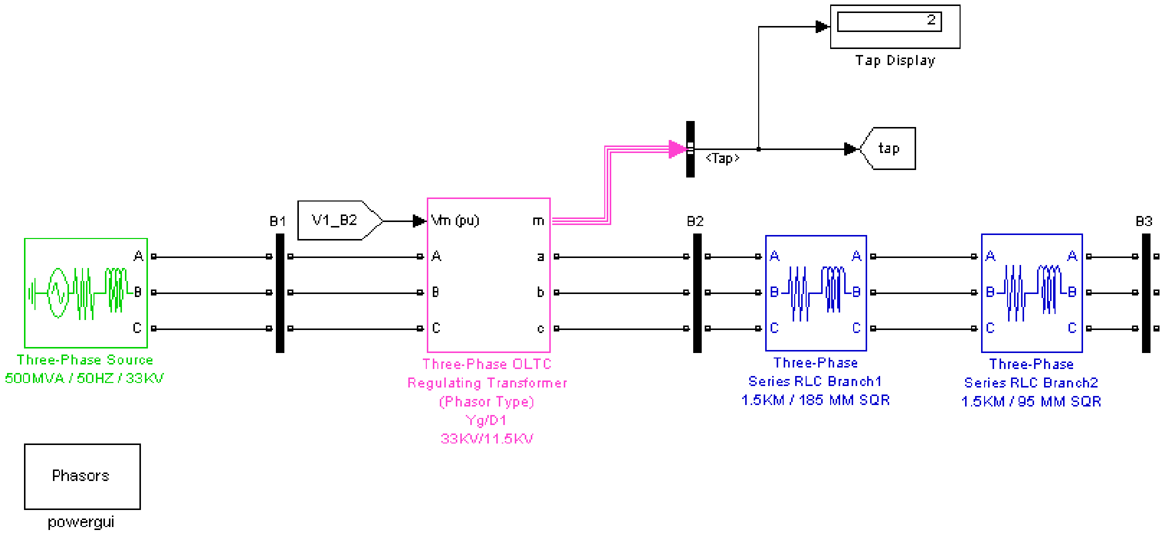


Figure 5*: Power network model with OLTC regulating transformer, the display shows the current tap position.*

2.4 Part 2: Distribution network modeling and simulation with a variable load

This part investigates the effect of changing the load demand on the voltage level at each bus bar of the modeled distribution network during a 24 hour time span. Table 3 contains the load demand values in KVA/customer used in the model. Figure 6 shows the typical daily load profile Test used for this part.

Time	0	6	7	8	9	12	15	16	17	18	24
Load /KVA	0.16	0.16	0.5	1	1.3	1.3	1.3	1	0.5	0.16	0.16

Table 3: *Typical Daily load profile data test*

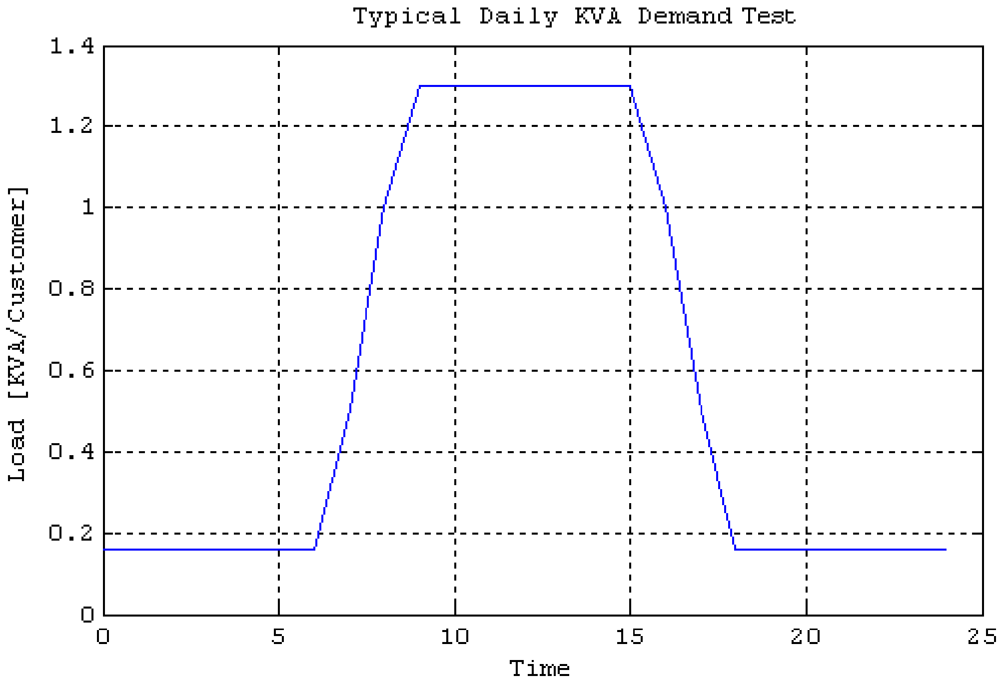
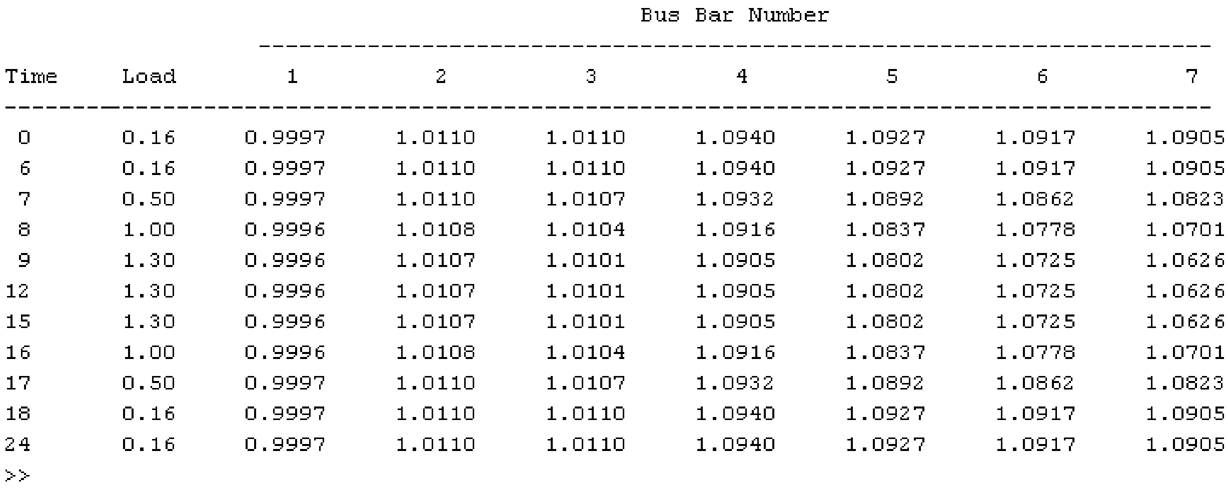


Figure 6: *Typical daily load demand Test in KVA/customer*

An M-file was used to set the parameters of the Simulink model blocks, and to control the simulation process by executing the following steps.

