Impact Analysis of Future Probabilistic Growth of Roof Top PV in Gulshan-e-Iqbal Feeder of LESCO

Raveena Kumari[a*], Kashif Imran[b], Arqam Ilyas[c], Farah-ul-Ain[d], Muhmmad Numan[e], Sohail Khan[f]

[a] *Department of Electrical Power Engineering, USPCAS-E, National University of Sciences and Technology, Islamabad 44000, Pakistan*
[b] *Department of Electrical Power Engineering, USPCAS-E, National University of Sciences and Technology, Islamabad 44000, Pakistan*
[c] *Department of Power Planning, Lahore Electric Supply Company (LESCO), Lahore 40050, Pakistan*
[d] *Department of Electrical Power Engineering, USPCAS-E, National University of Sciences and Technology, Islamabad 44000, Pakistan*
[e] *Department of Electrical Power Engineering, USPCAS-E, National University of Sciences and Technology, Islamabad 44000, Pakistan*
[f] *Sino-Pakistan Centre for Artificial Intelligence, Pak-Austria Fachhochschule: Institute of Applied Sciences and Technology, Haripur 22620, Pakistan*

Abstract

Increased intermittent PV penetration at the low voltage level of distribution system necessitates closer attention because it can potentially aggravate network's technical issues such as voltage violation, overloading of substation transformers, and line overloading. In this paper, placement of PV at multiple locations in distribution system was modelled using a probabilistic technique. Rather than adopting hit-and-trial method, this strategy has the advantage of providing a practical planning approach for assessing the implications of stochastic PV penetration in a distribution feeder. The research was carried out on 301-buses 11kV/ 0.41 kV MV/LV network model representing the Gulshan-e-Iqbal feeder of Lahore Electric Supply Company (LESCO) grid. The feeder's information was mapped in SynerGEE software, and analysis of network's parameters was performed by applying random number theory using PandaPower in Jupyter Notebook. The advantage of proposed approach was observed by using various combinations of PVs that can be connected to the feeder and the amount of injected active power that every node can handle. To study the impact of probabilistic penetration scenarios on performance parameters, including voltage profile and percentage loading, four different case studies were implemented and compared to the base case. The results verified the achievement of the strategy in identifying network sites with maximum voltage deviations, line overloading and transformer overloading. Finally, the overall hosting capacity of the feeder in all four cases was also determined.

Keywords: *Distributed PV Generation, PandaPower, LESCO, Line loading, voltage variation, Jupyter Notebook, SynerGEE*

1 INTRODUCTION

Every day, we rely on electricity, and depend on local electric companies to ensure that electricity is accessible whenever we need it. To produce more electricity, electric companies use a varied mix of energy resources. The potential development of globally installed technology is the primary reason for boosting sustainable energy worldwide; this is particularly true in distributed generation Photovoltaic (DG-PV) which has expanded dramatically and has numerous positive implications on the distribution system [1].

In Pakistan, NEPRA has set a goal of increasing the installed distributed power of renewable sources up to 1MW per feeder [2]–[4]. Due to the rising trend of net-metering [5], Lahore Electric Supply Company (LESCO) has added up to 70 MW of electricity via solar power net-metering connections [2], [6]. In 2021 National Electric Power Regulatory Authority (NEPRA) approved a license, allowing Additional 30 MW to be connected via net-metering with in few months [7]. LESCO's peak-day demand (summer) is between 4,000 and 4,500 MW. Due to the extreme heat, it reached the current summer's maximum peak of 4,300 MW just a few months ago. The company's demand drops to between 2,000 and 2,500MW on average throughout the winter [8]–[10].

Incorporating a significant quantity of sporadic DG-PV can eventually result in numerous operational challenges, such

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Corresponding author. Raveena Kumari, Tel.:NA
E-mail address: Muskanlohana118@gmail.com

as voltage profile violation and line loading compliance [11]. However, by integrating PV in the best feasible place, the problem can be rectified, which could reduce line losses and improve grid stability [12]. In addition to the conventional approaches, such as analytical methods [13] and planning techniques [14], the Artificial Intelligence optimization methodologies are also employed for planning and modeling DG-PV [15]. One of the parameters evaluated in assessing the dependability and the efficiency of a power grid's operation is the hosting capacity [16]. The author of [17] computed voltage characteristics to evaluate the impact of the various penetration scenarios.

