OPTIMUM USE OF SOLAR INVERTER BY FEEDING REACTIVE POWER AT THE NIGHT

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DECLARATION OF THE CANDIDATE AND SUPERVISORS

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ABSTRACT

Due to the significant increase in price of Grid Electricity, many countries are switching to Renewable sources. With the expanded Solar Net Metering system which is approved by the Ceylon Electricity Board in Sri Lanka, Domestic consumers and all Commercial consumers will be benefited after installing such a renewable energy system directly connected to the grid.

As a developing country Sri Lankan electricity system has many issues related to the under voltage. Therefore by improving the voltage profiles installation of capacitor banks either in customer end or utility side is being promoted.

“The PV inverters that are not utilized at the time of night peak can be operates in feeding reactive power to eliminate the low voltage occurrence during the night peak.”

This postgraduate research thesis describes the above mentioned proposal with theoretical background. An algorithm was developed to calculate operating power factors for existing PV inverters in the particular feeder which is having under voltage problems. The software was developed to calculate the operating power factors of any system with existing system information.

Economic Evaluation was carried out by proposing a reward scheme for customers and benefits to the utility were discussed. The net saving to the utility was positive, according to the case study result.

Proposed algorithm was discussed with a case study and the results are verified by modeling the same in SynerGee.

Finally, utilizing distributed PV inverters at night peak by feeding reactive power, low voltage issues and line losses can be reduced in that particular feeder.

This study was proposed to utility side where the problem identification and the relevant solution can be made accordingly.

ACKNOWLEDGEMENTS

Foremost, I would like to express my sincere gratitude to my supervisor Dr. Asanka Rodrigo for the continuous support given for the research, for the patience, motivation, enthusiasm, and immense knowledge. His remarkable guidance helped me throughout the research.

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K. K. Navoda

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LIST OF ABBREVIATIONS

AEE	Area Electrical Engineer
CEB	Ceylon Electricity Board
DD1, 2, 3, 4	Distribution Division 1,2,3,4
LKR	Sri Lankan Rupees
MV	Medium Voltage
USD	US Dollars

CHAPTER 1

INTRODUCTION

1.1 Background

Power is one of the most rapidly expanding industries in the modern world. In modern living style the need for power is unlimited. Due to that, since the demand for energy is tremendously going up, the supply also has to be increased. But fulfilling demand is difficult by using existing energy sources and also fuel cost is getting increases. More importantly, fuel is a scarce resource. Therefore running thermal power plants and other plants, which use fuel, will become more costly. With the increase of demand for energy around the world, now it is recognized that the usage of renewable energy such as solar, wind, tidal wave and bio mass is a mandatory need.

Due to the price of Grid Electricity is drastically increasing; many countries are being switched to Renewable sources. Energy from the Sun in the form of Solar can be used by any electricity consumer. Rooftop solar PV applications are basically divided into two main types, such as off grid and on grid applications. Off grid systems are been supplied for customer’s own loads and when the generation exceeds the load, excess energy can be stored in a battery system. On grid systems are connected to the utility network and power can be supplied back to the main grid when the generation exceeds the customer’s own load demand. Initially off grid systems were much more popular and widely used when compared to on- grid systems.

However, with the ability to sell excess energy to utility, on grid solar system has become the most popular system at present. Net Metering concept which was introduced in 2010 has been expanded in 2016 with the implementation of “Soorya Bala Sangramaya” program. The existing Net Metering concept was modified under three schemes to promote more and more grid connected renewables. The net metering scheme is applicable to the connections of PV systems to the low voltage network i.e. 400 V network and allowable capacity was limited to customer's contracted demand; subjected to a maximum of 1000 kVA since 2014.

1.1.1 Net Metering Scheme [7]

This is the firstly introduced scheme and continuing as it is. With the Net Metering concept approved by the Ceylon Electricity Board, Sri Lanka in 2010, all Domestic and Commercial customers are benefited by installing such renewable energy systems which is connected to the grid with 20 year agreement period. One meter including import and export registries, is installing to measure import and export energy of customer. The net energy consumption is billed and extra energy is carried forwarded as "**Energy Credit".**

1.1.2 Net Accounting Scheme [7]

This scheme also has same concept of above 1.1.1 Net Metering Scheme and additionally rather than carrying forward the extra export energy as Energy Credits customer will be paid with export tariff. If the customer has extra export energy he will be paid Rs 22.00 per unit during first 7 years and from 8 years to 20 years he will be paid Rs 15.50 per unit. Customer has to pay for extra import energy at the existing tariff rates.

The Net Accounting Scheme is only introduced to Solar Power Generation and not for any other renewable power generation.

1.1.3 Net Plus Scheme [7]

This scheme total energy generated by solar able to export to the grid through a separate meter and customer will be paid Rs 22.00 per unit during first 7 years and from 8 years to 20 years he will be paid Rs 15.50 per unit. The import energy by the customer will measure by another meter and he has to pay for it in existing electricity tariff rates.

1.1.4 Applicable standards [7]

The present net metering concept bounded several applicable standards. Most of the countries the standard applicable for PV system or other Distributed generation connections is IEEE 1547 which is the same used in Sri Lanka for PV and other renewable generations connected at Distribution level.

- The acceptable harmonic emission limits are as in the Table 1.1.

Table 1.1: The Harmonic limits of the accepted inverter

Individual harmonic order(h)	h<11	11<h<17	17<h<23	23<h<35	35<h	THD
Allowable Limit (%)	4	2	1.5	0.6	0.3	5

- The allowable DC injection is restricted to less than 0.5% of the full rated output current at the point of connection.
- The generating facility shall be automatically disconnected from the distribution network within half a second (0.5 second) when the supply is intentionally or automatically switched off.
- The generating facility, paralleling device shall be capable of withstanding 220% of the interconnection facility rated voltage.

The allowable operating power factor of the system is restricted to unity; it makes the PV inverter’s ability to inject or consume reactive power is restricted. The interconnection specifications applicable are, distribution system service voltage is within 06% of the nominal supply voltage and frequency is within 47 Hz to 52 Hz and both are stable for at least 3 minutes.

As the main inefficiency in use of solar net metering system is the output, that totally depends on the sun radiation which is not available in the night time.

1.1.5 Inverter Capabilities

The solar PV inverter is the main component for this whole concept which should capable to operate with variable power factors. Many solar inverter products with high technological features are currently available in Sri

Lankan market. The distribution network is connected by domestic PV inverter at several numbers of capacities, approximately 1kVA- 15kVA.

Table 1.2: Characteristics of inverters available in market

Product	Model	Output Power (kVA)	Output Voltage	Power Factor
Fronius IG Plus	25V-1	2.6	230V	0.85-1 ind./cap.
	30V-1	3.0	230V	0.85-1 ind./cap.
	35V-1	3.5	230V	0.85-1 ind./cap.
	50V-1	4.0	230V	0.85-1 ind./cap.
	60V-1	6.0	230V	0.85-1 ind./cap.
	60V-2	6.0	230V/400V	0.85-1 ind./cap.
	70V-2	6.5	230V/400V	0.85-1 ind./cap.
	100V-2	8.0	230V/400V	0.85-1 ind./cap.
	55V-3	5.0	230V/400V	0.85-1 ind./cap.
	60V-3	6.0	230V/400V	0.85-1 ind./cap.
	80V-3	7.0	230V/400V	0.85-1 ind./cap.
	100V-3	8.0	230V/400V	0.85-1 ind./cap.
	120V-3	10.0	230V/400V	0.85-1 ind./cap.
	150V-3	12.0	230V/400V	0.85-1 ind./cap.
Kaco	Powador 6.0 TL3	5.0	230V/400V	0.80 ind./cap.
	Powador 7.8 TL3	6.5	230V/400V	0.80 ind./cap.
	Powador 9.0 TL3	7.5	230V/400V	0.80 ind./cap.
	Powador 10.0 TL3	9.0	230V/400V	0.80 ind./cap.
	Powador 12.0 TL3	10.0	230V/400V	0.80 ind./cap.
	Powador 14.0 TL3	12.5	230V/400V	0.80 ind./cap.
	Powador 18.0 TL3	15.0	230V/400V	0.80 ind./cap.
	Powador 20.0 TL3	17.0	230V/400V	0.80 ind./cap.
Solar Edge	SE3000	3.0	230V/400V	0.95 ind./cap.
	SE3500	3.5	230V/400V	0.95 ind./cap.
	SE4000	4.0	230V/400V	0.95 ind./cap.
	SE5000	4.6	230V/400V	0.95 ind./cap.
	SE7k	7.0	230V/400V	0.95 ind./cap.
	SE8k	8.0	230V/400V	0.95 ind./cap.
	SE9k	9.0	230V/400V	0.95 ind./cap.
	SE10k	10.0	230V/400V	0.95 ind./cap.
	SE12.5k	12.5	230V/400V	0.95 ind./cap.
SunGrow	SH 5k	5.0	230V	0.80 ind./cap.
Sunny Boy	SMA SB3000TL	3.05	230V	0.95 ind./cap.
	SMA SB4000TL	4.05	230V	0.95 ind./cap.
	SMA SB5000TL	5.05	230V	0.95 ind./cap.

According to the Table 1.2 the inverters available in the market normally not having the provision of changing the power factor in the range of 0 to 1. But Sunny Central CP XT inverters newly introduced by SMA Solar Technology, America have the ability to change the power factor on required range and feed reactive power at night by switching to “Q at Night” mode. [14]

The solar power project of Fall River Mills Project (4 MW) in California implemented by Blue Oak Energy’s was installed the SMA inverter which is able to operates in “Q at Night” mode. The article regarding the project says that “The inverter has the ability to provide reactive power based on a function of the entire size of the inverter, not just on the level of generation. So, if cloudy skies drop solar generation from 100 percent to 10%, the inverter can use the other 90% of its remaining capacity to supply reactive power support and enhance utility grid power quality.” [10]

1.1.6 Literature Review

There are several researches have been done to allocate protective devices optimally in distribution networks using different methods. One of those studies which is described in “A multi-function grid connected PV system with reactive power compensation for the grid” by Huajun. Yu, Junmin. Pan, and An. Xiang. This research authors describe that the theory behind the inverter use to produce VAR which means applying appropriate phase shift between reference current and grid voltage this can be achieved. [9]

“Reactive Power Performance Requirements for Wind and Solar Plants” by A. Ellis, B. Kirby, C. Barker, E. Seymour, E. Von Engeln, J. MacDowell, J. R. Williams, L. Casey, R. Nelson, R. Walling and W. Peter paper described the internal arrangement of the solar grid tie inverter use to as a VAR injector. [2] Also paper “Single Phase and Three Phase P+Resonant Based Grid Connected Inverters with Reactive Power and Harmonic Compensation Capabilities” by Maknouninejad, M. Godoy Simoes and M. Zolot further describes the same arrangement with simulation results. [11] The simulation and practical results are obtained in the paper “Online Optimal Reactive Power Control Strategy of PV Inverters” by A.Cagnano and E.D. Tuglie with varying the parameters and tested with several scenarios. [1]

According to the tariff systems which are proposing the reactive power feeding concept in Germany, “Latent Opportunities for Localized Reactive Power Compensation” by A. Kozinda, T. Beach and V. Rao describes the concept for whole day. [5] This paper cost comparison was done based on two factors; those are cost to customer to produce reactive power and cost to utility to produce reactive power with the absence of inverter feeding method. Under that cost to customer is again considered with cost if the customer downgrades power factor and cost if the customer over sizes the inverter. On the other hand it describes the cost to utility by installing capacitor banks to compensate the reactive power requirement was instated feeding it by using inverter.

However reactive power feeding by using solar grid tie inverter concept is presently most popular research topic which can be accepted to Sri Lanka after analyzing the applicability.

1.2 Motivation

The present using Solar Grid Tie inverters are capable with supplying both active and reactive power to the grid by adjusting the operating power factor. This will be more benefited to eliminate system voltage stability issues happening during the night peak by feeding reactive power in to the system.

In addition to that since the rooftop solar considered as distributed generators the voltage stabilization can be easily controlled by feeding required reactive power changing with the power factor of the inverter.

Following reasons which are motivated me to choose this specific study area for my research.

- Solution for many under voltage issues in the night peak of the National Grid.
- Optimizing the use of inverter and enhance the efficiency solar installation.
- Present tariff methodology for net metering is also not addressed the feeding reactive power.

1.3 Objectives

- The first objective of this study was to develop an algorithm to find an optimum operating power factor for feed reactive power for each net metering customer.
- The second objective was to propose a tariff methodology for solar net metering including the reactive power feeding concept.

1.4 Problem Statement

The rapid increasing of installation of solar net metering systems normally operates only on day time for feeding active power to the grid. Even though with new concepts the solar power generation increased many uncertainties occurred in the Sri Lankan Power System. The utility, CEB has to invest more to ensure the reliability and the stability of the system. Since the Sri Lankan Electricity Grid is a small scale one the controlling of the generation displacing was predict according to the real time Power Demand. Therefore by connecting more small scale solar generators may effects the controllability of the Power System.

Solar power is only available at the day time but the maximum demand is always occurred at the night peak where the utility needs to establish stable Power Generator in the system to meet that demand. However obeying the Sri Lankan Government Policies, utility can convert this rapid growth of solar installations for another activity where to ensure the voltage stability of the network.