- Determines if the model is open using the **find_system** function.
- Opens the model and its subsystems, if not already opened using the **open_system** function.
- Changes the **Activepower** component of the **Three phase RLC load** block using the **set_param** function.
- Runs the simulation and collects the data using the **sim** function.
- Writes the results of the simulation to the **command window**.

The code of the M file is included in appendix 1.



```
                                                     Bus Bar Number
                         ------------------------------------------------------------------
Time      Load          1          2          3          4          5          6          7
-----------------------------------------------------------------------------------------
 0        0.16     0.9997     1.0110     1.0110     1.0940     1.0927     1.0917     1.0905
 6        0.16     0.9997     1.0110     1.0110     1.0940     1.0927     1.0917     1.0905
 7        0.50     0.9997     1.0110     1.0107     1.0932     1.0892     1.0862     1.0823
 8        1.00     0.9996     1.0108     1.0104     1.0916     1.0837     1.0778     1.0701
 9        1.30     0.9996     1.0107     1.0101     1.0905     1.0802     1.0725     1.0626
12        1.30     0.9996     1.0107     1.0101     1.0905     1.0802     1.0725     1.0626
15        1.30     0.9996     1.0107     1.0101     1.0905     1.0802     1.0725     1.0626
16        1.00     0.9996     1.0108     1.0104     1.0916     1.0837     1.0778     1.0701
17        0.50     0.9997     1.0110     1.0107     1.0932     1.0892     1.0862     1.0823
18        0.16     0.9997     1.0110     1.0110     1.0940     1.0927     1.0917     1.0905
24        0.16     0.9997     1.0110     1.0110     1.0940     1.0927     1.0917     1.0905
>>
```

Figure 7: *Screenshot of the command window showing the p.u. voltages at each bus bar of the modeled distribution network for various loading conditions.*

From the simulation results shown in figure 7, we can see that as the load level increases, the voltage drop across the modeled network components increases, this voltage drop is more evident on bus bars 4,5,6, and 7. But for the high voltage bus bars we see that the voltage level is almost constant due to the fact that the tap changer keeps the voltage within a prescribed level, and eliminates the effect of load variations.

The next step was to use a more detailed daily load profile as shown in figure 8. This time we used two different approaches to model the distribution network. The first approach uses an M file similar to that mentioned above, and the second approach uses a three phase dynamic load blocks as shown in figure 10, instead of the three phase RLC block. The simulation results are shown in figure 9.

Similar results were obtained from both approaches, but the three phase dynamic load worked much faster than the M file, so it was used to build the complete model of the distribution network as shown in part 3.