As stated in the above-mentioned literature, an extensive research has been conducted to determine the optimal location and suitable active power for PV in the distribution systems. The vast varieties of these approaches use deterministic PV models. This research proposes a probabilistic planning approach to highlight the nodes having weak hosting capacity after the placement of 1MW DG-PV into the feeder. Nodes or bus exceeding the voltage and thermal limits are not supposed to host PV units and are regarded as feeder`s sensitive spots. This paper is focused on four scenarios in which different PV values are evaluated and compared in order to detect weak nodes in Gulshan-e- Iqbal feeder.

This paper is divided into four sections. Section I provides a brief overview of the significance of this work. The feeder model is discussed in section 2 and methodology for the case studies is detailed in Section 3. In Section 4, the results of several scenarios are discussed. Finally, in section 5, this case study is concluded with some observations.

2 FEEDER MODELING

Gulshan-e-Iqbal's real MV/LV network has been chosen for this research work. The designated electric network feeder is operated by the Lahore Electric Supply Company (LESCO). The research was carried out on one of the 17 outgoing feeders of 132KV Allama Iqbal Town grid station. This radial grid structure represents 11KV feeder that is connected to 132KV grid via 40 MVA power transformers [18].

The data obtained from SynerGEE Electric software, was in raw format, which was inaccessible and imprecise for the research. As a result, we decided to study this feeder using OpenDSS software, where all the information of the feeder was configured. After a lot of data analysis, the research led us to choose JetBrains PyCharm, which has an OpenDSS conversion directory. The data from .mdb files to .dss files were successfully converted using GitHub's ditto conversion. Despite the fact that the data was converted correctly, SynerGEE's load flow findings were unable to match the OpenDSS results for some unknown reason. This prompted us to request an API license for SynerGEE software from LESCO, where the solver was installed in SynerGEE to run the Python editor. SynerGEE had a built-in Python Win editor, but it was an old version that made installing new packages and getting it to work nearly impossible. As a result, we used PandaPower software [19], an open-source python application in Jupyter Notebook to code all of the data mapped in SynerGEE and model the entire feeder network.

In this research, two primary software are used to model the Gulshan-e-Iqbal distribution feeder:

- SynerGEE Electric
- PandaPower

2.1. SynerGEE Electric

SynerGEE Electric is the software that Lahore Electric Supply Company (LESCO) uses to map and analyse the distribution feeder using Geographic Information System (GIS) technique [20], SynerGEE was used in our study to extract the information about network topology, technical parameters of lines, transformers, and loads from LESCO's October 2015 Annual plan. The data was shared by LESCO planning department in access format for Research purpose. In this paper, SynerGEE is used to map all observable information about the Gulshan-e-Iqbal feeder.

After the circuit has been mapped, the power flow is analysed, resulting in a tabular output that evaluates feeder's data summary, load summary and loss data summary. Some of the problematic parameters were estimated from the available data in order to develop an accurate network model of the Gulshan-e-Iqbal feeder.

- **Line Parameters**: Each line has a specific geometry, according to Pakistani standards Osprey, Dog, Panther, and Rabbit, are the most popular conductors used by LESCO at the 11 kV feeders. The bulk of low-tension conductors, are Ant conductors. All 240 lines are modeled based on their type, physical characteristics, conductor size, and physical layout. Low voltage electrical distribution lines have a series connection of R and X, therefore all of the line parameters were estimated using the original length of each line, which was given in R/km and X/km.

- **Short Circuit Current:** The short-circuit currents are calculated with the equivalent voltage source at the fault location. The calculation is based on the method of the equivalent voltage source according to IEC EN 60909.
- **Short Circuit Voltage:** During short circuit test, short link is connected to secondary winding and a reduced voltage is applied to primary side. Vsc typically 2-12% of rated voltage in Pakistan we take Vsc as 5%.

2.2. PandaPower

PandaPower is a Python lexicon that holds all network information and is an open source tool in Jupyter Notebook. PandaPower uses python package "pandas" to provide a tabular data structure which includes an element and a result table. The result table stores the outputs of power flow or optimal power flow functions, whereas the element database stores all user-specified input parameters.

In this paper, we used the built-in Python package of PandaPower to manually configure the network model. As this tool does not have graphical user interface, so each network element were manually entered using the Python programming language. We wanted to create an exact Gulshan-e-Iqbal feeder network; therefore we started with an empty network called Gushan-e-Iqbal.net. The feeder supports total of 301 buses with a rated voltage of 11kV/0.412kV, which serves as a baseline for per-unit system modelling. To establish a comprehensive network, 60 transformers, 240 lines, and 60 loads were modelled. A ZIP model is included in this network, which allows simulating loads with a constant current of 10% and a constant impedance of 40%. A power load of 50% of the distribution transformer's rated power is used to model loads. Once the network topology and technical parameters are calculated and configured, an external grid element represents a source voltage with a magnitude of 1.02pu and a voltage angle of 50 degrees is also used.