The effectiveness of this solar installation is zero during night time (5.00pm-6.30am next morning). The system voltage unbalance that exist during the night time it is possible that the net metering inverter can be used as VAR producer for the system which is required for maintaining the system voltage within its limits, which increase the efficiency in the use of net metering installation and help maintaining the grid voltage stability. [2][3][4][8]

This method is not yet popular within Sri Lanka since the tariff which now available does not address about the reactive power that is feed. As this feed is important in effective improvement of the night grid performance a suitable method promoting this feed can be made effective by proposing a new tariff that considers reactive power generation as well.

Finally the feasibility and the applicability of the total process have to be analyzed.

1.5 Scope of Work

For this research, scope of work is as follow.

01. Studied the Optimization problem solving done in the distribution network of other countries.
02. Studied the constraints which will affect the feeding reactive power.
03. Obtained an Objective Function to optimize the inverter operating power factors.
04. Data collection: Feeder loading, Low voltage percentage, Number of customers connected to the feeder and their capacities.

05. After the objective function was formulated the data from one feeder was fed into the function and got the results. Accuracy of the results was depending upon the accuracy of data collection.

06. Identified feeders to be analyzed as case studies for implementing the proposed method in to SynerGee Models and analyze the applicability and efficiency of the proposal.
07. According to the case study results propose new tariff for net metering.

CHAPTER 2

MATHEMATICAL MODELING

2.1 Technical Background

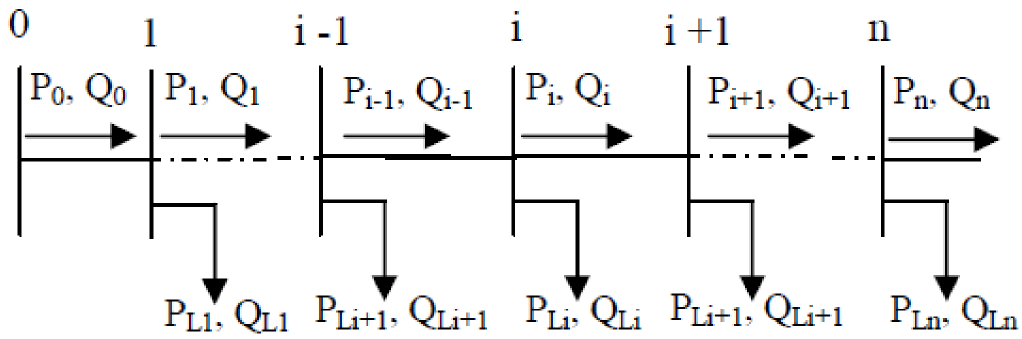


Figure 2.1: Line diagram of feeder points

The active loads and reactive loads were obtained in each point and power flow of throughout the line can be representing according to the above line diagram. The i^{th} point active power load and reactive power load were represented as P_{Li} and Q_{Li}. The active and reactive power at point i is represent as P_i and Q_i.

- Active Power at i+1 bus,

$$P_{i+1} = P_i - P_{Li+1} - R_{i,i+1} \cdot \frac{(P_i^2 + Q_i^2)}{|Vi|2}$$

- Reactive Power at i+1 bus,

$$Q_{i+1} = Q_i - Q_{Li+1} - X_{i,i+1} \cdot \frac{(P_i^2 + Q_i^2)}{|Vi|2}$$

- Line Loss between i^{th} and $i+1^{th}$ bus,

$$P_{Loss}(i, i+1) = R_{i,i+1} \cdot \frac{(P_i^2 + Q_i^2)}{|Vi|2}$$

Here the line resistance and line reactance between i^{th} and $i+1^{th}$ points were $R_{i,i+1}$ and $X_{i,i+1}$.

S (kVA) was denoted the installed solar inverter capacity, the operating power factor of the solar inverter Cosα need to fix according to the requirement of the reactive power at the particular location and the distribution line conditions (Minimum voltage, Power Loss, etc..).

Reduced distribution line loss between i^th^ and i+1^th^ points was denoted as,

$$P_{\text{Loss new}}(i, i+1) = R_{i,i+1} \cdot \frac{P_i^2 + (Q_i - S_i Sin\propto)^2}{|Vi\ new|2}$$

The current $I_{i,i+1}$ was represented as I_r and I_x where $I_r = I_{i,i+1}\,Cos\theta$, $I_x = I_{i,i+1}\,Sin\theta$ respectively (Cosθ is the power factor).

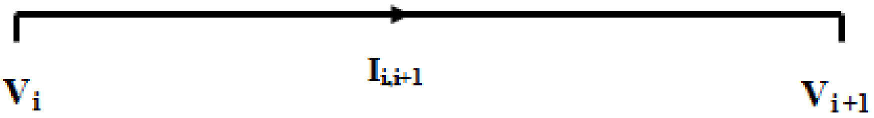


Figure 2.2: Current between two points

$$V_i = V_{i+1} + I_{i.i+1}(R_{i,i+1} + jX_{i,i+1})$$

$$V_i = V_{i+1} + (I_r - jI_x)(R_{i,i+1} + jX_{i,i+1})$$

$$V_i = V_{i+1} + I_r R_{i,i+1} + I_x X_{i,i+1}$$

$$V_i = V_{i+1} + I_{i,i+1} Cos\theta\, R_{i,i+1} + I_{i,i+1} Sin\theta\, X_{i,i+1}$$

Hence voltage drop between i^th^ and i+1^th^ point,

$$V_i - V_{i+1} = I_{i,i+1}(R_{i,i+1} Cos\theta + X_{i,i+1} Sin\theta)$$

Considering the scenario with feeding reactive power,

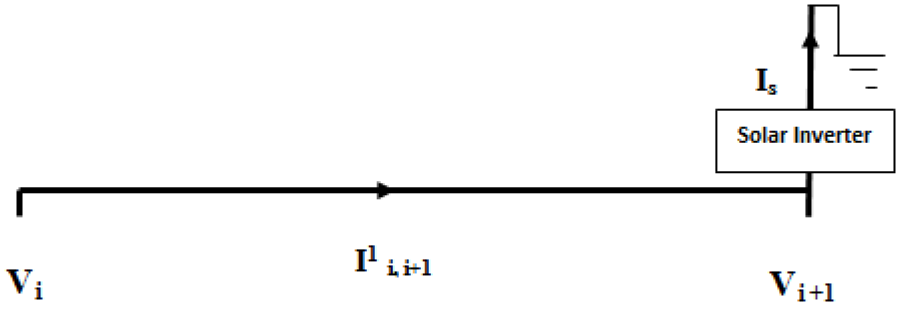


Figure 2.3: Current between two points with PV inverter

$$I^1_{i,\,i+1} = I_{i\,,i+1} + jI_s$$

Here I_s the current flow through the solar inverter,

$$I^1_{i,\,i+1} = I_r - jI_x + jI_s$$

Hence under above scenario voltage drop between i^{th} and $i+1^{th}$ point,

$$V_i - V_{i+1} = I^1_{\ i\,,i+1}\,(R_{i,i+1} + jX_{i,i+1})$$

$$V_i - V_{i+1} = I_r\,R_{i,i+1} + I_x\,X_{i,i+1} - I_s\,X_{i,i+1}$$

Before feeding of reactive power by solar inverter the representing voltage at $i+1^{th}$ point was,

$$V_{i+1} = V_i - I_r\,R_{i,i+1} - I_x\,X_{i,i+1}$$

After feeding of reactive power by solar inverter the representing voltage at $i+1^{th}$ point was,

$$V_{i+1} = V_i - I_r\,R_{i,i+1} - I_x\,X_{i,i+1} + I_s\,X_{i,i+1}$$

The voltage was improved and this improved voltage was maintained between the accepted standard tolerances margin is$\pm 6\%$.

The current I_s was adjusted within the allowed voltage tolerance margin. Due to the solar inverter capacity I_s was denoted as,

$Q = \frac{V \times I_s}{1000}$ here the Q was in kVAr which is feeding by the solar inverter.

$Q = S \sin \propto$ here the S was the apparent power of the solar inverter and the $\sin\alpha$ was operating power factor ($\cos \propto$) of the inverter which was set according to the requirement of voltage regulation.

2.2 Objective Function

The objective function was obtained as a sensitivity factor by considering the power loss function of a point. Line loss between ith and i+1th sections,

$$P_{Loss}(i, i+1) = R_{i,i+1} . \frac{(P_i^2 + Q_i^2)}{|Vi|2}$$

Sensitivity factor was defined as,

$$\frac{\partial P_{Loss}}{\partial Q_i} = \frac{2Q_i R_{i,i+1}}{{V_i}^2}$$

Sensitivity factor was to identify the locations where the power losses are high. This was defined as a function of reactive power since the concept is to feed reactive power by solar inverter and reduce line losses and maintain the system voltage within the margins.

2.3 General algorithm for VAR control with existing PV installations

The selected existing system (LV feeder) with PV installations, operational data considered as the inputs for the algorithm. The load data of each pole and the voltage profile on each pole were taken in to account for the model. Then by considering the data the locations were identified where the low voltage profiles were existing.

Existing installed solar inverter data such as the inverter capacity and specially the availability of the function of Q at night mode was collected.

The sensitivity factor was computed to each pole and the locations were identified where the power losses are high considering as a factor of reactive power.

According to the information of installed solar inverters the largest capacity of inverter was selected which was nearest location among the poles and which was having the highest loss.

The operating power factor of the inverter was set where it feeds required reactive power to eliminate low voltage issues and the voltage profiles of the poles were increased within the standards.

The voltage profiles were obtained again and the low voltage affected areas were selected and if issue was there then again the sensitivity factor for the selected feeder was computed with the modification and the next highest loss locations were identified.

Again next installed solar inverter was selected where having high capacity, nearest location among the poles which are having with highest losses and operation power factor was set as mention in above.

The function was repeated until, eliminate or reduce the low voltage problems of the selected feeder with existing solar installations.