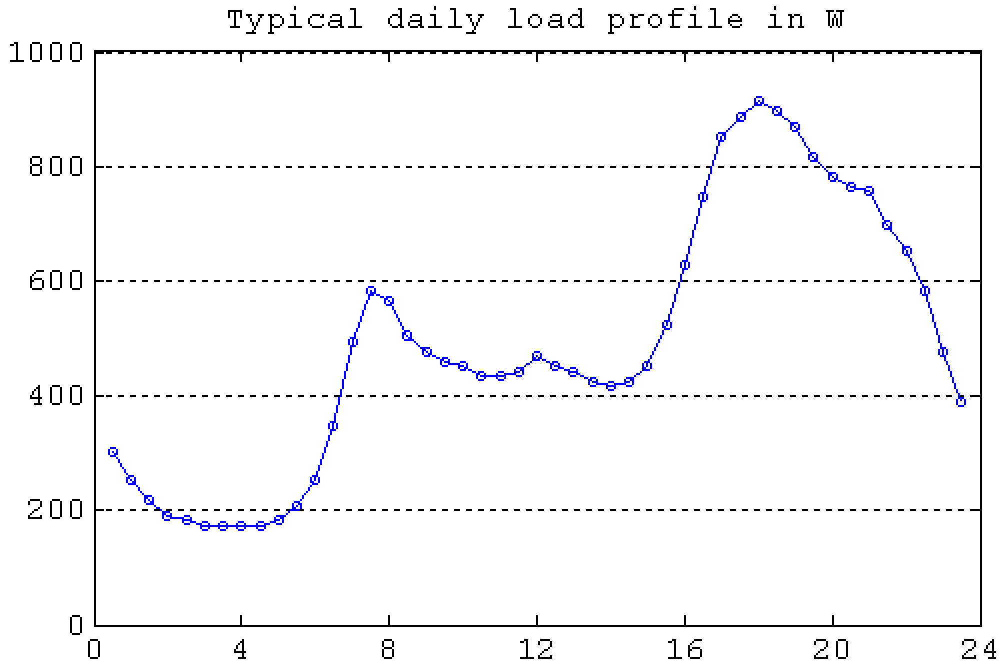


Figure 8*: Typical daily load profile 2*

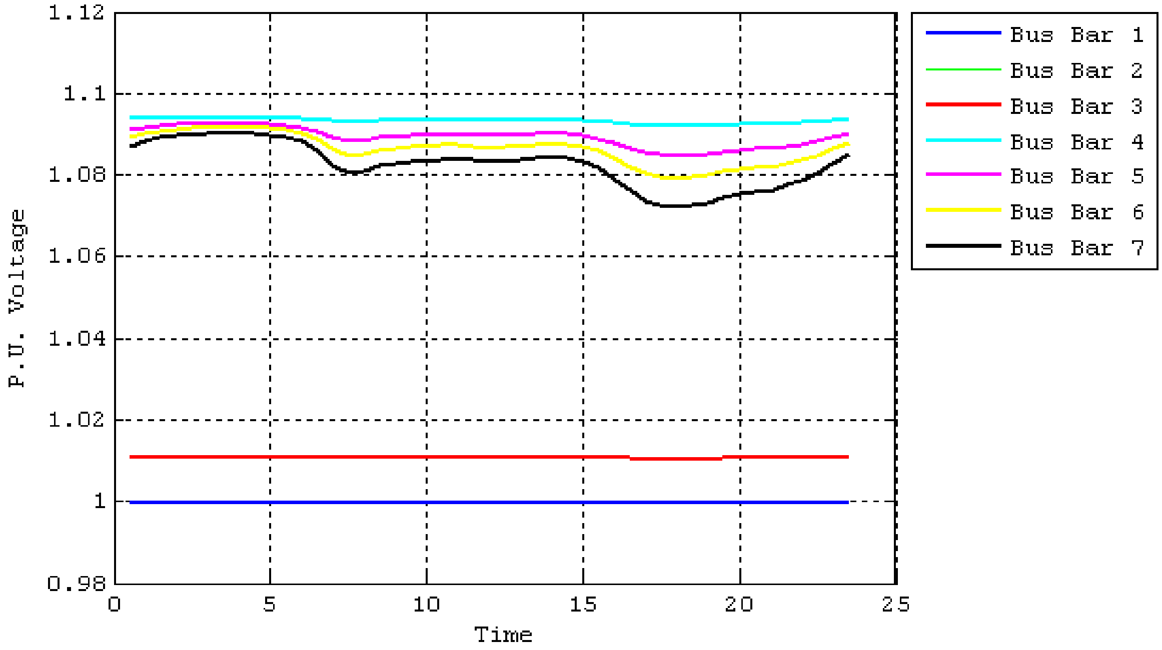


Figure 9: *Bus bars p.u. voltage level*

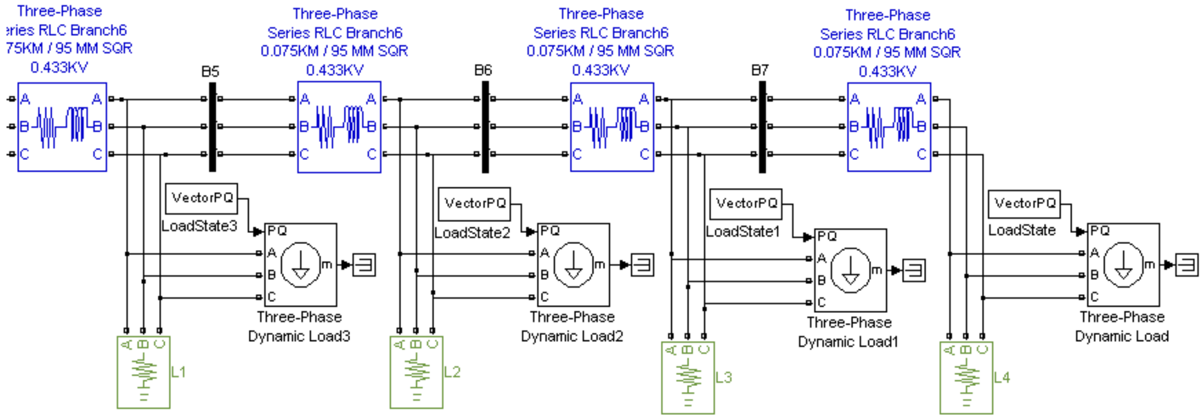


Figure 10: *A 0.4KV feeder model using three phase dynamic loads instead of the three phase RLC load*

2.5 Part 3: Modeling the 11KV feeder circuit

In this part we will model the 11KV feeder circuit. As the datasheet says, each 11KV feeder compromises two segments of a 3 core cable 1.5Km of 185mm^2 and 1.5Km of 95mm^2 with eight 500KVA substations evenly distributed along the feeder cable.

To reduce complexity of the model we used a subsystem block to represent each 500KVA substation and its load. Each subsystem block contains the 0.4KV feeder model is shown previously in figure 10. the detailed 11KV feeder model is shown in figure 12.

By simulating the model in Figure 12 the obtained results is shown in figure 11, we can see that voltage variations due to demand changes are still within the acceptable limits.

