

DETERMINING THE HOSTING CAPACITY OF SOLAR PHOTOVOLTAIC IN A RADIAL DISTRIBUTION NETWORK USING AN ANALYTICAL APPROACH

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Abstract— Integrating high Photovoltaic (PV) on distribution grid system has a positive impact by significantly reducing the losses and improving the voltage profile and also reduces the environmental pollution. However, integrating high proportions of PV in the distribution grid can bring the grid to its operational limits and result in power quality issues. The maximum PV capacity that can be integrated without incurring any grid impacts is referred to as the PV hosting capacity of the grid. This paper intends to evaluate the hosting capacity of solar PV in Dodhara-Chandani (DoC) distribution feeder as one of the feeder of Integrated Nepal Power System, considering grid parameters and operating condition in Nepal. Three main criteria were investigated for determining the hosting capacity of PV; reverse power flow, maximum voltage deviation of feeder and current carrying limit of conductor. The analysis has been performed by means of static load-flow simulation in Electrical Transient & Analysis Program and coding in MATLAB R2017a. This study showed that PV of rated capacity 687 kWp can be installed at a point of interconnection whereas an optimal placement of solar PV is found to be at 18th node (starting from the substation) considering minimum system losses. The minimum voltage profile at end of the feeder has improved by 8 % while the active power loss reduction of network is reduced by 83.6 % after the integration of solar PV. The results indicate voltage at different buses and the ampacity of most of the conductors have been improved after the integration of PV system into DoC feeder.

Key words—Penetration level, photovoltaic, Point of Interconnection, and hosting capacity.

I. INTRODUCTION

One of the technologies used to generate electricity in a renewable way is to use solar cells to convert the energy delivered by the solar irradiance into electricity. The progress in new technologies in the last few years has led to a significant decrease in the price of PV panels. Due to this, the large scale of solar PV is of raising interest both at national and global context. In 2005, the global installed capacity of solar PV was 5.1 GW, which had increased about 60 times by the year 2016 approximating the total global capacity to 303 GW of which 75 GW (up 48% over 2015) has been added last year only [11]. This accelerated growth of grid connected solar PV signifies the importance of grid connected solar PV system throughout the world. Moreover, the technical benefits include improvement of voltage, loss reduction, relieved transmission and distribution congestion, improved utility system reliability and power quality, increased the durability of the equipment and improved power quality [2]. However, solar PV systems integration in the distribution networks has led to some technical challenges such as reverse power flow and overvoltage as the power flows through the less resistible path. Moreover, the violation of the voltage profile may lead to the instability of the electric system [10], [15], all the distribution grid can host certain amount of solar PV without incurring any grid called as hosting capacity of that grid.

The hosting capacity of each network differs from one another and depends on various parameters of the feeder. The grid upgradation in terms of line conductor, line regulator needs to be done if the integration of solar PV beyond the hosting capacity is needed [14]. The intense of this research is to find the hosting capacity of a radial distribution network (RDN). Hosting capacity is correlated to optimal placement and sizing of solar PV while integrating into the grid and various methods have been proposed for it. The optimization technique in heuristic methods are the Genetic Algorithm which uses the strings instead of manipulating the objects themselves to get the results, but the principal challenge is coding of these objects into strings which may take a long time [7]. In [14] have suggested the smart method comprising of Binary Genetic Algorithm (BGA) and Bacteria Foraging Algorithm (BFA) for DG placement in the distribution network, their approach was the bridge by combining two different algorithms. In, [4], the authors used the metaheuristic method ABC for the optimal placement and sizing of DG for power loss reduction and improved voltage profile. The authors in [1] proposed a simple analytical method based on iterative search technique and Newton-Raphson method for the optimal sizing and allocation of DG in a network to lower the cost and loss effectively. The metaheuristic population-based algorithms are fast and required less storage, but they are probability based so their results cannot be guaranteed due to so many manipulations of parameters which they depend on the analytical equations. They used the analytical methods as benchmark methods.