Various scenarios have been used to test the system's behavior and capabilities in carrying the highest amount of PV. The strategy to be discussed in section 3 involves selecting a random location for PV installation based on their specific capacity, and then monitoring the system's voltage and loading constrain.

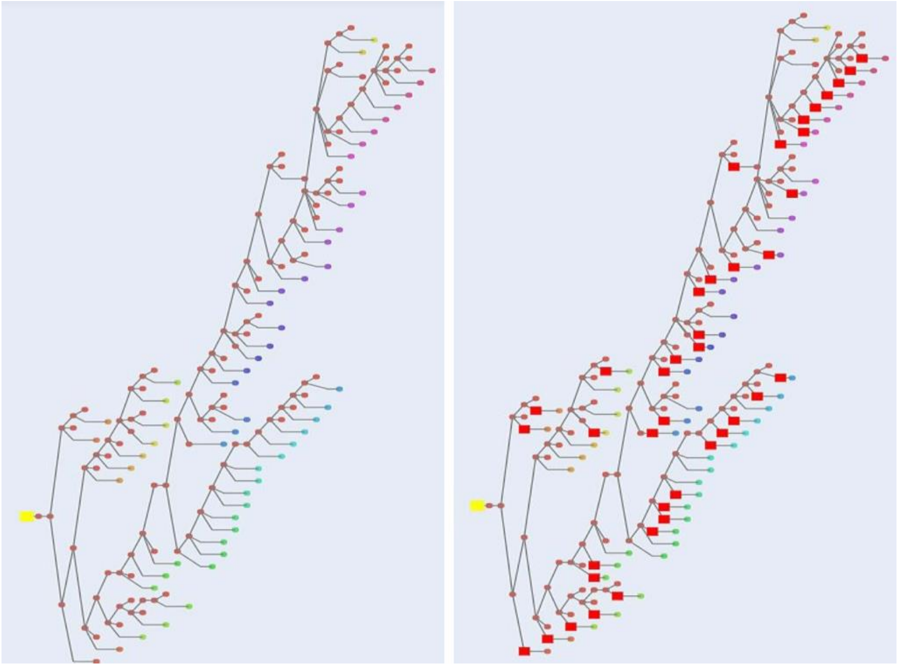

Fig. 1. Analysis of Gulshan-e-Iqbal feeder in pandapower without and with PV integration

To visualise the network, PandaPower provides two packages: Matplotlib and Plotly. The analysis of voltage violations and network overloading is represented in a bar graph created using Matplotlib, while the load flow results of the voltage profile used in the case studies are plotted using the Plotly function. Fig 1 shows how the Plotly function in Jupyter Notebook is used to visualise the network feeder before and after PV deployment, with different color coding indicating different parameters of Gulshan-e-Iqbal feeder. Bus, transformer, and loads are represented by red, yellow, and purple circles, respectively. Furthermore, the yellow square box on the right side of the graphs represents the connection of the external grid, whilst the red square box on the right side of the graphs indicates the PV randomly put on different load buses.

3 Formulating strategic planning for installing PV in the feeder

Since the distribution system has been plagued by problems in recent years, additional issues such as imbalance in voltage magnitude and system overloading due to non-optimal placement of distributed generation (DG) cannot be tolerated. As a result, it is crucial to determine the hosting capacity of the network. We are testing 1MW benchmark for installing DG-PV in Gulshan-e-Iqbal feeder, utilising various combination of PV capacity. Data is acquired in access format and mapped in SynerGEE, then configured and programmed in PandaPower.

To determine the hosting capacity, we must first determine the maximum number of PVs that can be connected to the system, Different cases have been built to place various numbers of PV units in the feeder. In the start, we placed 28 PV units with two active power ratings, namely 20 DG's of 0.03 MW and 8 DG's of 0.05 MW, totaling 1MW. The outcome is then compared with the Base Case scenario in which no DG is connected. After that, the amount of PV is increased to 40, 50, and 100 units. When we increase the number of PVs to be integrated into the system, the capacity of PV is reduced to keep the total at 1MW.