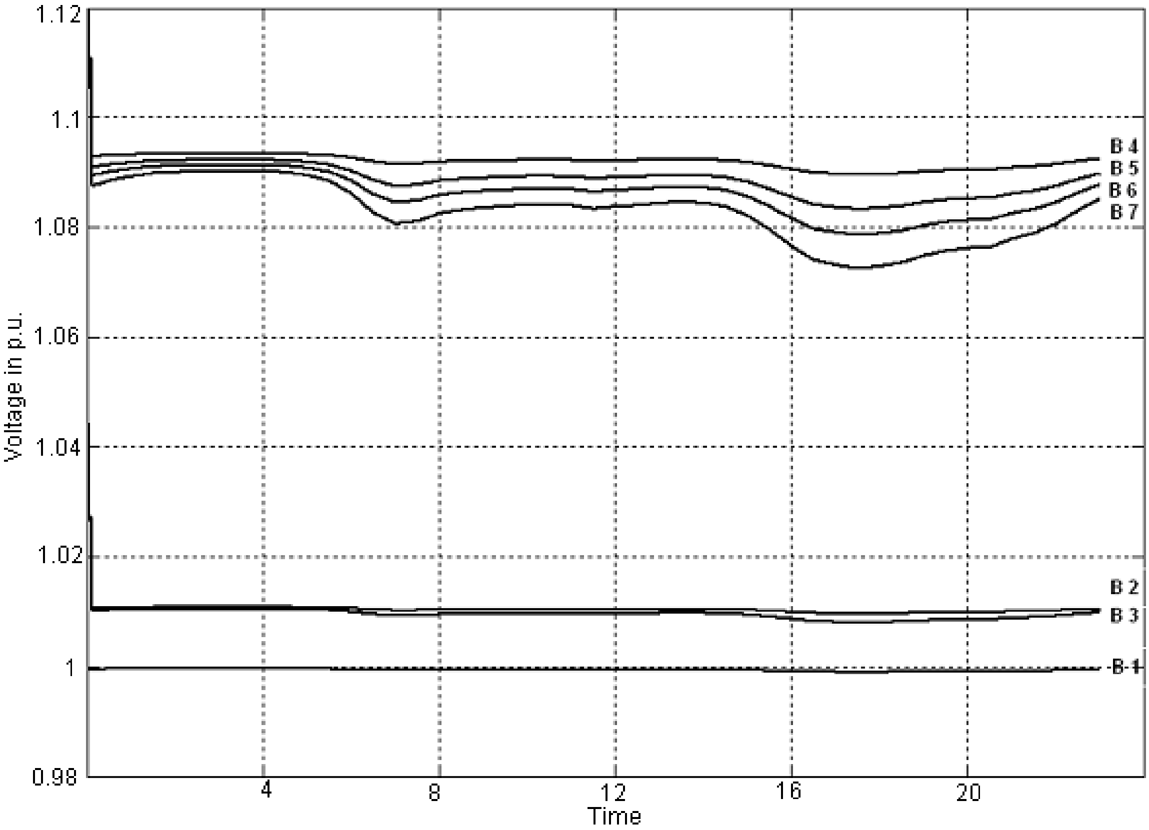


***Figure 11**: Simulation results of the 11KV detailed feeder*

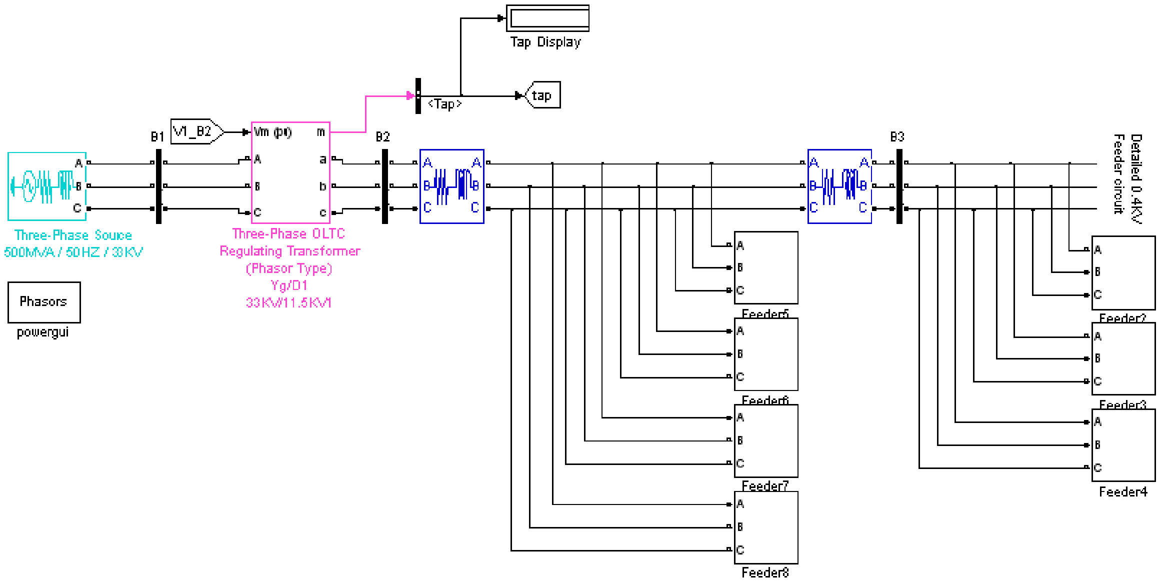


***Figure 12**: A model of the detailed 11KV feeder circuit*

2.6 Part 4: Modeling the entire distribution network

In this part of the project we are going to build the complete model of the distribution network using the 11KV feeder model shown in figure 12. Figure 13 shows how two 33/11.5KV 15MVA transformers are connected in parallel to supply the 11KV substation. Five 11 KV feeders are represented as subsystems to reduce the complexity of the model with the sixth feeder shown in details as in figure 12.

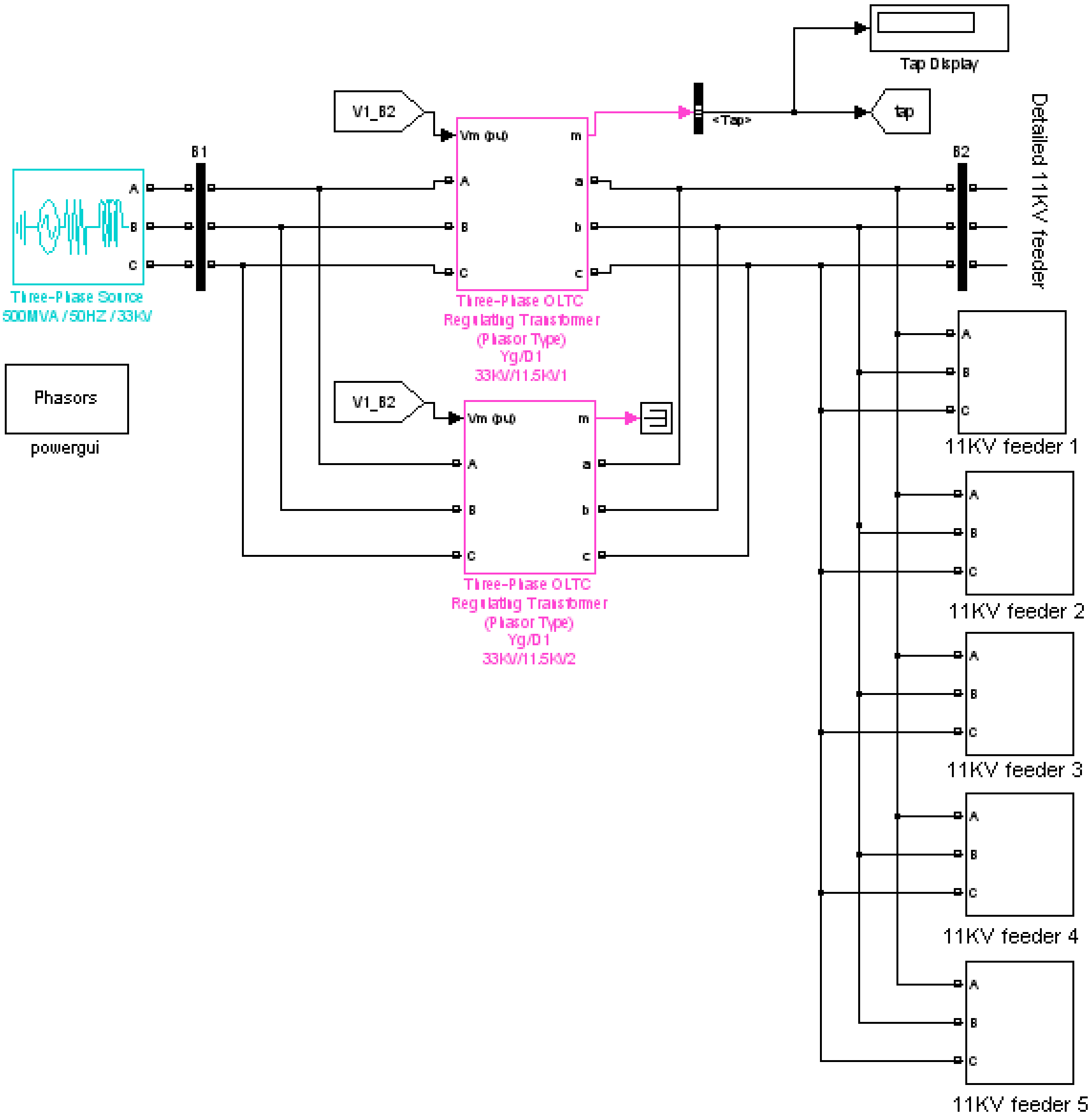


***Figure 13**: The complete distribution network model*

2.7 Part 5: Integrating PV generators into the distribution network model

In this part we are going to add the amount of power produced by embedded PV generators to the distribution network model. Figure 14 shows the typical daily load profile of a residential customer for the summer and winter times. Figure 16 shows a representation of the typical daily generation profile for a 2KW PV system during the summer and winter time.

We used both profiles to study the effect of using distributed small scale generators in one of the 11KV feeders.

From figure 14 we see that the load profile follows an expected pattern, the load is minimal from the midnight until the early morning hours where it starts to rise until it reaches the first peak at about 8 o'clock, and then the demand decreases slowly and remains almost constant from 12 midday until about 4 o'clock where it starts to increase again until it reaches the second beak at about 6 o'clock.

When the demand is maximum – i.e. 1.3KVA / customer – each customer uses his local PV generator to cover some or most of this demand, and any extra power needed will be drawn from the utility distribution network. This is why we used PV generators in the first place; to reduce the amount of power drawn from the utility power grid in order to reduce greenhouse gases emissions.

But when the demand is minimum – i.e. 0.16 KVA / customer – in some parts of the day there will be a considerable amount of power produced by each PV generator. This means that each customer will be able to cover his entire power demand, and the extra amount of power produced by the local PV system will be injected into the distribution network.