2.4 Data Flow for the Study

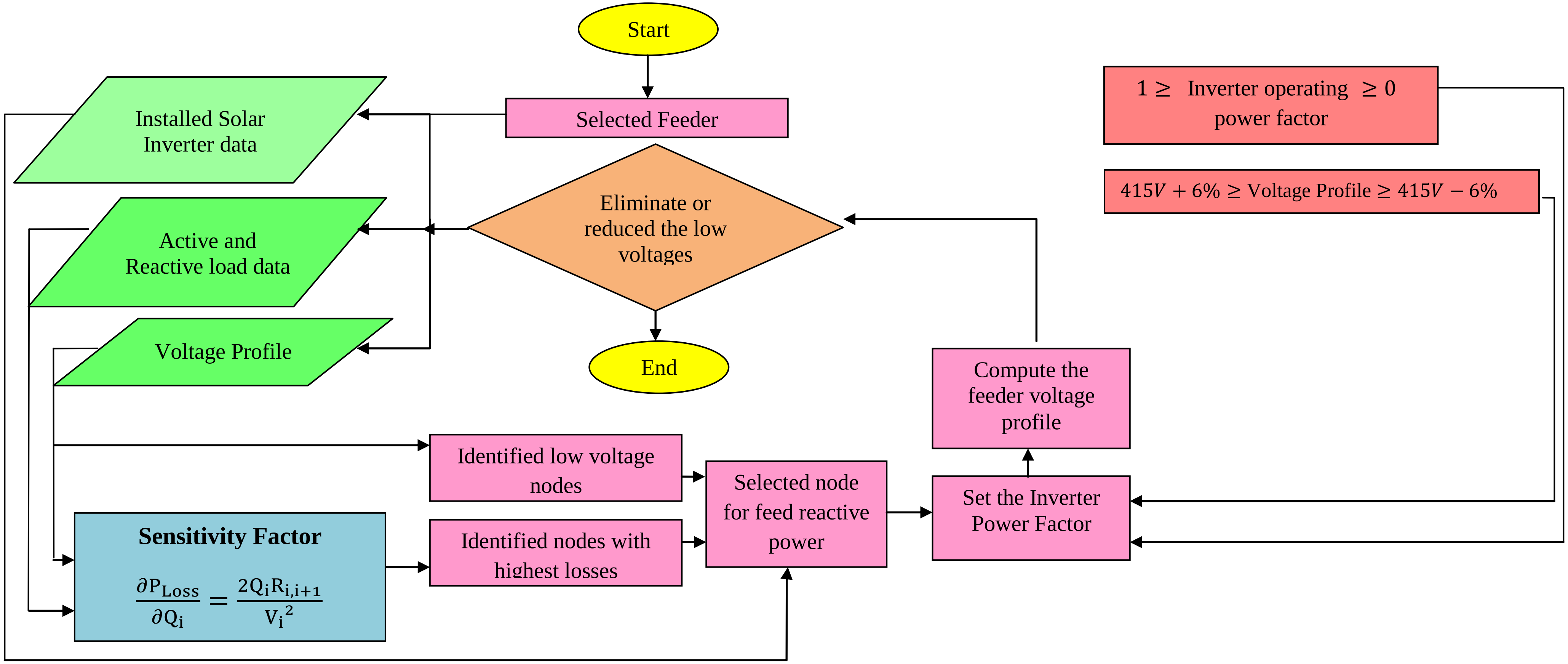


Figure 2.4: Data Flow for the Study

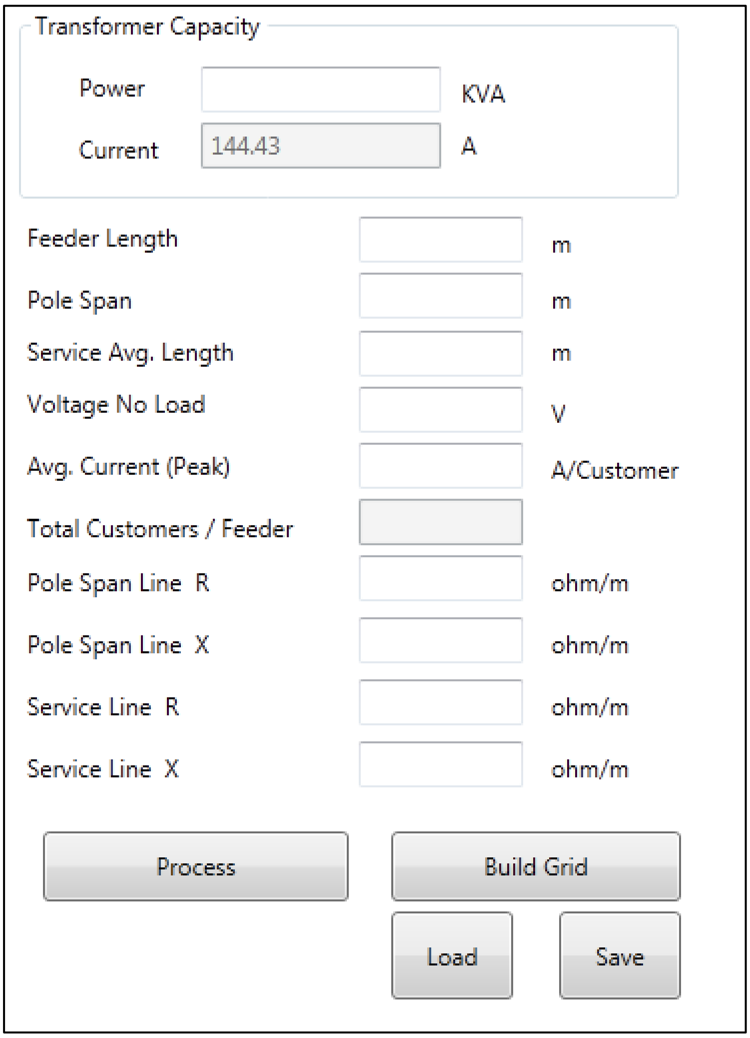
CHAPTER 3

IMPLEMENTATION OF THE ALGORITHM

The interface was designed for compute the algorithm shown in Figure 3.2.

3.1 Input Data to the Analyzer

The ratings of particular transformer and feeder have to input to the Analyzer was shown in Figure 3.1.



Transformer Capacity

Power KVA

Current 144.43 A

Feeder Length m

Pole Span m

Service Avg. Length m

Voltage No Load V

Avg. Current (Peak) A/Customer

Total Customers / Feeder

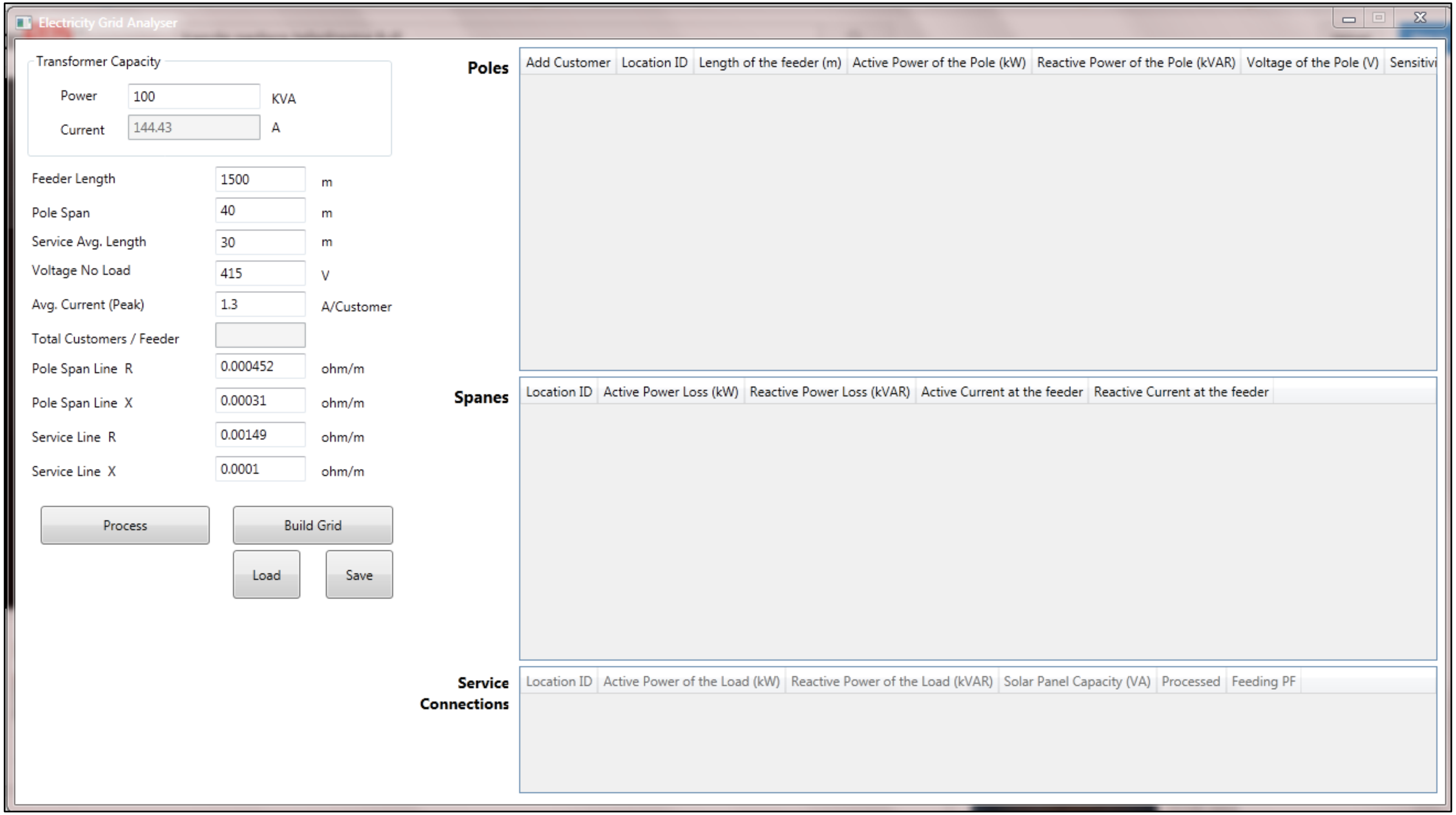
Pole Span Line R ohm/m

Pole Span Line X ohm/m

Service Line R ohm/m

Service Line X ohm/m

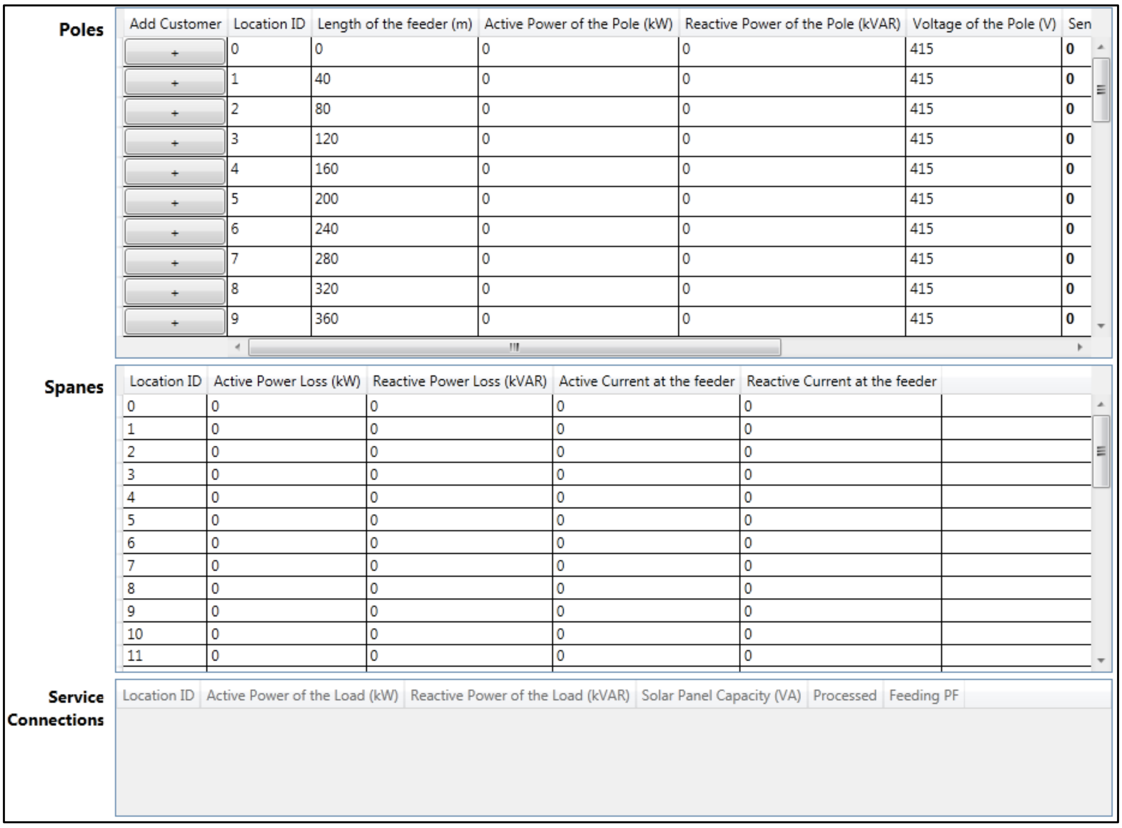
Figure 3.1: Parameter input interface



Power 100 KVA
Current 144.43 A
Feeder Length 1500 m
Pole Span 40 m
Service Avg. Length 30 m
Voltage No Load 415 V
Avg. Current (Peak) 1.3 A/Customer
Total Customers / Feeder
Pole Span Line R 0.000452 ohm/m
Pole Span Line X 0.00031 ohm/m
Service Line R 0.00149 ohm/m
Service Line X 0.0001 ohm/m

Figure 3.2: Electricity Grid Analyzer interface

After the input of system ratings by clicking “Build Grid” button and the feeder features were displayed on right side shown in Figure 3.3.



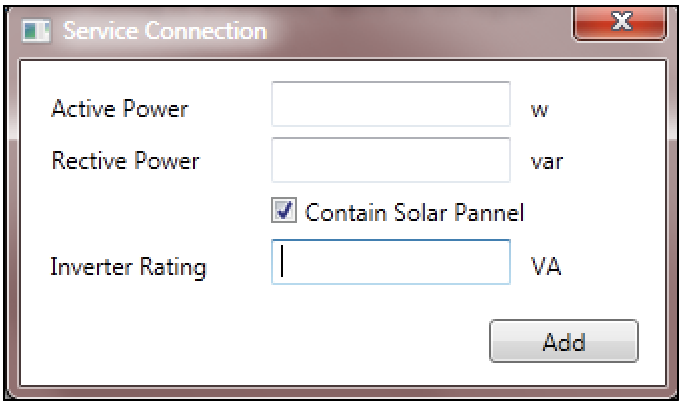
Add Customer	Location ID	Length of the feeder (m)	Active Power of the Pole (kW)	Reactive Power of the Pole (kVAR)	Voltage of the Pole (V)	Sen
+	0	0	0	0	415	0
+	1	40	0	0	415	0
+	2	80	0	0	415	0
+	3	120	0	0	415	0
+	4	160	0	0	415	0
+	5	200	0	0	415	0
+	6	240	0	0	415	0
+	7	280	0	0	415	0
+	8	320	0	0	415	0
+	9	360	0	0	415	0

Location ID	Active Power Loss (kW)	Reactive Power Loss (kVAR)	Active Current at the feeder	Reactive Current at the feeder
0	0	0	0	0
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
5	0	0	0	0
6	0	0	0	0
7	0	0	0	0
8	0	0	0	0
9	0	0	0	0
10	0	0	0	0
11	0	0	0	0

Location ID	Active Power of the Load (kW)	Reactive Power of the Load (kVAR)	Solar Panel Capacity (VA)	Processed	Feeding PF

Figure 3.3: Parameter input interface

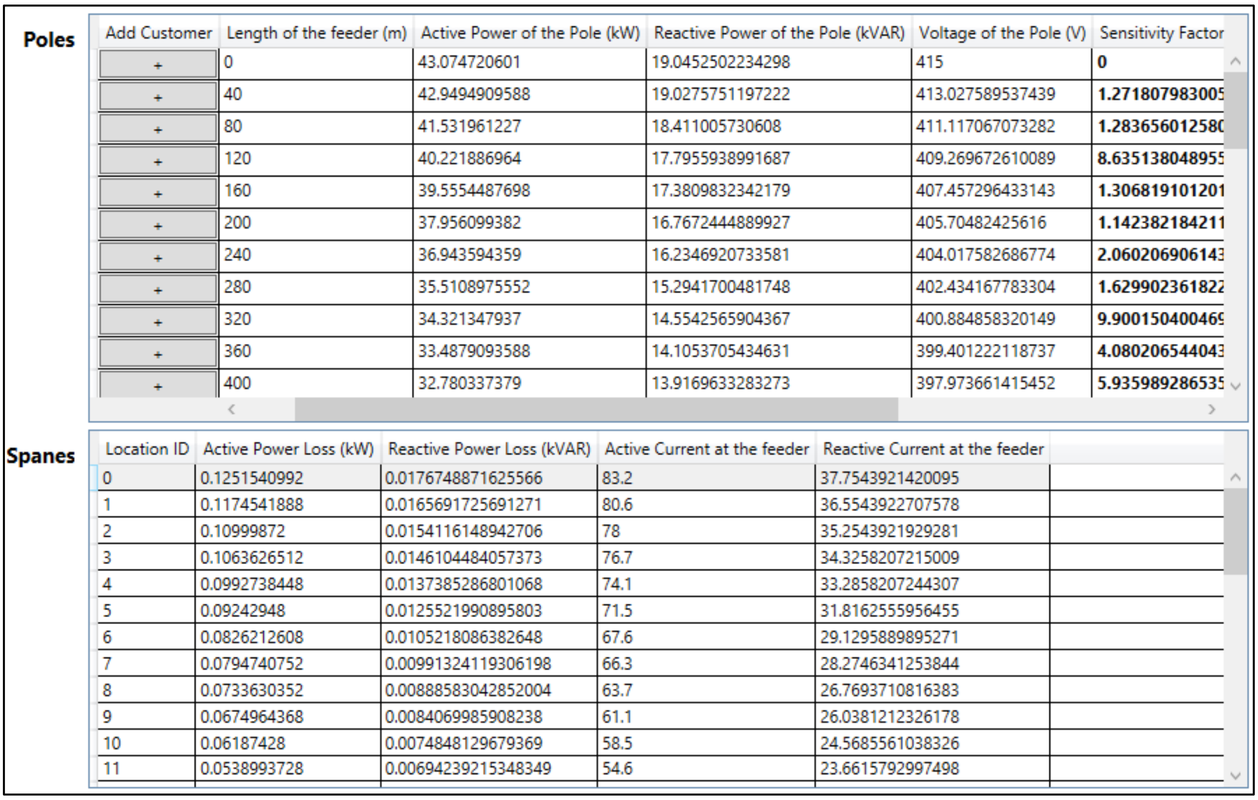
The no of customer loads on each pole was input by clicking Add Customer “+” button. Once press that the window shown in Figure 3.4 was appeared and the active, reactive loads of each customer and the inverter rating if available were input.