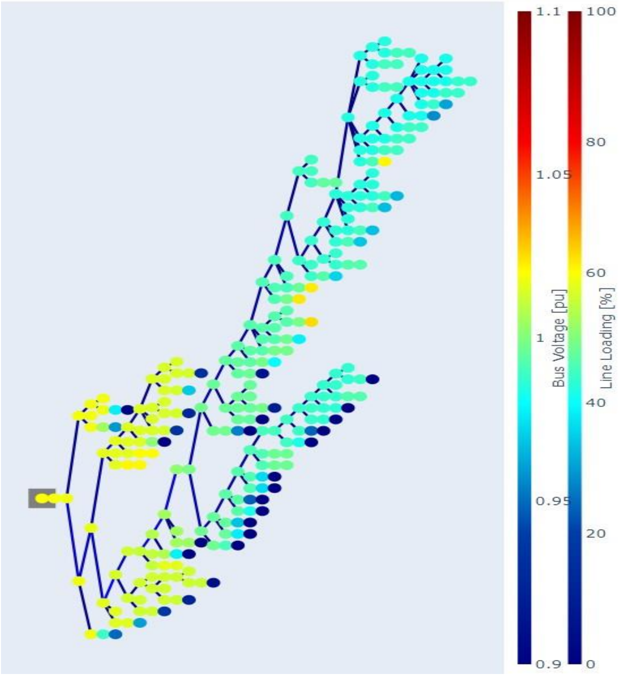

Fig. 2. The impact of PV integration on bus voltage and line-loading (BASE CASE)

After selecting the amount and size of the plant, the ranking of various locations for PV placement has been ascertained using a Monte Carlo probabilistic method, which employs random variable theory to evaluate system state and generate a series of random numbers; these numbers can be used to select the nodes for PV allocation. In the third stage, the whole network is manually created in PandaPower including all buses, transformers, switches, lines, loads and external grid. Now, different numbers of PV units are placed in load connection point with total PV plant size of 1MW. Run the power flow to find voltages, line loading and transformer loading for each case. Analyse and compare power flow results of all four cases using Matplotlib.

In the final stage, set the voltage and loading constrains according to Grid Performance and Grid Rules, and evaluate the Hosting capacity of the created network and interpret the result of all four cases using pie chart in PandaPower. PVs are not supposed to be installed on load buses or transformers that exceed voltage and heat limits. Therefore, the system's weak hosting capacity is determined by the network's weak point where the line and transformer loads both of which must be less than 50% [21] as well as voltage rise which has to be below 1.05 pu [22]. If any constraint is violated, the node is considered as the weak point of the feeder which needs to be reinforced. PV deployment should be targeted on nodes with higher hosting capacity to maintain the stability of the system.

TEST CASE SCENARIO

DG-PV with various generating capacities is integrated at different load buses to carry out the proposed methodology. Exemplary case studies are being conducted in this regard to demonstrate the effects of dispersed PV generation on the Low voltage feeder.

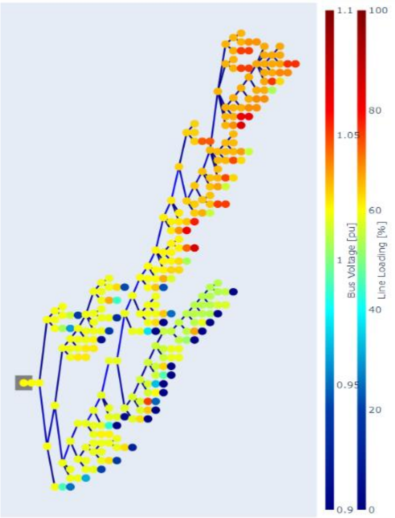

Fig. 3. The impact of PV integration on bus voltage (CASE 1)

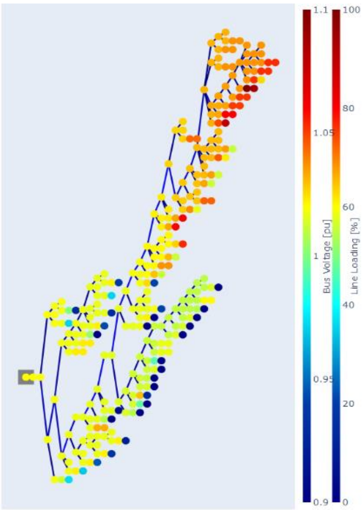

Fig. 4. The impact of PV integration on bus voltage (CASE 2)