Figure 15 shows how we subtracted the total amount of power produced by distributed PV generators from the total demand to simulate the effect of distributed PV generators on the power system. Figure 17 shows the simulation results for a high penetration of PV generation in the 11KV feeder during the summer time. And figure 18 shows the impact of PV generation during the winter.

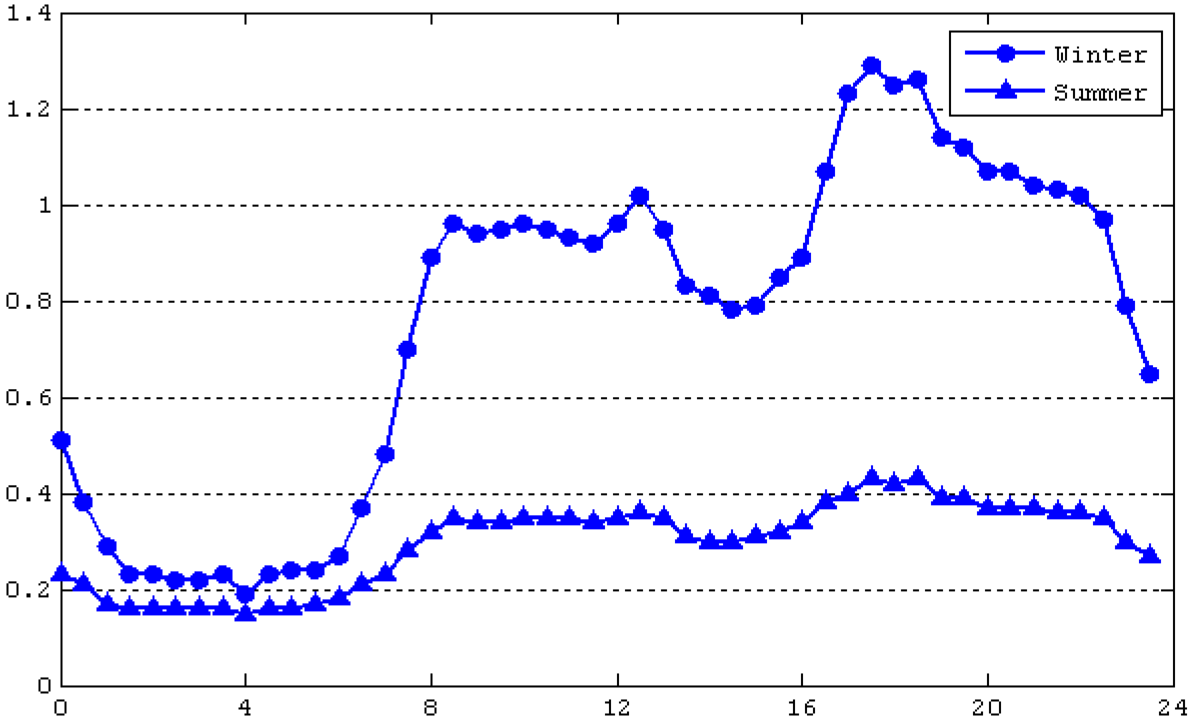


Figure 14: *Typical Daily load profile of residential customers- data provided by the supervisor taken from National Grid, UK.*

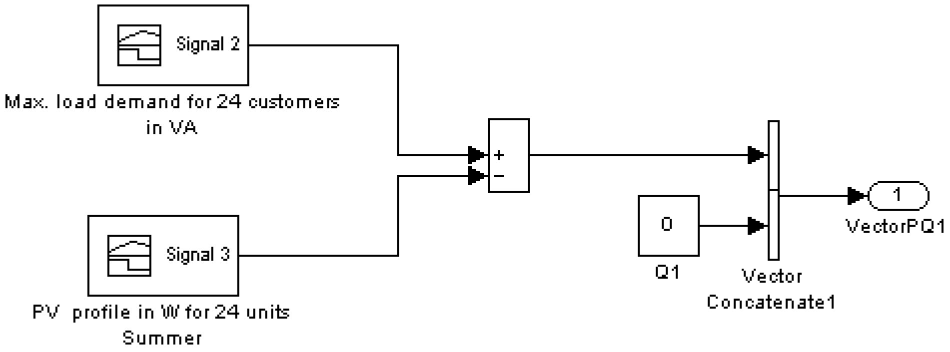


Figure 15: *Integrating PV generators into the distribution network*

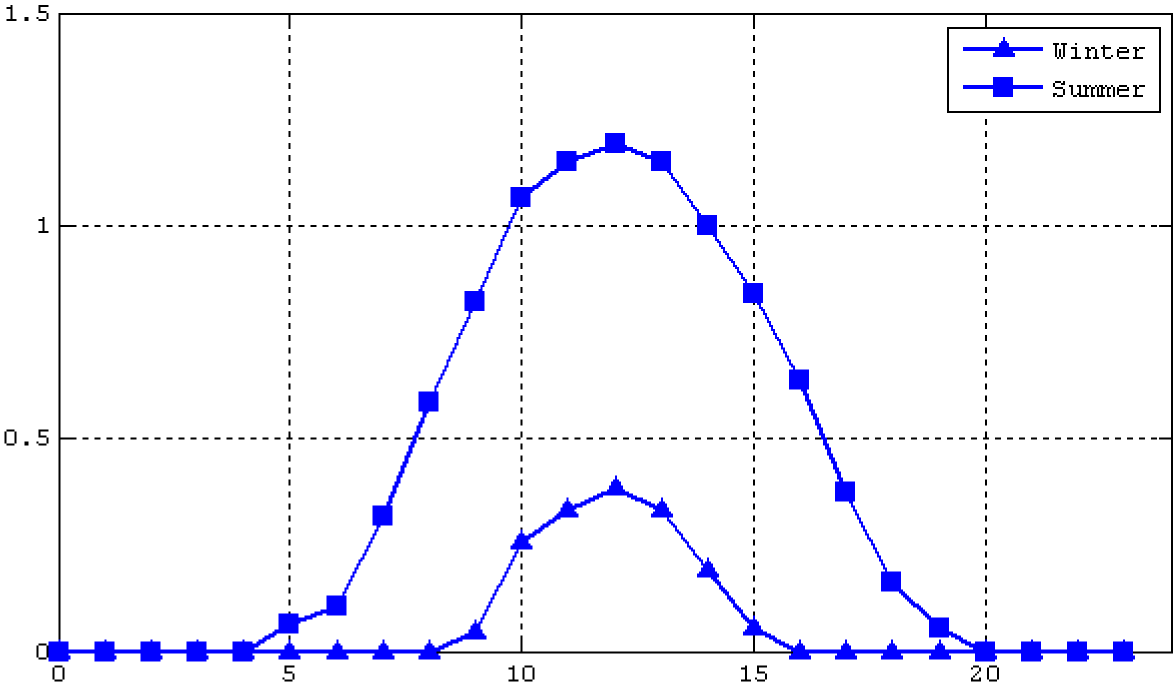


Figure 16: *Typical Daily generation profile for 2KW PV installation- data provided by the supervisor taken from National Grid, UK.*