II. BACKWARD AND FORWARD PROPAGATION METHOD

Load flow analysis in electric power system helps to determine the real and reactive power losses, the amount of current flowing through the lines, and the voltage magnitude and phase angle at different nodes. It is important in the planning of the new power installation and upgrading or extension of the existing power system, thus the results of the load flow is the starting point for other analyses of the electric power system [16]. Distribution system with large number of buses have high R/X ratio, thus decoupling assumptions are not valid. So, the conventional Newton Raphson and Fast Decouple methods fail to effectively evaluate the load flow analysis, thus the load flow analysis in the radial network can be done by using Backward and Forward Propagation Method (BFPM) which has proved to be very effective. It starts with some assumed voltages at each bus, except the source node. In the backward propagation, adds all the load currents and downstream branch currents (computed at the assumed voltages) to compute current in the upstream branch. Starting from the source node, in the forward propagation, it updates the bus voltages utilizing the branch currents computed in the backward propagation. Backward-forward propagation continues till voltages at all the buses converge within pre-specified tolerance. This method is based on computation of Bus-Injection to Branch-Current (BIBC) Matrix and Branch-Current to Bus-Voltage (BCBV) Matrix. The BIBC matrix is responsible for the variation between the bus current injection and branch current, and the BCBV matrix is responsible for the variation between the branch current and bus voltage [8].

III. METHODOLOGY APPROACH

3.1 Formulation of the objective function

The objective function of this study is to minimize the total branch loss as follows [12]:

$$\text{Minimize, } P_{TL} = \sum_{y=1}^N I_y^2 \times R_y \quad \text{Equation (1)}$$

Where, P_{TL} is total active power losses in the system, I_y is the current magnitude flowing from node y to node $y+1$, R_y is the resistance of branch y and N is the total number of branches.

The main objective function is subjected to inequality constraints which are tabulated below:

Table 1: Impact constraints and thresholds

Impact constraints	Defined thresholds
Bus voltage	$0.95 \text{ p.u.} \leq V \leq 1.05 \text{ p.u.}$
Feeder capacity limit	$ I_y \leq I_{y\max} $
Reverse power flow	Power reversal at the substation transformer

3.2 Optimization technique for the integration of solar PV into the grid

An analytical optimization technique called maximum active power loss saving of lines is used to find an optimal placement and sizing of solar PV into the grid, where it evaluates the current injected at each node and calculates the power losses saving when this current is injected at that node.

Consider a network of N branches, if solar PV is placed at node 'm' from the substation and β set branches are branches located between the source node and the node at which solar PV of injection current ' I_s ' is placed. The current flow in β branch set will be changed by the solar PV current injected while the current flowing in the rest of the network remains unaffected. The total active power loss in the system before solar PV integration in the network can be calculated using Equation (1). Furthermore, the total active power loss in the system with an integration of the solar PV at node 'm' in the radial distribution network is computed as follow:

$$(P_{TLPV})_m = \sum_{y=1}^m (I_y - I_s)^2 \times R_y + \sum_{y=m+1}^N I_y^2 \times R_y \quad \text{Equation (2)}$$

Now the active power saving at each node is calculated by subtracting the total power loss with solar PV from the total based loss without solar PV as shown below:

$$P_s = -2I_s \sum_{y=1}^m I_y \times R_y - I_s^2 \times \sum_{y=1}^m R_y \quad \text{Equation (3)}$$

The maximum value of power saving is found by equating to zero the derivative of the power saving with respect to its equivalent solar PV current injected at node m.

$$\begin{aligned} \frac{\partial P_s}{\partial I_s} &= -2 \sum_{y=1}^m I_y \times R_y - 2I_s \times \sum_{y=1}^m R_y = 0 \\ \Rightarrow I_s &= \frac{(-\sum_{y=1}^m I_y \times R_y)}{\sum_{y=1}^m R_y} \quad \text{Equation (4)} \end{aligned}$$