☑ Contain Solar Pannel

Figure 3.4: Service connection data input interface

After adding all the customer loads and PV inverter ratings, the current voltage profile, branch current and sensitivity factors were automatically computed.



Add Customer	Length of the feeder (m)	Active Power of the Pole (kW)	Reactive Power of the Pole (kVAR)	Voltage of the Pole (V)	Sensitivity Factor
+	0	43.074720601	19.0452502234298	415	**0**
+	40	42.9494909588	19.0275751197222	413.027589537439	**1.27180798300**
+	80	41.531961227	18.411005730608	411.117067073282	**1.28365601258**
+	120	40.221886964	17.7955938991687	409.269672610089	**8.63513804895**
+	160	39.5554487698	17.3809832342179	407.457296433143	**1.306819101201**
+	200	37.956099382	16.7672444889927	405.70482425616	**1.142382184211**
+	240	36.943594359	16.2346920733581	404.017582686774	**2.06020690614**
+	280	35.5108975552	15.2941700481748	402.434167783304	**1.62990236182**
+	320	34.321347937	14.5542565904367	400.884858320149	**9.90015040046**
+	360	33.4879093588	14.1053705434631	399.401222118737	**4.08020654404**
+	400	32.780337379	13.9169633283273	397.973661415452	**5.93598928653**

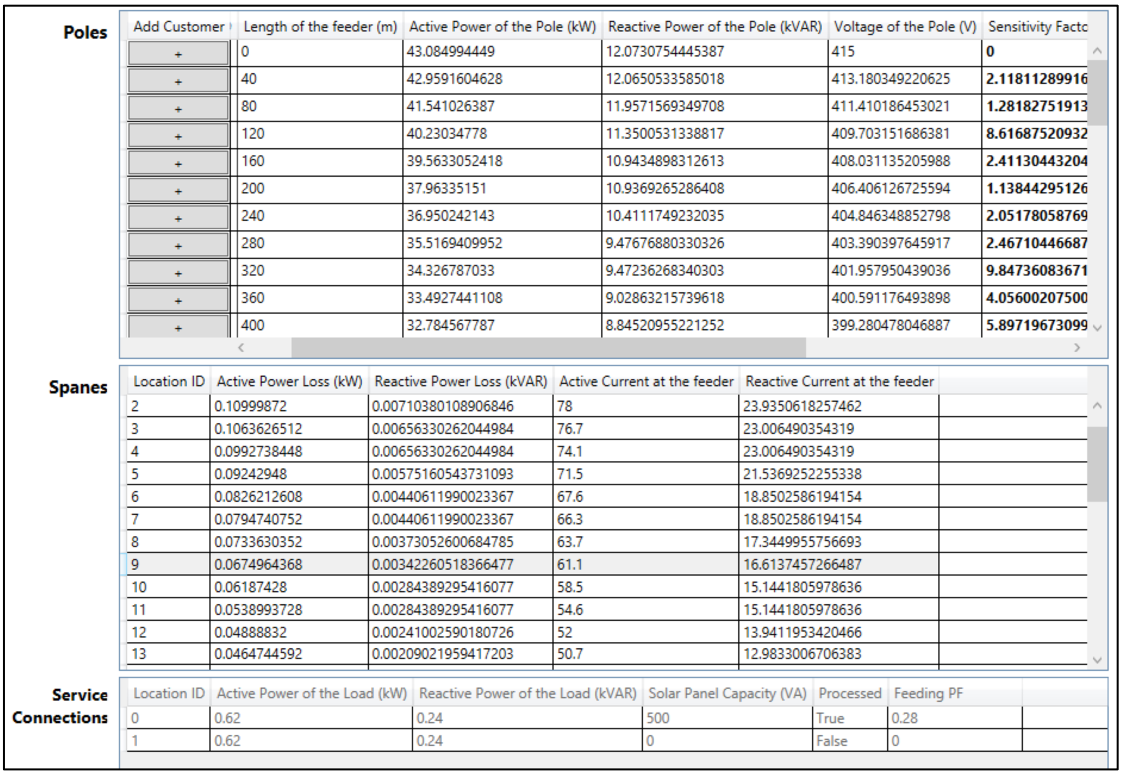
Location ID	Active Power Loss (kW)	Reactive Power Loss (kVAR)	Active Current at the feeder	Reactive Current at the feeder
0	0.1251540992	0.0176748871625566	83.2	37.7543921420095
1	0.1174541888	0.0165691725691271	80.6	36.5543922707578
2	0.10999872	0.0154116148942706	78	35.2543921929281
3	0.1063626512	0.0146104484057373	76.7	34.3258207215009
4	0.0992738448	0.0137385286801068	74.1	33.2858207244307
5	0.09242948	0.0125521990895803	71.5	31.8162555956455
6	0.0826212608	0.0105218086382648	67.6	29.1295889895271
7	0.0794740752	0.00991324119306198	66.3	28.2746341253844
8	0.0733630352	0.00888583042852004	63.7	26.7693710816383
9	0.0674964368	0.0084069985908238	61.1	26.0381212326178
10	0.06187428	0.0074848129679369	58.5	24.5685561038326
11	0.0538993728	0.00694239215348349	54.6	23.6615792997498

Figure 3.5: Entered data interface

By clicking “Process” button the algorithm was ran and after several iterations the optimum feasible solutions for operating power factors of inverters were decided.

3.2 Output Data from the Analyzer

Operating Power Factor of each inverter, voltage profile, branch current and power loss were obtained after processing the input data.



Poles

Add Customer	Length of the feeder (m)	Active Power of the Pole (kW)	Reactive Power of the Pole (kVAR)	Voltage of the Pole (V)	Sensitivity Facto
+	0	43.084994449	12.0730754445387	415	**0**
+	40	42.9591604628	12.0650533585018	413.180349220625	**2.11811289916**
+	80	41.541026387	11.9571569349708	411.410186453021	**1.28182751913**
+	120	40.23034778	11.3500531338817	409.703151686381	**8.61687520932**
+	160	39.5633052418	10.9434898312613	408.031135205988	**2.41130443204**
+	200	37.96335151	10.9369265286408	406.406126725594	**1.13844295126**
+	240	36.950242143	10.4111749232035	404.846348852798	**2.05178058769**
+	280	35.5169409952	9.47676880330326	403.390397645917	**2.46710446687**
+	320	34.326787033	9.47236268340303	401.957950439036	**9.84736083671**
+	360	33.4927441108	9.02863215739618	400.591176493898	**4.05600207500**
+	400	32.784567787	8.84520955221252	399.280478046887	**5.89719673099**

Spanes

Location ID	Active Power Loss (kW)	Reactive Power Loss (kVAR)	Active Current at the feeder	Reactive Current at the feeder
2	0.10999872	0.00710380108906846	78	23.9350618257462
3	0.1063626512	0.00656330262044984	76.7	23.006490354319
4	0.0992738448	0.00656330262044984	74.1	23.006490354319
5	0.09242948	0.00575160543731093	71.5	21.5369252255338
6	0.0826212608	0.00440611990023367	67.6	18.8502586194154
7	0.0794740752	0.00440611990023367	66.3	18.8502586194154
8	0.0733630352	0.00373052600684785	63.7	17.3449955756693
9	0.0674964368	0.00342260518366477	61.1	16.6137457266487
10	0.06187428	0.00284389295416077	58.5	15.1441805978636
11	0.0538993728	0.00284389295416077	54.6	15.1441805978636
12	0.04888832	0.00241002590180726	52	13.9411953420466
13	0.0464744592	0.00209021959417203	50.7	12.9833006706383

Service Connections

Location ID	Active Power of the Load (kW)	Reactive Power of the Load (kVAR)	Solar Panel Capacity (VA)	Processed	Feeding PF
0	0.62	0.24	500	True	0.28
1	0.62	0.24	0	False	0

Figure 3.6: Output data interface

Once select the pole (Location ID) the particular service connection loads connected to that pole with new computed results in the table Service Connections was shown in the Pole table.

CHAPTER 4

CASE STUDY

A sample model was created for case study considering the features shown in Table 4.1. Parameters of the sample feeder are shown in Table 4.2.

Table 4.1 System features

Transformer Capacity (kVA)	100
Feeder Length (m)	1500
Average Pole Span (m)	40
Fly Conductor Resistance (Ohm/m)	0.000452
Fly Conductor Reactance (Ohm/m)	0.000321
Average Service Wire Length (m)	30
25mm^2 ABC Service Wire Resistance (Ohm/m)	0.00149
25mm^2 ABC Service Wire Reactance (Ohm/m)	0.0001
Total Customers per Feeder (1 Phase)	64

Table 4.2 Parameters of the sample feeder

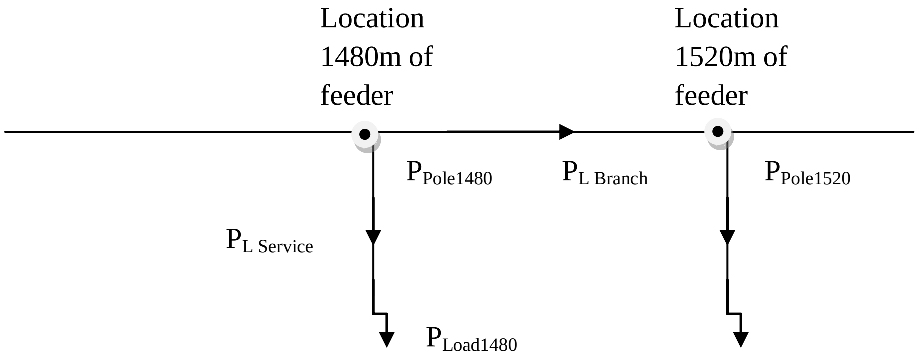
Length of the Feeder (m)	No of service connections connected to the pole	Installed inverter Capacity (kVA)	Active Power Load (kW)	Reactive Power Load (kVAr)
0				
40	2	0.5	1.20	0.60
80	2		1.30	0.60
120	1		0.56	0.40
160	2	1	1.50	0.60
200	2		0.92	0.51
240	3		1.36	0.94
280	1	2	1.11	0.73
320	2		0.75	0.44

360	2		0.64	0.18
400	2		0.45	0.25
440	3	3	1.28	0.30
480	2		1.33	0.61
520	1		0.95	0.70
560	1	0.5	0.64	0.37
600	2		1.20	0.50
640	3	1.5	1.37	0.14
680	1		0.94	0.27
720	3	0.5	2.20	1.20
760	2		1.06	0.52
800	1	2	1.12	0.60
840	2	0.5	1.23	0.47
880	1		0.86	0.70
920	1		0.81	0.50
960	2	2	1.80	0.62
1000	3		2.21	0.72
1040	2		1.25	0.76
1080	1	0.5	0.94	0.45
1120	2		1.68	0.49
1160	1		0.85	0.73
1200	1	1	1.20	0.35
1240	1		0.76	0.27
1280	2	3.5	0.91	0.50
1320	1		0.80	0.20
1360	1	0.5	0.61	0.37
1400	1	1	0.68	0.34
1440	2		0.80	0.26
1480	1		1.50	0.31
1520	1		0.75	0.30