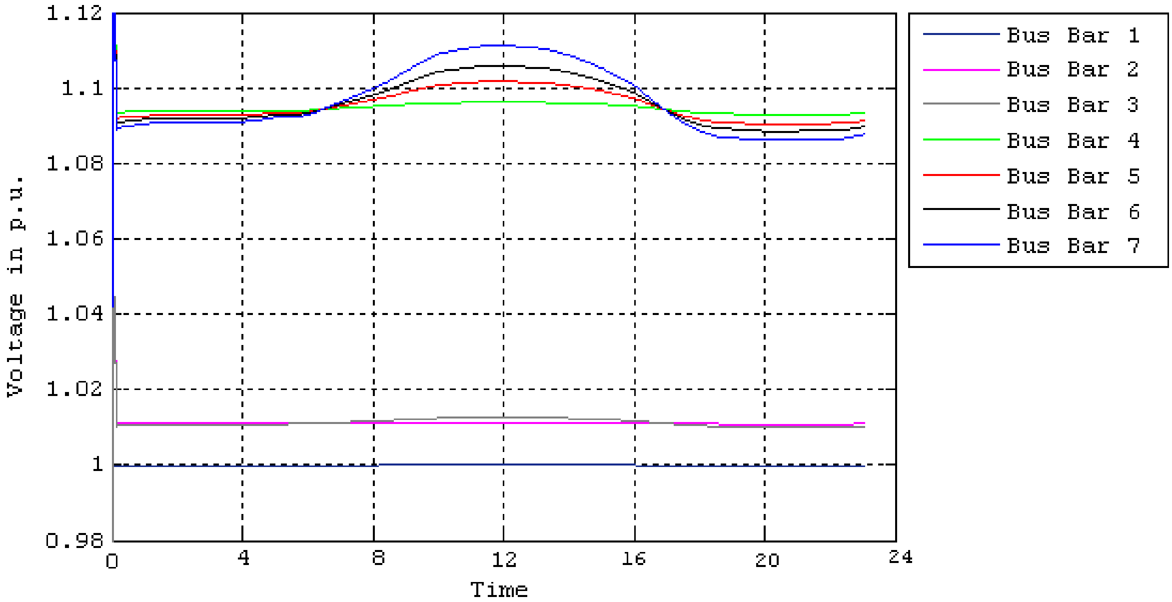


Figure 17: *Simulation results for a high concentration of PV generators in the 11Kv feeder (summer profile)*

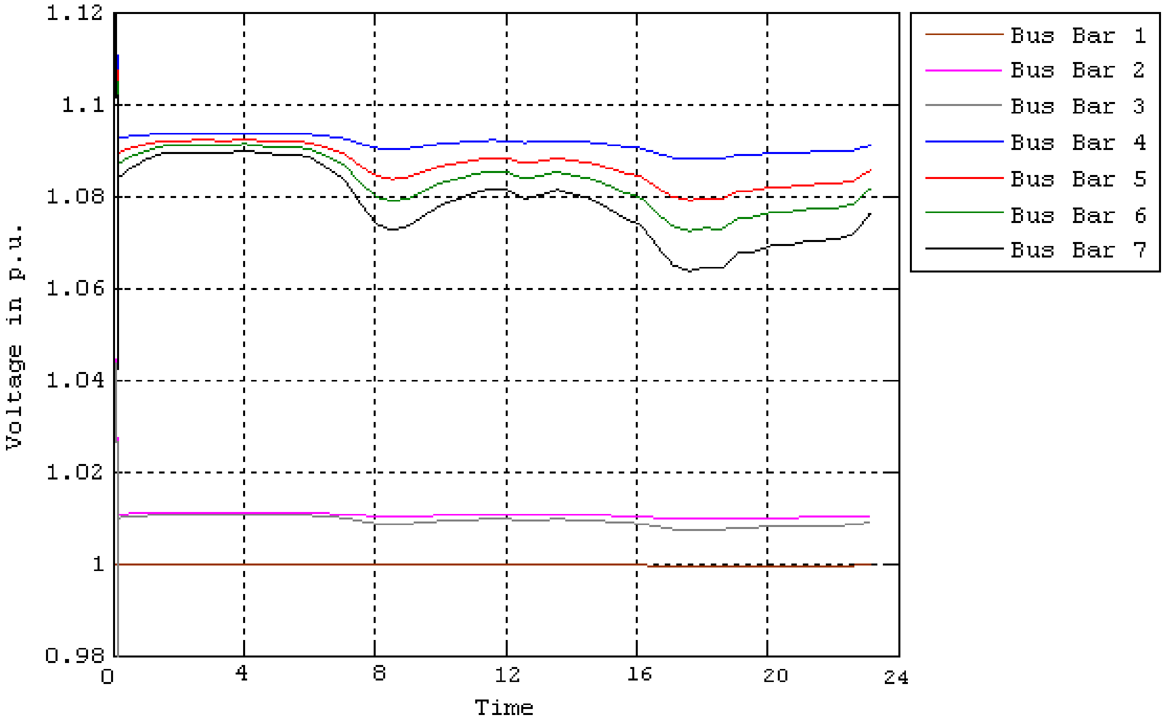


Figure 18: *Simulation results for a high concentration of PV generators in the 11Kv feeder (winter profiles)*

From the simulation results for the summer and winter profiles shown in figures 17 and 18 above, we can see that for high penetration of embedded PV generators there is a significant impact on the voltage level as we move towards the far end of the distribution network.

This happens when the load level is not high enough to consume the entire amount of power injected into the distribution network by distributed PV generators (during the summer time when the generation level of PV installations is high and the demand is low).

Form figure 18 we can see that the voltage level remains below the acceptable +10% limit, but still we note that there is a small increase in the voltage level if we compare the results to those obtained without integrating PV generators into the system.

There are many possible approaches to mitigate the negative impact of large penetration of PV generators on the quality of voltage in the power systems, such as using an OLTC regulating transformer instead of the fixed tap position 11 / 0.4 KV transformer. Or we could simply limit the amount of penetration of PV generators in the distribution network, but this does not solve the root cause of the problem.

The method of using OLTC regulating transformers will be investigated in the discussion part of the report.

2.8 Part 6: Power system response to sudden changes in irradiance

In this part we are going to investigate the effect of rapid changes in the PV generators output on the power network as a whole.