From Equation (5), the value of the current injected at each node can be evaluated respectively and these computed current values are replaced in Equation (3) for all the nodes, then the node with higher power saving is identified and selected as candidate for Solar PV placement. The optimal solar PV size at selected node m is calculated using the current injected at optimal branch and its corresponding voltage magnitude as:

$$(P_{spv})_m = \frac{-|V| \sum_{y=1}^m I_y \times R_y}{\sum_{y=1}^m R_y} \tag{Equation (5)}$$

Algorithm of maximum power loss saving technique

- Step1:** Read line and load data
- Step2:** Compute BIBC & BCBV Matrix
- Step3:** Set initial voltage (V) = 1 p.u.
- Step4:** Calculate the Branch current using backward propagation
- Step5:** Calculate the bus voltage using forward propagation
- Step6:** Check, Is $\Delta V(k) - \Delta V(k - 1)$ less than convergence criteria if not got to Step3 and repeat the whole procedure.
- Step7:** Calculate the lines losses using Equation (1).
- Step8:** Compute Solar PV Current injected using Equation (4) for each Node
- Step9:** Compute Loss Saving using Equation (3) & Select Maximum Saving as Siting Candidate
- Step10:** Compute an Optimal Size of Solar PV & its corresponding Power Loss
- Step11:** Compute new Load Flow with the Solar PV injected
- Step12:** Check, Is $\Delta V(k) - \Delta V(k - 1)$ less than convergence criteria if not go to Step9 and repeat the whole procedure
- Step13:** Print Minimum Loss and Bus No.at which Minimum Loss occurs and Solar PV Hosting Capacity

IV. GRID CONFIGURATION

The selected real network 'Dodhara-Chandani Feeder' is one of the feeder of Nepal where the end-user to this part of the grid is mainly commercial and domestic ones. This is an 11 kV distribution feeder with 44 number of buses, which receives power from 5 MVA, 33/11 kV power transformer situated at Dodhara-Chandani distribution substation. Load and line data of DoC feeder has been attached as Appendix-A.

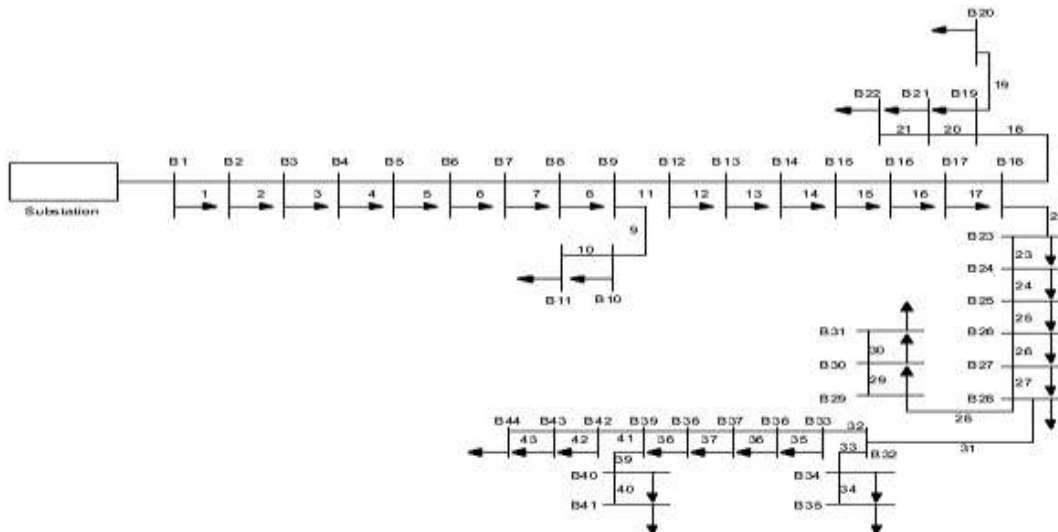


Figure 1: Single line diagram of DoC feeder

Load Profile

Among the four seasons, summer season has been used for this analysis because it has the highest load as shown in Figure 2. A minimum representative loading (899 kW) at 1 pm which is 65% loading to that of absolute load (1374 kW) at 8 pm is chosen as the PV integration time to grid because during this time voltage grid is already high so that the grid operation limit would not be incurred.