4.1 Specimen Calculation

1. Active Power at a location

Considering the Feeder Length 1480m location,



$P_{Pole1480}$ – Active Power at the Location 1480m

$P_{Pole1520}$ - Active Power at the Location 1520m

$P_{L\ Branch}$ – Active Power Loss between Location 1480m and 1520m

$P_{L\ Service}$ – Active Power Loss of Service wire at the Location 1480m

$P_{Load1480}$ – Active Power Load at the Location 1480m

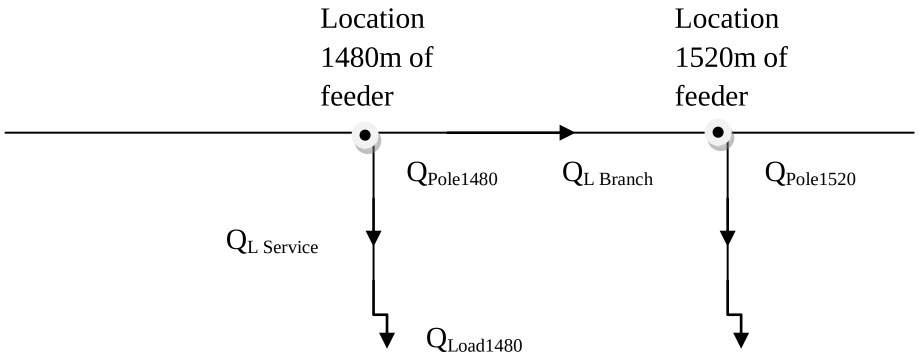
$$P_{Pole1480} = P_{Pole1520} + P_{L\ Branch} + P_{L\ Service} + P_{Load1480}$$

$$= 0.75008\text{kW} + (1.3\text{A}^2 \times 40\text{m} \times 0.000452\ \Omega/\text{m}) + (1.3\text{A}^2 \times 40\text{m} \times 0.000452\ \Omega/\text{m}) + (1.3\text{A}^2 \times 30\text{m} \times 0.00149\Omega/\text{m}) + 1.5\text{kW}$$

$$= 2.25\ \text{kW}$$

2. Reactive Power at a location

Considering the Feeder Length 1480m location,



$Q_{Pole1480}$ – Reactive Power at the Location 1480m

$Q_{Pole1520}$ - Reactive Power at the Location 1520m

$Q_{L\ Branch}$ – Reactive Power Loss between Location 1480m and 1520m

$Q_{L\ Service}$ – Reactive Power Loss of Service wire at the Location 1480m

$Q_{Load1480}$ – Reactive Power Load at the Location 1480m

$$Q_{L\ Branch} = (((1.3\text{A}/ (\text{Cos}\ (\text{Tan}^{-1}(0.3/0.75))))^2 - (1.3\text{A})^2) \times 40\text{m} \times 0.000309\ \Omega/\text{m})/1000$$

$$= 8 \times 10^{-6}\text{kVAr}$$

$Q_{L\ Service}$ $= (((1.3A/ (\mathrm{Cos}\ (\mathrm{Tan}^{-1}(0.31/1.5))))^2 - (1.3A)^2)\times 30m\times 0.000102\ \Omega/m)/1000$

$= 2\times 10^{-7}kVAr$

$Q_{Pole1480}$ $= Q_{Pole1520} + Q_{L\ Branch} + Q_{L\ Service} + Q_{Load1480}$

$=0.300001kVAr+0.000008kVAr+0.0000002kVAr +0.31kVAr$

$= 0.61kVAr$

3. Voltage at a location

Voltage was computed according to the equation,

$$V_{i+1} = V_i - I_r R_{i,i+1} - I_x X_{i,i+1} + I_s X_{i,i+1}$$

The calculated voltage at the location 1480m is 388.111V.

4. Sensitivity Factor

Sensitivity Factor was calculated at the 1480m location applying,

$$\frac{\partial P_{Loss}}{\partial Q_i} = \frac{2Q_i R_{i,i+1}}{{V_i}^2}$$

$$\frac{\partial P_{Loss}}{\partial Q_{1480}} = \frac{2Q_{1480}R_{1480,1520}}{{V_{1480}}^2}$$

$$= \frac{2\times 610.009^2\times 40\times 0.000452}{388.111^2}$$

$$= 0.09VAr\Omega V^{-2}$$

Active power, Reactive power, Pole Voltages and Sensitivity Factors at all the poles were calculated according to the above mentioned specimen.

Table 4.3 Output parameters of the feeder

Length of the Feeder (m)	Active Power at the Pole (kW)	Reactive Power at the Pole (kVAr)	Voltage at pole (V)
0	43.07	19.05	415.00
40	42.95	19.03	413.03
80	41.53	18.41	411.12

120	40.22	17.80	409.27
160	39.56	17.38	407.46
200	37.96	16.77	405.70
240	36.94	16.23	404.02
280	35.51	15.29	402.43
320	34.32	14.55	400.88
360	33.49	14.11	399.40
400	32.78	13.92	397.97
440	32.26	13.65	396.61
480	30.91	13.34	395.33
520	29.53	12.72	394.11
560	28.53	12.01	392.93
600	27.84	11.64	391.78
640	26.61	11.13	390.69
680	25.19	10.98	389.67
720	24.22	10.70	388.69
760	22.00	9.50	387.80
800	20.92	8.97	386.97
840	19.78	8.37	386.18
880	18.52	7.89	385.44
920	17.65	7.19	384.75
960	16.82	6.69	384.08
1000	15.01	6.06	383.47
1040	12.78	5.34	382.95
1080	11.51	4.58	382.50
1120	10.57	4.13	382.08
1160	8.88	3.63	381.71
1200	8.03	2.90	381.38
1240	6.83	2.55	381.08
1280	6.06	2.28	380.81
1320	5.14	1.78	380.61
1360	4.34	1.58	380.43
1400	3.73	1.21	380.28
1440	3.05	0.87	380.17
1480	2.25	0.61	380.11
1520	0.75	0.30	380.08

According to the algorithm in Figure 2.4 after calculating the sensitivity factor the highest power loss point among them and check the nearest available PV inverter for that particular point were selected and the lowers possible power factor without violating the voltage limitations was set. Then the feeding reactive power of the inverter was set and again the sensitivity factor for next highest power loss point was calculated and the iterations were done until the system can get the maximum reactive power from the available inverters under the voltage limits and without disturbing the stability of the system.

The final operating power factors, where to feed reactive power by minimize the low voltage problem on each installation are shown in the Table 4.4.

Table 4.4 Computed operating power factors

Length of the Feeder (m)	Installed inverter Capacity (kVA)	Final Operating Power Factor
40	0.5	0.00
160	1.0	0.80
280	2.0	0.93
440	3.0	0.99
560	0.5	0.67
640	1.5	0.99
720	0.5	0.00
800	2.0	0.95
840	0.5	0.28
960	2.0	0.95
1080	0.5	0.44
1200	1.0	0.94
1280	3.5	0.99
1360	0.5	0.67
1400	1.0	0.94

The results for voltage profiles are shown in the Table 4.5 and Figure 4.1.

Table 4.5 Computed voltage profiles

Length of the Feeder (m)	Voltage at pole (V)		Voltage increment %
	Before Feeding Reactive Power	After Feeding Reactive Power	
0	415.00	415.00	0.00%
40	413.03	413.18	0.04%
80	411.12	411.41	0.07%

120	409.27	409.70	0.11%
160	407.46	408.03	0.14%
200	405.70	406.41	0.17%
240	404.02	404.85	0.20%
280	402.43	403.39	0.24%
320	400.88	401.96	0.27%
360	399.40	400.59	0.30%
400	397.97	399.28	0.33%
440	396.61	398.04	0.36%
480	395.33	396.86	0.39%
520	394.11	395.75	0.41%
560	392.93	394.67	0.44%
600	391.78	393.62	0.47%
640	390.69	392.62	0.49%
680	389.67	391.70	0.52%
720	388.69	390.80	0.54%
760	387.80	389.99	0.56%
800	386.97	389.25	0.58%
840	386.18	388.53	0.60%
880	385.44	387.85	0.62%
920	384.75	387.21	0.64%
960	384.08	386.60	0.65%
1000	383.47	386.05	0.67%
1040	382.95	385.57	0.68%
1080	382.50	385.17	0.69%
1120	382.08	384.78	0.70%
1160	381.71	384.46	0.71%
1200	381.38	384.17	0.73%
1240	381.08	383.91	0.74%
1280	380.81	383.67	0.74%
1320	380.61	383.48	0.75%
1360	380.43	383.32	0.75%
1400	380.28	383.18	0.76%
1440	380.17	383.07	0.76%
1480	380.11	383.01	0.76%
1520	380.08	382.98	0.76%

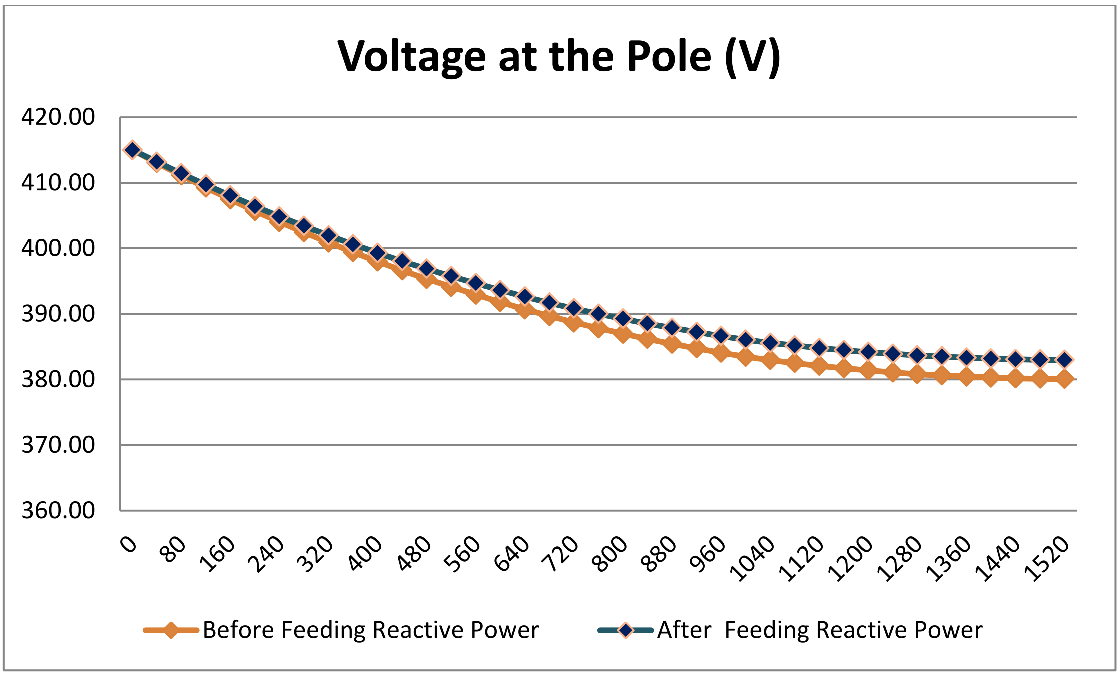


Figure 4.1: Graph of voltage profiles

According to the resultant voltage profiles it can be seen that when the absences of feeding reactive power low voltage profile was obtained starting from 640m of feeder length and downwards. Once the reactive power feeding was enabled the low voltage profile was started from 720m length of the feeder. The point of 640m and 680m feeder locations voltage were eliminated from low voltage issue. Considering the all locations the voltage was increased slightly.

The obtained results for reactive power variation of the feeder are shown in the Table 4.6 and Figure 4.2.

Table 4.6 Computed reactive power variation

Length of the Feeder (m)	Reactive Power at pole (kVAr)		Reactive Power Reduction %
	Before Feeding Reactive Power	After Feeding Reactive Power	
0	19.05	12.07	36.61%
40	19.03	12.07	36.59%
80	18.41	11.96	35.05%
120	17.80	11.35	36.22%
160	17.38	10.94	37.04%

200	16.77	10.94	34.77%
240	16.23	10.41	35.87%
280	15.29	9.48	38.04%
320	14.55	9.47	34.92%
360	14.11	9.03	35.99%
400	13.92	8.85	36.44%
440	13.65	8.58	37.12%
480	13.34	8.58	35.70%
520	12.72	7.96	37.43%
560	12.01	7.26	39.59%
600	11.64	7.25	37.66%
640	11.13	6.75	39.34%
680	10.98	6.75	38.51%
720	10.70	6.48	39.47%
760	9.50	5.78	39.18%
800	8.97	5.26	41.44%
840	8.37	5.25	37.24%
880	7.89	5.25	33.42%
920	7.19	4.55	36.66%
960	6.69	4.05	39.40%
1000	6.06	4.05	33.20%
1040	5.34	3.33	37.66%
1080	4.58	2.57	43.90%
1120	4.13	2.57	37.79%
1160	3.63	2.07	42.99%
1200	2.90	1.34	53.80%
1240	2.55	1.34	47.46%
1280	2.28	1.07	53.07%
1320	1.78	1.07	39.89%
1360	1.58	0.87	44.94%
1400	1.21	0.87	28.10%
1440	0.87	0.87	0.00%
1480	0.61	0.61	0.00%
1520	0.30	0.30	0.00%

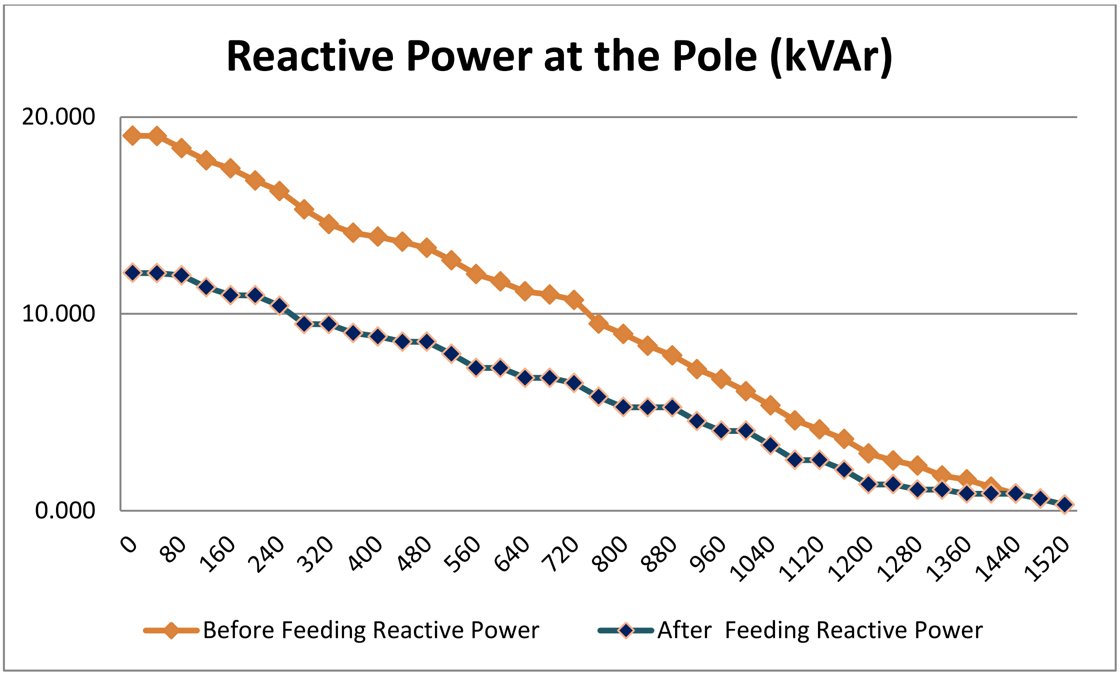


Figure 4.2: Graph of reactive power variation

According to the reactive power variation it can be seen that the 19.045 kVAr of the reactive power feeding from transformer was reduced and that balance was fed by the distributed solar PV inverters in the feeder.