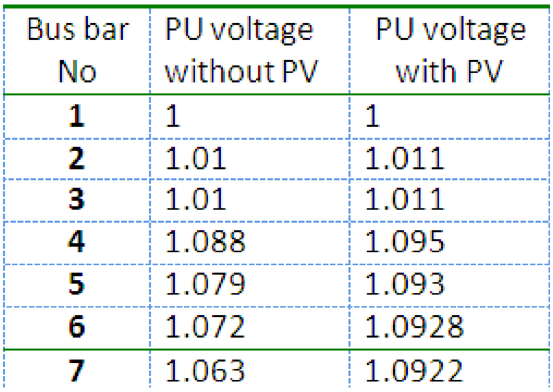
As we saw earlier, PV systems depend on sunlight to generate electrical power. This means that any changes in the level of solar irradiance can change the output of the PV system rabidly. This is what happens when clouds suddenly move over an area with large concentration of PV generators. These sudden changes in the output of PV generators could cause undesirable voltage variations in the power system.

For this part we built two models, one for a maximum demand of 1.3KVA/customer and the other for 0.16KVA/customer assuming that the output of PV generators changes from zero to a maximum of 1.2KW/unit then back to zero again.

For both cases we see that irradiance fluctuations have no effect on the voltage level at bus bars 1 and 2 due to the use of OLTC transformers, but we can see that the voltage level follows the pattern of change in PV output power with a slight voltage drop at bus bars 4, 5, 6, and 7. This voltage drop is more evident when the load is minimal.

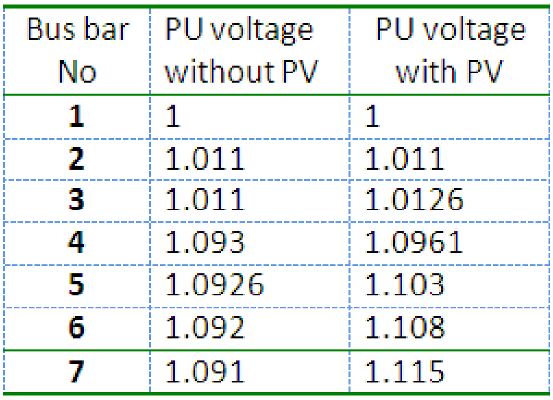
Rapid changes in irradiance level could also cause sudden tripping of the PV system due to false operation of the under voltage protection relay used with grid connected PV generators.

Table 4: *1.3KVA / customer*



Bus bar No	PU voltage without PV	PU voltage with PV
1	1	1
2	1.01	1.011
3	1.01	1.011
4	1.088	1.095
5	1.079	1.093
6	1.072	1.0928
7	1.063	1.0922

Table 5: *0.16KVA / customer*



Bus bar No	PU voltage without PV	PU voltage with PV
1	1	1
2	1.011	1.011
3	1.011	1.0126
4	1.093	1.0961
5	1.0926	1.103
6	1.092	1.108
7	1.091	1.115

II. DISCUSSION

The main problem with integrating small scale photovoltaic generation systems into the utility power grid is the increase in the system voltage level. This increase in voltage becomes more evident when the demand drops to its minimum value, in our case 0.16KVA / customer. When this happens the voltage level rises above the +10% acceptable limit.

The problem happens when the amount of power generated by PV generators is high and the demand is low, in this case the customer does not consume the whole amount of power generated by the PV system, causing this extra power to flow back into the power system. As a result the voltage level rises above 1.1 p.u. The reverse active power flow could cause malfunctioning of protection systems and on load tap changers.

One of the possible measures to mitigate the effect of large voltage fluctuations especially with sudden changes in irradiance level is the use of an on load tap changer with each 11/0.433 KV transformer to control the voltage level at the 0.4KV feeder circuit.

We can apply this method to the distribution network model by replacing the 11/0.433 KV three phase two winding transformer block with a 500KVA 50Hz three phase OLTC regulating transformer. The reference voltage of the OLTC block should be taken from bus bar 7 – the farthest bus bar in the network – to make sure that the voltage level at each bus bar remains within the acceptable limits – from 0.94 to 1.1 p.u.

We are going to use an OLTC block similar to that used for the 33/11.5 KV transformer. Figure 19 shows only the detailed 0.4KV to illustrate the changes made on the 11/0.433 KV transformer. The simulation results are shown in figure 20.

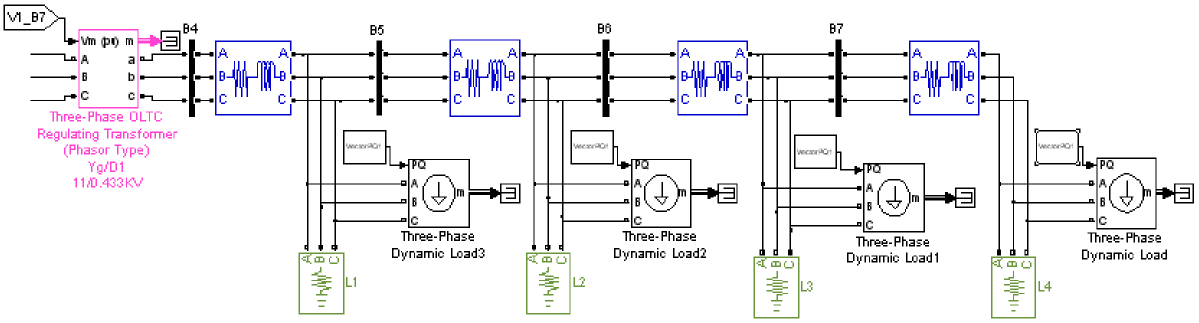


Figure 19: the detailed 0.4KV feeder with a 11/0.433 KV OLTC regulating transformer

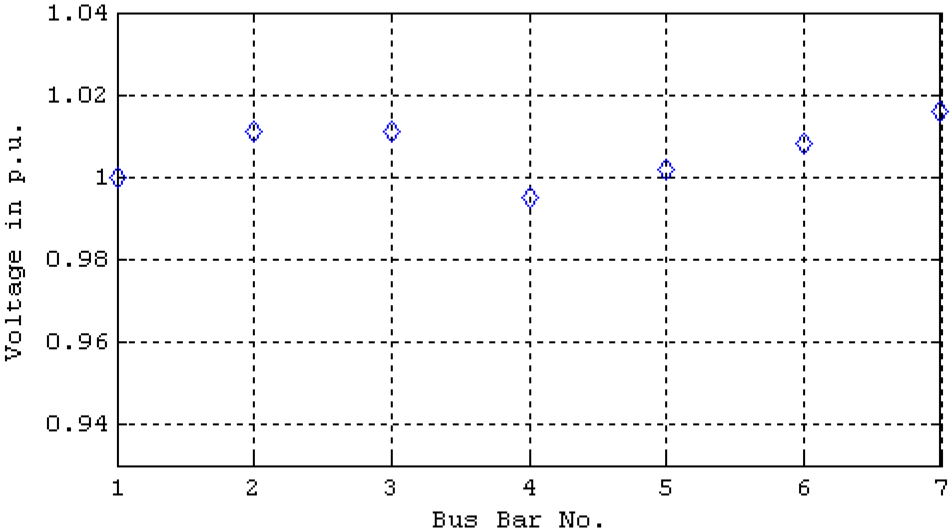


Figure 20: simulation results for the detailed 0.4KV feeder with a 11/0.433KV OLTC transformer

It can be seen from figure 20 that the OLTC regulating transformer kept the voltage within the -6/+10% acceptable limits.