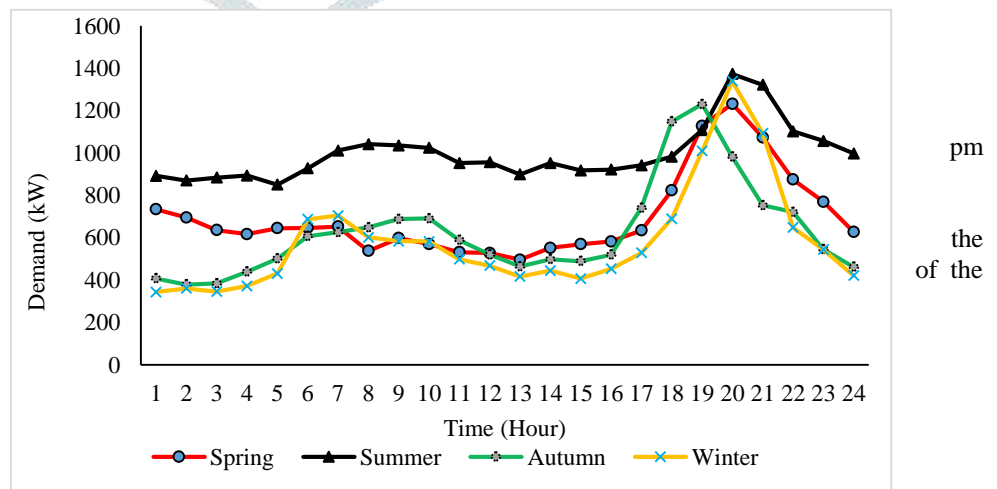


Figure 2 : Average daily demand of 2017/18 for various seasons of DoC feeder. (Source: Mahendranagar DCS, 2017/18)

V. RESULTS AND DISCUSSION

5.1 Grid Analysis without PV panels

Modelling of the existing proposed feeder in ETAP is done using grid parameters. The static load flow analysis of proposed feeder for summer season was performed considering both the cases, with and without PV. This analysis tests whether the steady state operating constraints are violated along with the penetration of solar PV at various interconnection during different study cases. The results analysis of single solar PV optimal placement and sizing were carried out with the help of MATLAB R2017a coding, and the comparisons were made with the existing methods. Based on these analysis, the hosting capacity of the Dodhara-Chandani RDN was determined. The initial load flow simulation without integration of solar photovoltaic was carried out under ETAP and the summary of the result is presented in Table 2.

Table 2: Base load flow result of Dodhara-Chandani feeder and tested system

Total load (kVA)	897+j395
Total active loss of line (kW)	73.28
Minimum voltage (p.u.)	0.9046 p.u.
Minimum voltage occurred at bus no.	44

5.2 Optimal placement and sizing of a solar PV

With an implication of maximum power saving analytical optimization approach an optimal placement and sizing of a solar PV into the grid is evaluated using MATLAB R2017a and is summarized in Table 3.

Table 3: Summary of optimal placement and sizing of SPV injected into the grid

Optimal siting (node no.)	18
Optimal size (kW)	687
Total active power loss of line (kW)	12.02
Minimum voltage occurred node number	43
Minimum voltage (p.u.)	0.977

An optimal size of solar PV thus obtained from MATLAB is simulated into ETAP again and results are obtained.