The obtained results for total current variation of the feeder are shown in the Table 4.7 and Figure 4.3.

Table 4.7 Computed current variation

Length of the Feeder (m)	Branch Current (A)		Total Current Reduction %
	Before Feeding Reactive Power	After Feeding Reactive Power	
0-40	91.37	87.00	4.78%
40-80	88.50	84.46	4.57%
80-120	85.60	81.59	4.68%
120-160	84.03	80.08	4.71%
160-200	81.23	77.59	4.49%
200-240	78.26	74.67	4.58%
240-280	73.61	70.18	4.66%
280-320	72.08	68.93	4.37%
320-360	69.10	66.02	4.45%

360-400	66.42	63.32	4.67%
400-440	63.45	60.43	4.76%
440-480	59.51	56.66	4.78%
480-520	56.64	53.84	4.95%
520-560	55.07	52.34	4.97%
560-600	53.58	51.08	4.67%
600-640	50.76	48.29	4.88%
640-680	47.02	44.52	5.31%
680-720	45.68	43.17	5.50%
720-760	41.25	39.08	5.26%
760-800	38.35	36.24	5.52%
800-840	36.88	34.98	5.16%
840-880	34.10	32.47	4.76%
880-920	32.48	30.94	4.76%
920-960	30.97	29.48	4.83%
960-1000	28.23	26.96	4.49%
1000-1040	24.15	22.87	5.30%
1040-1080	21.14	19.97	5.53%
1080-1120	19.70	18.70	5.06%
1120-1160	17.00	16.00	5.93%
1160-1200	15.38	14.50	5.68%
1200-1240	14.03	13.22	5.74%
1240-1280	12.65	11.86	6.22%
1280-1320	9.71	9.31	4.17%
1320-1360	8.38	7.97	4.94%
1360-1400	6.89	6.70	2.72%
1400-1440	5.45	5.45	0.00%
1440-1480	2.72	2.72	0.00%
1480-1520	1.40	1.40	0.00%

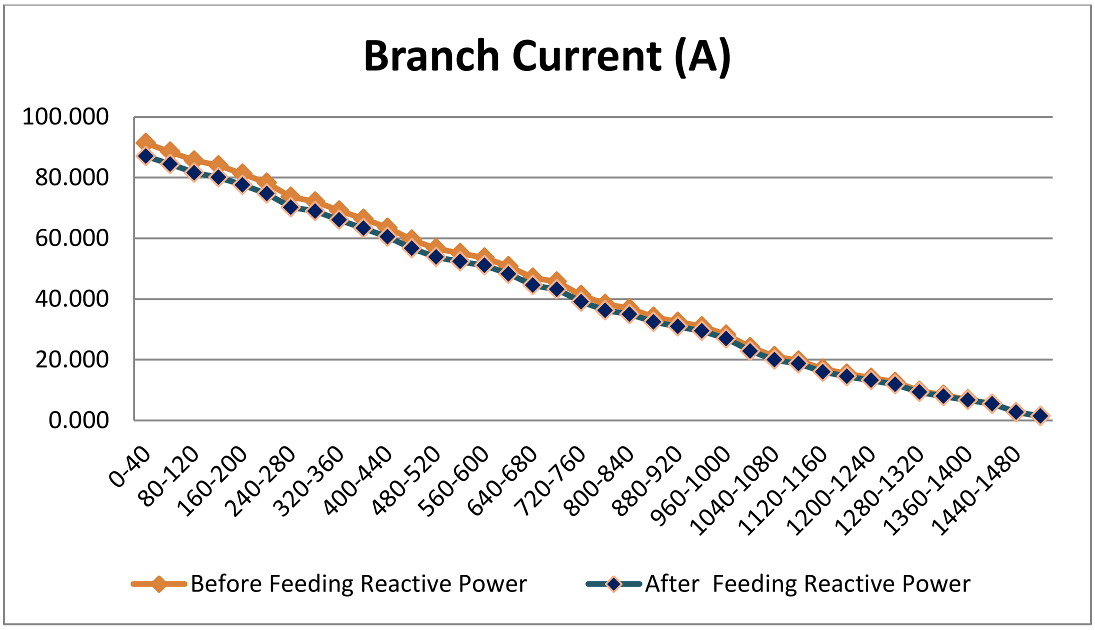


Figure 4.3: Graph of current variation

The obtained results for power loss variation of the feeder are shown in the Table 4.8 and Figure 4.4.

Table 4.8 Computed power loss variation

Length of the Feeder (m)	Power Loss (kW)	
	Before Feeding Reactive Power	After Feeding Reactive Power
0-40	0.167	0.151
40-80	0.157	0.143
80-120	0.147	0.133
120-160	0.141	0.128
160-200	0.132	0.120
200-240	0.122	0.112
240-280	0.108	0.099
280-320	0.104	0.095
320-360	0.095	0.087
360-400	0.088	0.080
400-440	0.081	0.073
440-480	0.071	0.064
480-520	0.064	0.058
520-560	0.061	0.055
560-600	0.057	0.052

600-640	0.052	0.047
640-680	0.044	0.040
680-720	0.042	0.037
720-760	0.034	0.031
760-800	0.029	0.026
800-840	0.027	0.024
840-880	0.023	0.021
880-920	0.021	0.019
920-960	0.019	0.017
960-1000	0.016	0.015
1000-1040	0.012	0.010
1040-1080	0.009	0.008
1080-1120	0.008	0.007
1120-1160	0.006	0.005
1160-1200	0.005	0.004
1200-1240	0.004	0.003
1240-1280	0.003	0.003
1280-1320	0.002	0.002
1320-1360	0.001	0.001
1360-1400	0.001	0.001
1400-1440	0.001	0.001
1440-1480	0.000	0.000
1480-1520	0.000	0.000

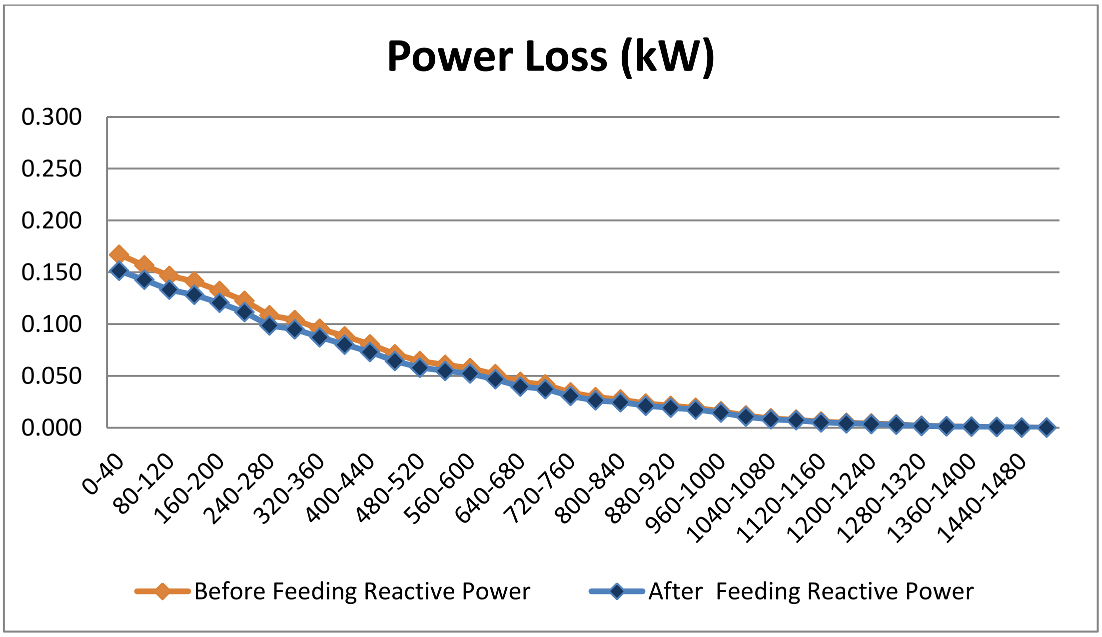


Figure 4.4: Graph of power loss variation

According to the case study total power loss of all the branches before feeding reactive power was 1.95kW and after feeding reactive power the total power loss was 1.77kW. Total reduction of power loss was 9.26%.

CHAPTER 5

MODEL VALIDATION

The Case Study results obtained by the developed algorithm were compared with the results obtained by the SynerGee 3.5 software for the same Case Study.

The feeder details at Table 4.1 and Table 4.2 have modeled in SynerGee is shown in Figure 5.1.

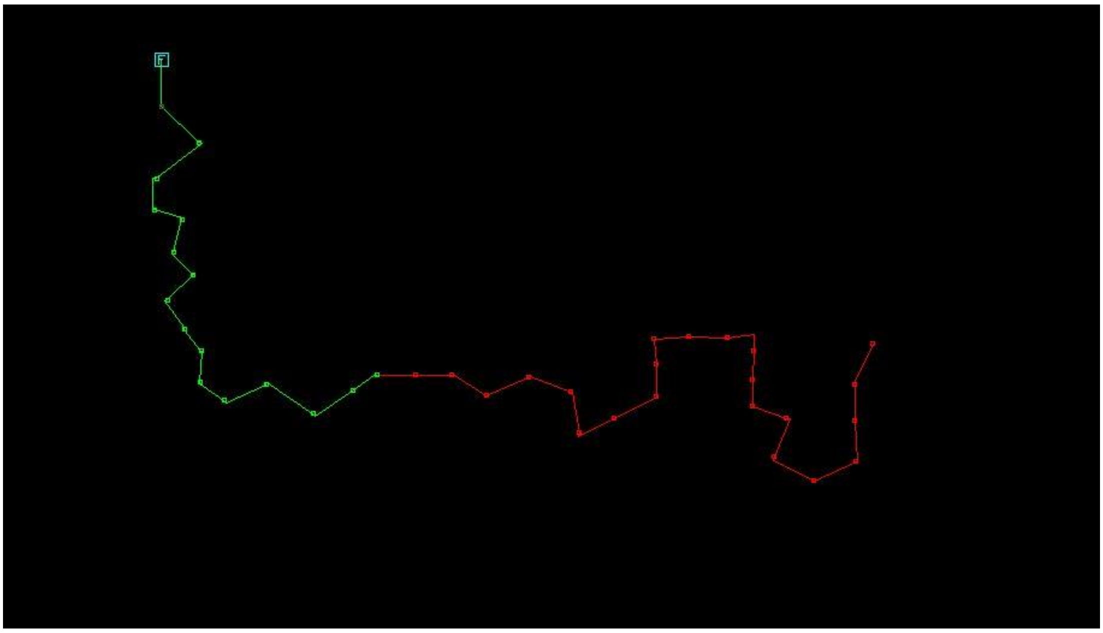
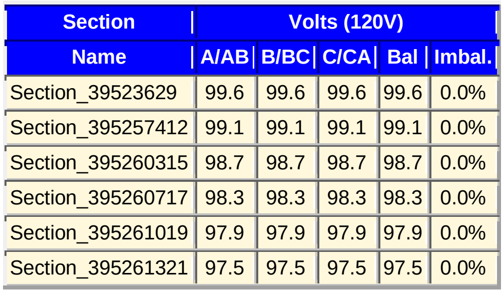


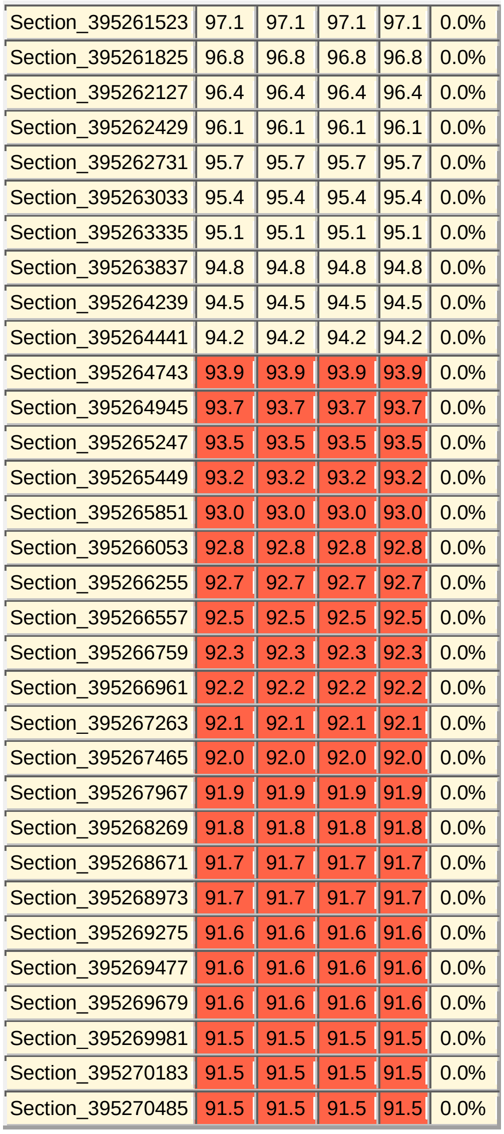
Figure 5.1: SynerGee model of case study feeder

According to the parameter of the feeder and the connected loads the low voltage scenario was shown after 640m of the feeder length.