III. CONCLUSIONS

- The simulation results show that before adding amount of power produced PV generators to the distribution network model, the voltage level at all bus bars remained within the +10%, -6% acceptable limits. This means we do not need an OLTC mechanism with the 11/0.433 KV transformer. But we had to use an OLTC with the 33/11.5 KV transformer to keep the voltage level within the acceptable limits.
- When small scale distributed PV generators were added to the distribution network model, it was noted that for small concentration of PV generators there was a small increase in the voltage level when moving towards bus bar 7, but this increase in voltage does exceed the 1.1 p.u. upper limit.
- When the number of PV generators is high and the demand is low, it was noted that the bus voltage level exceeded the +10% limit. But when the demand is high the voltage level remained below 1.1 p.u.
- Any changes in the level of solar irradiance can change the output of the PV system rabidly. This is what happens when clouds suddenly move an area with large concentration of PV generators. These sudden changes in the output of PV generators could cause undesirable voltage variations in the power system.
- One of the possible measures to overcome the effect of large voltage variations especially with rapid changes in irradiance is the use of OLTC regulating transformer on the 0.4KV substation to keep the voltage level within the acceptable limits.

IV. FURTHER WORK

In this project a dynamic model of the photovoltaic system with intermittency effect was not built. For example a switch can be used to show this intermittency effect on the voltage level on the grid. Instead of using some typical values for the amount of power generate by the PV during the summer and winter time, it is recommended to build a complete model of a photovoltaic generator with a switch to get more accurate results in the future.

One way to overcome the voltage variation problem associated with large concentration of photovoltaic generators was considered. Further research should be done to find out other ways to mitigate this problem.

Bibliography

- D P Kothari, 2002 Basic Electrical Engineering, Second Edition
- Marks, T, 1996 Handbook IEE Wiring Regulations BS7671, William Ernest Publishing
- Nagsarkar, T. K., and Sukhija, M. S., 2005 basic Electrical Engineering
- Shavemaker, P, Slvis, L, 2008 Electrical Power Systems Essentials, Wiley.
- Weedy, B.M, Cory, B.J, 1998 Electric Power Systems 4 Ed., Wiley

REFERENCES

[1]. Enolar (n. d.) Solar Power Plants / Power Station [online] available from <http://www.enolar.com/products11.htm> [15 Apr 2009]
[2]. David McMahon (2007) Matlab Demystified. USA: Mc graw hill
[3]. Matlab help

[4]. Nick Jenkis, Ron Allan, Peter Crosley, Daniel Krischen and Goran Strbac (2008) ed. by Professor A.T. Johns and Professor D.F Warne Embedded Genration. London: The Institution of Electrical Engineers

[5]. Weatherization Works (n. d.) Solar Retrofits for weatherization and remodels- lesson 5 [online] available from <http://www.pasolar.ncat.org/lesson05.php#solar> [15 Apr 2009]

[6]. Wiley (2003) ed. by Antonio Luque, Steven Hegedus Handbook of Photovoltaic Science and Engineering. : Wiley-VHC

Appendix 1: M file code

```
%{
This m-file excutes the follwoing steps:
1- Ensures that the model is open.
2- Coverts the load value into strings.
3- Calls "set_param" function to change the load value during simulation.
4- Calls "sim" function which runs the simulation and return the data used
  for plotting.
6- Creates a matrix to save the results of simulation.
7- Plots the data, and edits the figure.
%}
Time=[0 6 7 8 9 12 15 16 17 18 24];
Load=[0.16 0.16 0.5 1 1.3 1.3 1.3 1 0.5 0.16 0.16 ]; %Typical load demands
TotalLoad=Load*24e3; %Compute the total load for 24 customers
N=length(Load); %Determine the number of times we will run the simulation
SimulationOutput=[]; %Simulation results matrix

%The following if statement makes sure that the simulink model is open
if  isempty(find_system('Name','Model_With_Variable_Load ')),
open_system('Model_With_Variable_Load'); open_system('Model_With_Variable_Load/signals')
end

for j=1:N
   %Determine the load demand
   LoadDemand=num2str(TotalLoad(j));
   %Set the parameters of the three phase RLC loads
   set_param('Model_With_Variable_Load/L1','Activepower',LoadDemand)
   set_param('Model_With_Variable_Load/L2','Activepower',LoadDemand)
   set_param('Model_With_Variable_Load/L3','Activepower',LoadDemand)
   set_param('Model_With_Variable_Load/L4','Activepower',LoadDemand)
   %Run the simulation and collect the results
   [timeVector,stateVector,outputVector] = sim('Model_With_Variable_Load');
   [NoOfRows,NoOfCols]=size(outputVector);
   SimResult=outputVector(NoOfRows,:);
   SimulationOutput=[SimulationOutput;SimResult];
end

%Plot the results
%subplot(2, 1, 1)
figure(1)
plot(Time, Load)
title('Typical Daily KVA Demand')
xlabel('Time')
ylabel('Load [KVA/Customer]')
grid on

%subplot(2,1,2)
figure(2)
```

```
BusBarNo=[1 2 3 4 5 6 7];
for i=1:N
   plot(BusBarNo,SimulationOutput(i,:),'x')
   hold on
end
title('Bus Bars PU voltages For Various loading conditions')
xlabel('Bus Bar No.')
ylabel('PU Voltage')
grid on

%Write the results to the MatLab Command Window
PrintMatrix=[Time' Load' SimulationOutput];
clc
fprintf('                                         Bus Bar Number \n')
fprintf('                  -------------------------------------------------------------------\n')
fprintf('Time       Load       1         2         3         4         5         6         7 \n')
fprintf('-------------------------------------------------------------------------------------------- \n')
fprintf('%2d        %1.2f     %1.4f     %1.4f     %1.4f     %1.4f     %1.4f     %1.4f     %1.4f \n',PrintMatrix')


%=========================================================================
```

Appendix 2: Molded network blocks parameters

33/11.5 KV transformers

- OLTC and voltage regulator parameters

OLTC on: winding 1
Voltage step per tap (p.u.): 0.0167
OLTC minimum and maximum tap positions: -12, +6
Reference voltage (p.u.): 1
Dead band (p.u.): 0.025

- Transformer parameters

Nominal power (VA): 15e3
Frequency (Hz): 50
Winding 1 voltage: 33KV
Winding 2 voltage: 11.5KV

Source
Phase – phase voltage (KV): 33
Frequency (Hz): 50
Fault level (VA): 500e6

Base voltages
Bus bar 1: 33KV
Bus bars 2 and 3: 11 KV
Bus bars 4 through 7: 0.4KV

11/0.433KV transformer
Nominal power (VA) and frequency (Hz) : 500e3, 50
Winding 1 voltage phase – phase (rms): 11e3
Winding 2 voltage phase – phase (rms): 0.433e3