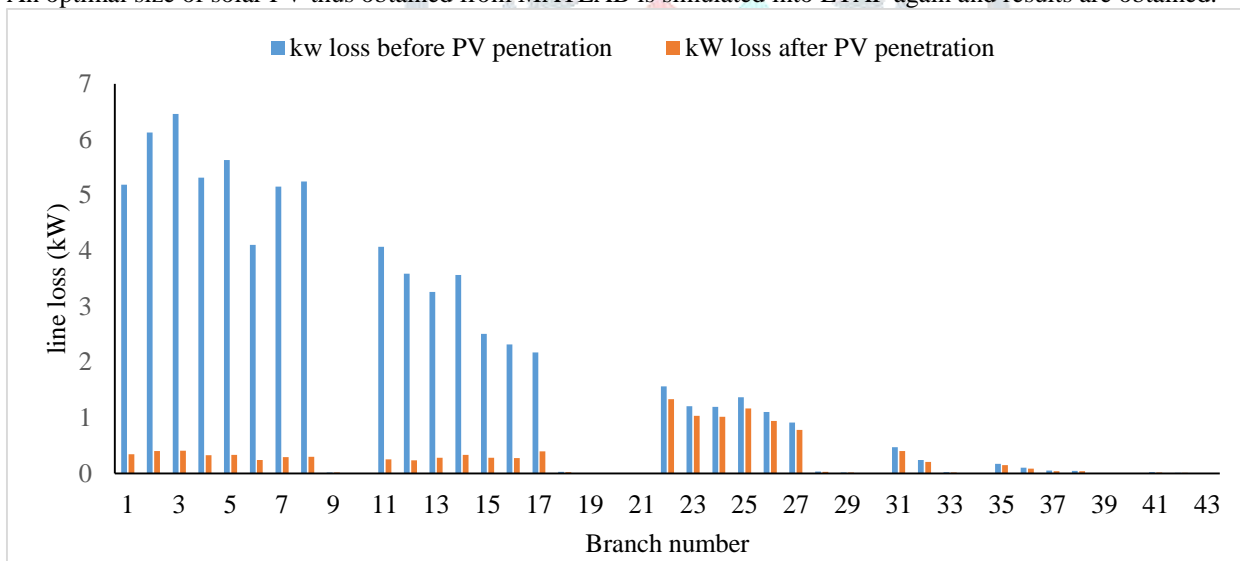


Figure 3: Comparison of kW losses of lines after PV penetrated into DoC feeder

The active power losses in the branches located between the source and the node at where the solar PV was placed have drastically reduced due to the injection of active power by PV. It is about six times lesser than the initial losses. However, beyond the optimal node, there was only a slight power loss reduction.