Table 5.1: Results of model without PV inverter installation



Section	Volts (120V)				
Name	A/AB	B/BC	C/CA	Bal	Imbal.
Section_39523629	99.6	99.6	99.6	99.6	0.0%
Section_395257412	99.1	99.1	99.1	99.1	0.0%
Section_395260315	98.7	98.7	98.7	98.7	0.0%
Section_395260717	98.3	98.3	98.3	98.3	0.0%
Section_395261019	97.9	97.9	97.9	97.9	0.0%
Section_395261321	97.5	97.5	97.5	97.5	0.0%



Section_395261523	97.1	97.1	97.1	97.1	0.0%
Section_395261825	96.8	96.8	96.8	96.8	0.0%
Section_395262127	96.4	96.4	96.4	96.4	0.0%
Section_395262429	96.1	96.1	96.1	96.1	0.0%
Section_395262731	95.7	95.7	95.7	95.7	0.0%
Section_395263033	95.4	95.4	95.4	95.4	0.0%
Section_395263335	95.1	95.1	95.1	95.1	0.0%
Section_395263837	94.8	94.8	94.8	94.8	0.0%
Section_395264239	94.5	94.5	94.5	94.5	0.0%
Section_395264441	94.2	94.2	94.2	94.2	0.0%
Section_395264743	93.9	93.9	93.9	93.9	0.0%
Section_395264945	93.7	93.7	93.7	93.7	0.0%
Section_395265247	93.5	93.5	93.5	93.5	0.0%
Section_395265449	93.2	93.2	93.2	93.2	0.0%
Section_395265851	93.0	93.0	93.0	93.0	0.0%
Section_395266053	92.8	92.8	92.8	92.8	0.0%
Section_395266255	92.7	92.7	92.7	92.7	0.0%
Section_395266557	92.5	92.5	92.5	92.5	0.0%
Section_395266759	92.3	92.3	92.3	92.3	0.0%
Section_395266961	92.2	92.2	92.2	92.2	0.0%
Section_395267263	92.1	92.1	92.1	92.1	0.0%
Section_395267465	92.0	92.0	92.0	92.0	0.0%
Section_395267967	91.9	91.9	91.9	91.9	0.0%
Section_395268269	91.8	91.8	91.8	91.8	0.0%
Section_395268671	91.7	91.7	91.7	91.7	0.0%
Section_395268973	91.7	91.7	91.7	91.7	0.0%
Section_395269275	91.6	91.6	91.6	91.6	0.0%
Section_395269477	91.6	91.6	91.6	91.6	0.0%
Section_395269679	91.6	91.6	91.6	91.6	0.0%
Section_395269981	91.5	91.5	91.5	91.5	0.0%
Section_395270183	91.5	91.5	91.5	91.5	0.0%
Section_395270485	91.5	91.5	91.5	91.5	0.0%

The result obtained by the algorithm was used and the inverters were placed along the feeder with the operating power factors according to the Table 4.4 and the Figure 5.2 is shown the model that includes with PV inverter installations.

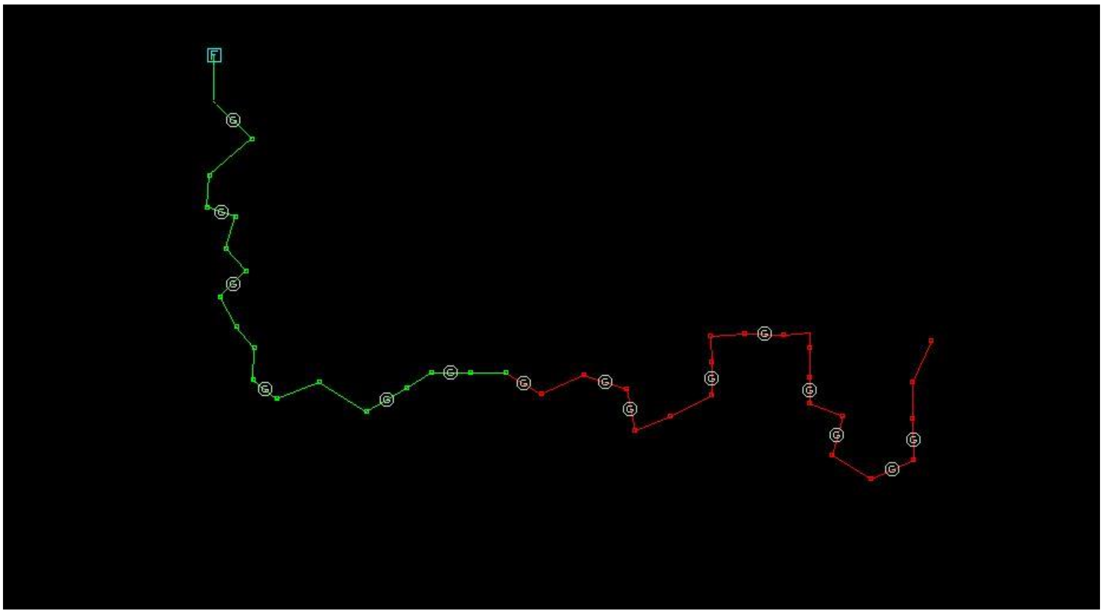
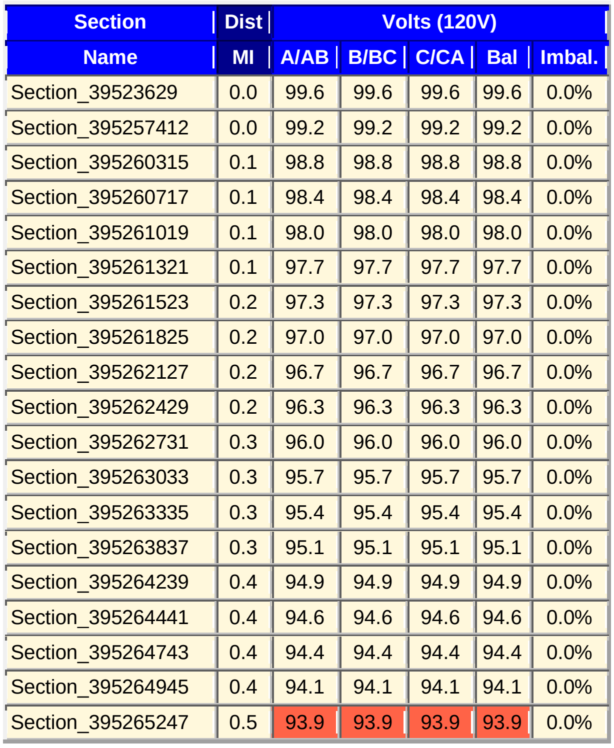


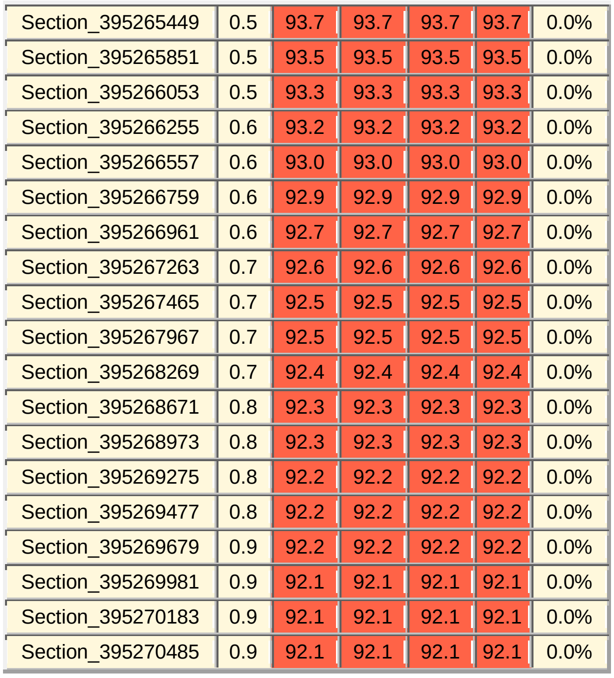
Figure 5.2: SynerGee model of case study feeder with PV inverter installations

After run the load flow analysis the low voltage issue was eliminated until 720m away length of the feeder which was obtained as the same result by the implemented algorithm.

Table 5.2: Results of model with PV inverter installation



Section	Dist	Volts (120V)				
Name	MI	A/AB	B/BC	C/CA	Bal	Imbal.
Section_39523629	0.0	99.6	99.6	99.6	99.6	0.0%
Section_395257412	0.0	99.2	99.2	99.2	99.2	0.0%
Section_395260315	0.1	98.8	98.8	98.8	98.8	0.0%
Section_395260717	0.1	98.4	98.4	98.4	98.4	0.0%
Section_395261019	0.1	98.0	98.0	98.0	98.0	0.0%
Section_395261321	0.1	97.7	97.7	97.7	97.7	0.0%
Section_395261523	0.2	97.3	97.3	97.3	97.3	0.0%
Section_395261825	0.2	97.0	97.0	97.0	97.0	0.0%
Section_395262127	0.2	96.7	96.7	96.7	96.7	0.0%
Section_395262429	0.2	96.3	96.3	96.3	96.3	0.0%
Section_395262731	0.3	96.0	96.0	96.0	96.0	0.0%
Section_395263033	0.3	95.7	95.7	95.7	95.7	0.0%
Section_395263335	0.3	95.4	95.4	95.4	95.4	0.0%
Section_395263837	0.3	95.1	95.1	95.1	95.1	0.0%
Section_395264239	0.4	94.9	94.9	94.9	94.9	0.0%
Section_395264441	0.4	94.6	94.6	94.6	94.6	0.0%
Section_395264743	0.4	94.4	94.4	94.4	94.4	0.0%
Section_395264945	0.4	94.1	94.1	94.1	94.1	0.0%
Section_395265247	0.5	93.9	93.9	93.9	93.9	0.0%



Section_395265449	0.5	93.7	93.7	93.7	93.7	0.0%
Section_395265851	0.5	93.5	93.5	93.5	93.5	0.0%
Section_395266053	0.5	93.3	93.3	93.3	93.3	0.0%
Section_395266255	0.6	93.2	93.2	93.2	93.2	0.0%
Section_395266557	0.6	93.0	93.0	93.0	93.0	0.0%
Section_395266759	0.6	92.9	92.9	92.9	92.9	0.0%
Section_395266961	0.6	92.7	92.7	92.7	92.7	0.0%
Section_395267263	0.7	92.6	92.6	92.6	92.6	0.0%
Section_395267465	0.7	92.5	92.5	92.5	92.5	0.0%
Section_395267967	0.7	92.5	92.5	92.5	92.5	0.0%
Section_395268269	0.7	92.4	92.4	92.4	92.4	0.0%
Section_395268671	0.8	92.3	92.3	92.3	92.3	0.0%
Section_395268973	0.8	92.3	92.3	92.3	92.3	0.0%
Section_395269275	0.8	92.2	92.2	92.2	92.2	0.0%
Section_395269477	0.8	92.2	92.2	92.2	92.2	0.0%
Section_395269679	0.9	92.2	92.2	92.2	92.2	0.0%
Section_395269981	0.9	92.1	92.1	92.1	92.1	0.0%
Section_395270183	0.9	92.1	92.1	92.1	92.1	0.0%
Section_395270485	0.9	92.1	92.1	92.1	92.1	0.0%

According to the results obtained from the algorithm and the SynerGee model the percentage of the voltage at each node is shown in the Table 5.3.