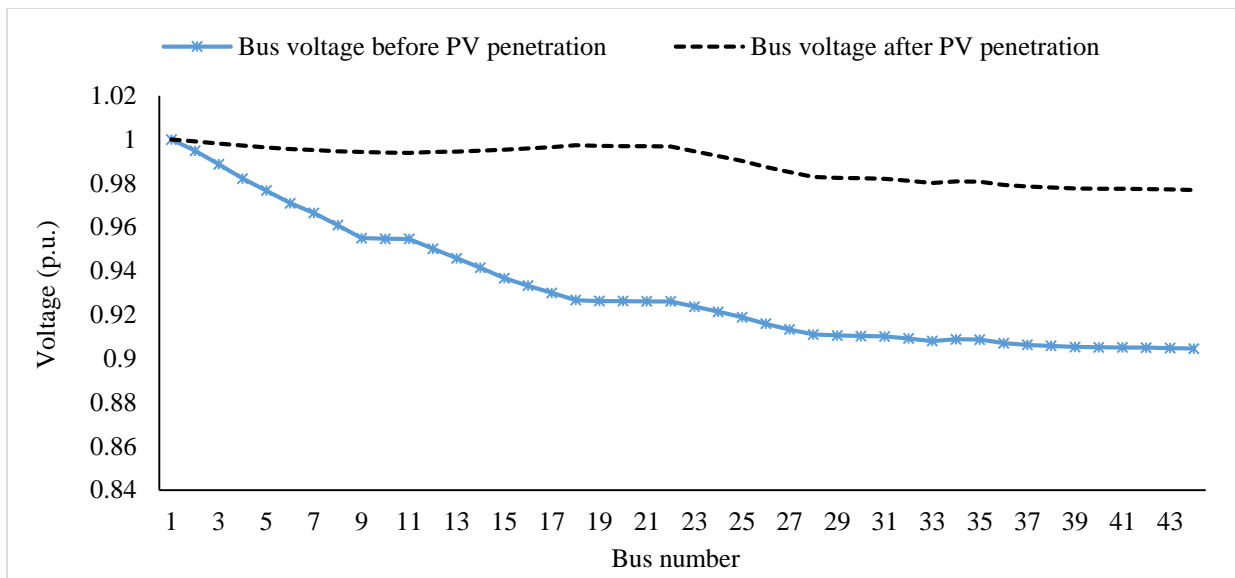


Figure 4: Comparison of bus voltage after PV penetrated into DoC feeder

An integration of solar PV has improved the whole network voltage profile and has reduced the overall current magnitude flowing in the network, thus the voltage drop across the distribution lines has been decreased. The minimum voltage profile at 43 node of DoC feeder, has improved by 8%, after an integration of solar PV into the grid.

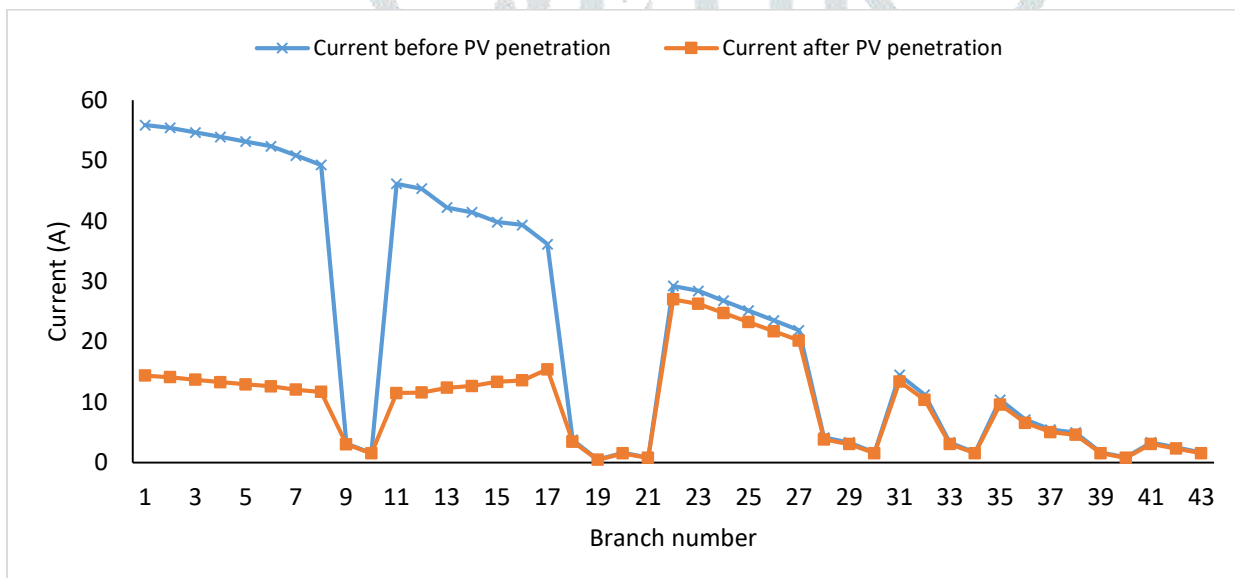


Figure 5: Comparison of line current when PV penetrated into DoC feeder

The solar PV integration has supplied the total or part of that particular zone load demand, hence reducing the current flow from the source to a load of a given location. The graph above showed that the ampacity of the line conductors (lines between substation and POI) is increased when solar PV is integrated into the grid.

The proposed method for determining the hosting capacity of Solar PV into the grid is tested into IEEE33-bus standard system [9] and is compared with existing methods where the proposed method is found satisfactory to others.