Table 5.3: Percentage of voltage at each node

Length of the Feeder (m)	Voltage at the Pole (%)	
	Algorithm Results	SynerGee model Results
0	100.00%	100.00%
40	99.56%	99.6%
80	99.13%	99.2%
120	98.72%	98.8%
160	98.32%	98.4%
200	97.93%	98.0%
240	97.55%	97.7%
280	97.20%	97.3%
320	96.86%	97.0%
360	96.53%	96.7%
400	96.21%	96.3%
440	95.91%	96.0%
480	95.63%	95.7%
520	95.36%	95.4%

560	95.10%	95.1%
600	94.85%	94.9%
640	94.61%	94.6%
680	94.39%	94.4%
720	94.17%	94.1%
760	93.97%	93.9%
800	93.79%	93.7%
840	93.62%	93.5%
880	93.46%	93.3%
920	93.30%	93.2%
960	93.16%	93.0%
1000	93.02%	92.9%
1040	92.91%	92.7%
1080	92.81%	92.6%
1120	92.72%	92.5%
1160	92.64%	92.5%
1200	92.57%	92.4%
1240	92.51%	92.3%
1280	92.45%	92.3%
1320	92.41%	92.2%
1360	92.37%	92.2%
1400	92.33%	92.2%
1440	92.31%	92.1%
1480	92.29%	92.1%
1520	92.28%	92.1%

Compare to the results from implemented algorithm and the SynerGee model the percentage of voltages with feeding reactive power obtained at the same nodes are almost same in both scenarios. Therefore the validity of proposed algorithm for reactive power feeding and its implemented software version was accepted.

CHAPTER 6

ECONOMIC EVALUATION

6.1 Energy Cost Saving due to Feeding Reactive Power

The economic evaluation was conducted considering the energy saving at selling end. The average cost per unit at selling end was taken as Rs 15.06. [6]

6.1.1 Loss reduction due to reactive power feeding by solar inverter [12]

Reduced distribution line loss between ith and i+1th points was denoted as,

$$P_{\text{Loss}}\ (i, i+1) = R_{i,i+1} I^2_{i,i+1}$$

The reduction of loss as a percentage,

$$\text{Reduced Loss \%} = 1 - \frac{\text{P Loss After Feeding Reactive Power (i,i+1)}}{\text{P Loss Before Feeding Reactive Power (i,i+1)}}\ 100\%$$

The cost saving due to the reduction of loss was represented considering the distribution system loss.

Saving of Cost (Per Year) = Saving of loss × Average cost per unit × Peak Hours × 365

Considering the Cast Study the saving of cost due to the reduction of loss was calculated,

Saving of Cost (Per Year) = 0.181kW×Rs 15.06 per kWh×4hr×365

= Rs 3979.76

6.1.2 Increased line capacity due to reactive power feeding by solar inverter [12]

The line current without compensation =91.365 A

The line current with compensation =87.001 A

The reduction in line current $=1- \frac{91.365}{87.001} 100\%$

$=4.78\%$

Considering the Cast Study the saving of cost due to the increased line capacity was calculated,

Saving of Cost (Per Year) = 0.0478 ×43.07kW×Rs 15.06 per kWh×4hr×365

= Rs 45266.88

6.1.3 Increased Maximum Transfer Capability [12]

$$P_{max} = \frac{V^2\ (-k+\sqrt{1+k^2})}{2X} \qquad \text{Where } k = Q/P$$

Considering the starting point of the feeder,

The maximum transfer capability without compensation $=\frac{V^2(-(\frac{19.045}{43.07})+\sqrt{1+(\frac{19.045}{43.07})^2})}{2X}$

$= 0.3256\ \frac{V2}{X}$

The maximum transfer capability with compensation $= \frac{V^2(-(\frac{12.073}{43.07})+\sqrt{1+(\frac{12.073}{43.07})^2})}{2X}$

$= 0.3791\ \frac{V2}{X}$

The increment in capability $= \frac{0.3791-0.3256}{0.3256} \times 100\%$

$=16.43\%$

Considering the Cast Study the saving of cost due to the increased line capacity was calculated,

Saving of Cost (Per Year) = 0.1643 ×43.07kW×Rs 15.06 per kWh×4hr×365

= Rs 155593.07

6.2 Tariff Methodology

6.2.1 Present Background

The benefits discussed in the Economic Analysis are rewarded to utility due to the feeding of reactive power to the system. Therefore a tariff method needs to be addressed to reward the same to the customer. Before proposing such tariff the tariff for reactive power consumption also needs to be introduced. Sri Lankan tariff system for Bulk Customers only includes charging the Maximum Demand Charge which was the only consent on reactive consumption only for a 15 minutes period. Actually the production cost related to the reactive power was calculated as the generation cost since the tariff system was cost reflective. The purpose for introducing Maximum Demand Charge was to encourage the customer for Demand Side Management and minimize the system voltage reduction and harmonics etc.

Considering the tariff systems in other countries there were several methods of charging for reactive power. Per kVAr rates in three blocks for reactive power were introduced Singapore and Spain. From April 2010, a common charging method was forced across all UK Electricity Supply Companies. The way the reactive power charge was calculated was; the customer was ‘allowed’ to use reactive power up to a third of the active power consumed for free, ‘allowed’ reactive power = 0.33 x total kWh. The charge was only applied by reducing the allowed reactive power from total consumed reactive power. In German distribution network operators charge in average 1.1 c€/kVArh (0.0-2.7 c€/kVArh) if the power factor was lower than 0.9 (in average). [13]

6.2.2 Proposal for Reactive Tariff in Sri Lanka

Proposing the reactive power tariff for Sri Lankan system it is need only to encourage the Demand Side Management. Therefore rate was defined bit higher than the cost of market price of per kVAr when installing the capacitor bank to improve the power factor. Then the customers were insisted to installed such system and improve the power quality rather than paying higher rate for each month.

Considering the Case Study results calculation was computed when a capacitor banks fixed at customer end. The assumptions were made in Table 6.1. [13]

Table 6.1: Assumptions made for economic analysis

Life time of the capacitor bank	5 years
Annual maintenance cost (% of capital cost)	2%
Cost of installing 1kVAr	Rs 3000
Rate of return on equity	20%

6.2.3 Specimen Calculation [13]

Considering the pole 40m away from the transformer required reactive power was 0.6 kVAr and assuming 1kVAr capacitor bank were installed operates at the peak time.

Total reactive energy required per year =0.6×4×365

= 876 kVArh

Total cost of installing reactive power required = 1×3000

= Rs 3000.00

Maintenance cost per year = 3000×0.02

= Rs 60.00

If the rate per kVArh was 'R'considering the annual cash flow,

Present value of benefits = Present value of total cost

$$R\times \sum_{x=1}^{5} \frac{876}{(1+0.2)^x} = 3000+ \sum_{x=1}^{5} \frac{60}{(1+0.2)^x}$$

R = Rs 1.830 per kVArh

Levelized cost for “Reactive Energy” by each pole for Case Study is shown in Table 6.2.

Table 6.2: Levelized cost for “Reactive Energy” by each pole

Length of the Feeder (m)	Reactive Power Load (kVAr)	Assumed Capacitor bank (kVAr)	Capital Cost (Rs)	Present Value of Maintenance Cost (Rs)	Present Value of Total kVArh per Year (kVArh)	Rate of per kVArh (Rs)
0						
40	0.6	1	3000	1794.37	2619.78	1.830
80	0.6	1	3000	1794.37	2619.78	1.830
120	0.4	0.5	1500	897.184	1746.52	1.373
160	0.6	1	3000	1794.37	2619.78	1.830
200	0.51	1	3000	1794.37	2226.81	2.153
240	0.94	1	3000	1794.37	4104.32	1.168
280	0.73	1	3000	1794.37	3187.39	1.504
320	0.44	0.5	1500	897.184	1921.17	1.248
360	0.18	0.5	1500	897.184	785.933	3.050
400	0.25	0.5	1500	897.184	1091.57	2.196
440	0.3	0.5	1500	897.184	1309.89	1.830
480	0.61	1	3000	1794.37	2663.44	1.800
520	0.7	1	3000	1794.37	3056.41	1.569
560	0.37	0.5	1500	897.184	1615.53	1.484
600	0.5	1	3000	1794.37	2183.15	2.196
640	0.14	0.5	1500	897.184	611.281	3.922
680	0.27	0.5	1500	897.184	1178.9	2.033
720	1.2	1	3000	1794.37	5239.55	0.915
760	0.52	1	3000	1794.37	2270.47	2.112
800	0.6	1	3000	1794.37	2619.78	1.830
840	0.47	0.5	1500	897.184	2052.16	1.168
880	0.7	1	3000	1794.37	3056.41	1.569
920	0.5	1	3000	1794.37	2183.15	2.196
960	0.62	1	3000	1794.37	2707.1	1.771
1000	0.72	1	3000	1794.37	3143.73	1.525
1040	0.76	1	3000	1794.37	3318.38	1.445
1080	0.45	0.5	1500	897.184	1964.83	1.220
1120	0.49	0.5	1500	897.184	2139.48	1.120

1160	0.73	1	3000	1794.37	3187.39	1.504
1200	0.35	0.5	1500	897.184	1528.2	1.569
1240	0.27	0.5	1500	897.184	1178.9	2.033
1280	0.5	1	3000	1794.37	2183.15	2.196
1320	0.2	0.5	1500	897.184	873.259	2.745
1360	0.37	0.5	1500	897.184	1615.53	1.484
1400	0.34	0.5	1500	897.184	1484.54	1.615
1440	0.26	0.5	1500	897.184	1135.24	2.112
1480	0.31	0.5	1500	897.184	1353.55	1.771
1520	0.3	0.5	1500	897.184	1309.89	1.830

The computed average cost per kVArh according to the case study was Rs 1.809, when installing capacitor bank in customer end. Therefore for encouraging customers to feed reactive power at the peak time by using installed solar PV inverters the reward was introduced by crediting Rs 2.00 per kVArh.

The reward could be given for the customers in case study is shown in the Table 6.3.

Table 6.3: Rewards paid back to customers

Length of the Feeder (m)	Installed inverter Capacity (kVA)	Final Operating Power Factor	Reward paid back to the customer (Rs)
40	0.5	0	1460
160	1	0.8	1752
280	2	0.931	2131.6
440	3	0.9949	876
560	0.5	0.6726	1080.4
640	1.5	0.9949	438
720	0.5	0	1460
800	2	0.9539	1752
840	0.5	0.28	1401.6
960	2	0.9507	1810.4

1080	0.5	0.4358	1314
1200	1	0.9367	1022
1280	3.5	0.9897	1461.46
1360	0.5	0.6726	1080.4
1400	1	0.9404	992.8

Cost benefit analysis was computed by use the case study results.

Total saving by reactive power feeding per year = 204839.71 Rs

Total rewards to the customers per year = 20032.66 Rs

Net saving to the utility per year = 184807.05 Rs

CHAPTER 7

DISCUSSION, CONCLUSION AND RECOMMENDATION

7.1 Discussion

The concept of feeding reactive power is a well-known solution to eliminate the low voltage issues occurred along the feeder. Installing capacitor banks are the most common method and that’s a separate cost added activity. The installation of capacitors can be done in both ways by the customer or by the utility. I have gone through many of the research papers and various proposals of analyzing the results of installing capacitor banks in either customer or utility sides.

With the rapid popularity of renewable energy concept in the world, Sri Lankan Government also has started to motivate to add more renewables to power system. Under that concept Government has invited the customers to install more solar power generation modules and feed active power to the utility. Considering electricity generation by solar power many of the researches have made with several proposals to increase the efficiency of the generation or methods of store generated energy. Due to the absence of solar power at night, the generating module is not 100% utilized for full day.

According to the load curve of the Sri Lanka the peak of the demand is occurred at night time where the solar power generation is totally equal to zero. Therefore the installed PV inverters can be used to feed reactive power by changing the power factor in which the efficiency of the solar generation module can be fully utilized. Several researches have been carried out regarding this concept but this is totally new to Sri Lanka.

Since the Sri Lanka has a small grid system mainly controlled under one utility and even the concept is benefited, it is needed to be controlled to avoid several adverse circumstances. This research thesis theoretically identifies the concept and to avoid the practical issues such as over voltages, proposes a theoretical algorithm which calculates “Optimum Operating power factor” for each PV inverter installation.

“Sensitivity Factor” was introduced to identify the critical locations where it is necessary to attend first, under the limitations of “over voltage”. The operating power factor for each PV inverter (which the customers who accepts to feed reactive power at night peak) needs to be decided by the utility according to the behavior of the particular power system.

“Rewarding Method” is also proposed to encourage the customers and to utilize their inverters at night.

This research thesis discussed the whole concept with the modification which is suitable for the Sri Lankan Power System.

7.2 Conclusion

According to the case study when selecting the optimal operating power factor for the existing installed PV inverters, conclusions can be finalized as follows.

1. Even with the small capacities of distributed PV inverters can be used to eliminate the low voltage for some extent. According to the case study it fixed the voltage around 80m of the feeder.
2. Since the concept is introduced for the night peak solar generation module is mostly utilized and the efficiency of the installation increased.
3. Due to the reduction of reactive power feeding from the transformer it has reduced the total line current and caused to reduce the power loss of the total system. According to the case study the reduction of power loss is 9.26%.
4. Even after the rewarding back to the customers the net saving due to the feeding reactive power using the installed PV inverters to the utility is positive and according to the case study it is nearly 185000 LKR per year.

7.3 Recommendations

As per the research, when promoting feeding reactive power with existing installed PV inverters following recommendations can be made.

1. The behavior of the feeder parameter values at the night peak needs to be analyzed such as voltage, power loss along the feeder before computing the

power factors. By analyzing the whole feeder under the limitations the operating power factor for each inverter has to be decided by the utility and to be informed to the customer.

2. Solar inverter manufactures have to manufacture their products with the provision of changing the power factor setting by the user and with the ability to program the setting on hourly basis.
3. General Public, including the customers who wish to connect solar power generation module, are need to be educated on selection of proper PV inverters which are capable of operating in reactive mode as well.
4. The rewarding method for reactive feeding by PV inverters needs to be introduced to customers in order to encourage them maintaining the stability of the system voltage.

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