Table 4: Comparison of different methods for optimal placement and sizing of Solar PV into IEEE33bus-tested system

Method used	ABC [3]	Firefly [5]	IA [9]	Proposed method
Optimal bus no.	6	30	6	6
Optimal size (kWp)	2400	1190.4	2601	2474
Loss reduction (%)	48.20	48.74	47.39	47.8
Voltage profile at 18 node (p.u.)	0.964	0.9398	0.9425	0.9484

VI. CONCLUSION

Location and capacity of solar PV are the two important parameters for the computation of hosting capacity of solar PV in any system. An analytical optimization method based on the maximum power saving method was used for the single solar PV system placement and sizing. The analysis of the results showed that the solar PV must be placed in particular location in order to get minimum losses. So, hosting capacity of solar PV into the Dodhara-Chandani feeder with minimum loss is found to be 687 kWp at node 18. The integration of the solar PV in the system has reduced the active power loss by 83.6% for DoC feeder. The voltage

profile of weak bus has increased by 0.0724 p.u. Hence, the integration of solar system in the distribution system reduces the losses and improves the voltage profile and line loading capacity of the network.

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Appendix-A : Line and load data of DoC feeder

Br. No.	S.N.	R.N.	Load (R.N.)		Tr. kVA (R.N.)	R(Ω)	X (Ω)
			P _L (kW)	Q _L (kVAr)			
1	1	2	12	5	15	0.4539	0.1449
2	2	3	20	8	25	0.5446	0.1739
3	3	4	20	8	25	0.5900	0.1884
4	4	5	20	8	25	0.4992	0.1594
5	5	6	20	8	25	0.5446	0.1739
6	6	7	40	16	50	0.4085	0.1304
7	7	8	40	16	50	0.5446	0.1739
8	8	9	-	-	-	0.5900	0.1884
9	9	10	40	16	50	0.4765	0.1521
10	10	11	40	16	50	0.4992	0.1594
11	9	12	20	8	25	0.5219	0.1666
12	12	13	79	32	100	0.4765	0.1521
13	13	14	20	8	25	0.4992	0.1594
14	14	15	40	16	50	0.5673	0.1811

Br. No.	S.N.	R.N.	Load (R.N.)		Tr. kVA (R.N.)	R(Ω)	X (Ω)
			P _L (kW)	Q _L (kVAr)			
15	15	16	12	5	15	0.4312	0.1377
16	16	17	79	32	100	0.4085	0.1304
17	17	18	79	32	100	0.4539	0.1449
18	18	19	40	16	50	0.4765	0.1521
19	19	20	12	5	15	0.5446	0.1739
20	19	21	20	8	25	0.5219	0.1666
21	21	22	20	8	25	0.5446	0.1739
22	18	23	20	8	25	0.4992	0.1594
23	23	24	40	16	50	0.4085	0.1304
24	24	25	40	16	50	0.4539	0.1449
25	25	26	40	16	50	0.5900	0.1884
26	26	27	40	16	50	0.5446	0.1739
27	27	28	79	32	100	0.5219	0.1666
28	28	29	20	8	25	0.4765	0.1521
29	29	30	40	16	50	0.4312	0.1377
30	30	31	40	16	50	0.5446	0.1739
31	28	32	-	-	-	0.6127	0.1956
32	32	33	20	8	25	0.5219	0.1666
33	33	34	40	16	50	0.4992	0.1594
34	34	35	40	16	50	0.5446	0.1739
35	33	36	79	32	100	0.4312	0.1377
36	36	37	40	16	50	0.5446	0.1739
37	37	38	12	5	15	0.4312	0.1377
38	38	39	-	-	-	0.4629	0.1478
39	39	40	20	8	25	0.4765	0.1521
40	40	41	20	8	25	0.5219	0.1666
41	39	42	20	8	25	0.4992	0.1594
42	42	43	20	8	25	0.4765	0.1521
43	43	44	40	16	50	0.5446	0.1739

Note: Br. No.= Branch Number, S.N.= Sending Node, R.N.= Receiving Node,