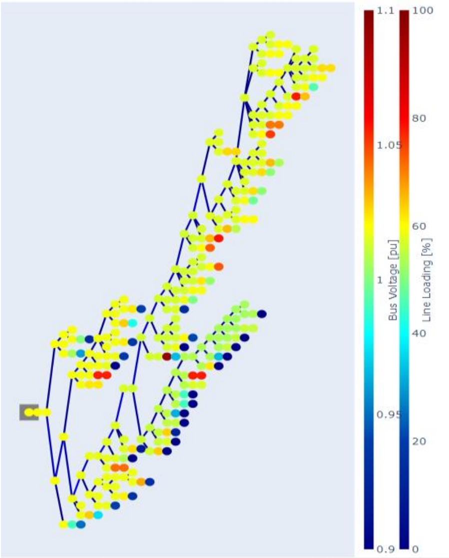

Fig. 5. The impact of PV integration on bus voltage (CASE 3)

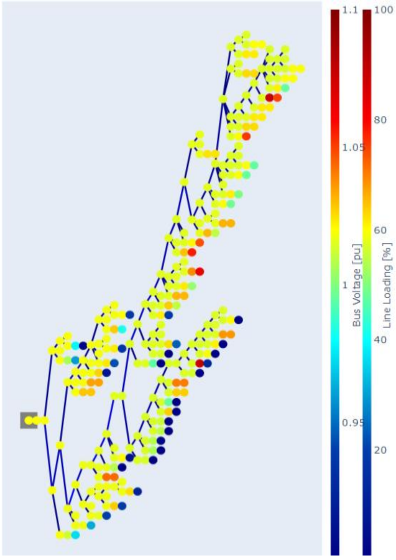

Fig. 6. The impact of PV integration on bus voltage (CASE 4)

- ***BASE CASE***: In this Base Case scenario, the network's load flow is carried without any PV connections. Fig 2 depicts the bus voltages of Gulshan-e-Iqbal`s Low voltage feeder in (p.u). The vibrant colors show the magnitude of voltage shift on each bus. The dark blue nodes represent the lowest voltage on any bus, whereas the dark red nodes represent the highest voltage value. Based on the Grid Code and NEPRA`s Performance Standards (Distribution) Rules, 2005 [21], [22] analysis of the Base case scenario does not show any voltage violation because the maximum voltage value on bus number 198 is 1.0255 pu.
- ***CASE 1:*** Fig 3 depicts the feeder's bus voltage profile with 28 PV distributed generation. In this scenario, the entire PV penetration is separated into two halves. Two active power ratings are now available for the system: 20 DGs of 0.03MW and 8 DGs of 0.05MW. The plot in Fig 3 represents that the voltage limit violates at some of the buses. The red colored circle in the plot shows that there are total 16 numbers of busses that exceed the voltage limit i.e. 1.05 pu. The maximum rise in voltage in this case, is 1.07 pu on bus 198.
- ***CASE 2:*** In this example scenario, the same plot is replicated with 40 PV units installed in the systems, divided into 30 units of 0.02MW PV units and 10 units of 0.04MW PV units making total capacity of 1MW. Fig 4 shows that when the number of PV units increases from 30 to 40, the number of buses influenced by high voltage decreases. There are a total of 11 buses with a voltage greater than 1.05 pu. However, due to a drop in PV capacity, the maximum value of the voltage climbs to 1.11921 pu in this situation.
- ***CASE 3:*** In this case, 50 PV units with a capacity of 0.02MW are randomly distributed. Fig 5 shows that a total of 8 buses exceed the voltage limit, with the highest voltage being 1.0927 on bus number 159.
- ***CASE 4:*** In the last case scenario, we increase the number of DG-PV to 100 units with 0.01MW of generating capacity. Fig 6 depicts the voltage index of feeder at various buses. It can be observed that there are extremely few buses, say only 5, which violate the Distribution Grid Code criterion. The maximum voltage value is found on bus 134 i.e. 1.0927 pu.

3.1. Pseudo Code For Stochastic Placement Of PV

```
Create PV_bus_index_array
For CASE 1,
From 1 – 60 indexes, generate 28
    random samples using MCS, and store them in
    PV_bus_index_array= random.sample(range(1, 60), 28)
Return_bus_number_arr = net[“bus”].number.values
Return_bus\_type_arr = net[“bus”].type
Return_bus_name_arr = net[“bus”].name
Return_bus_Vm_pu_arr = net[“res bus”].Vm\_pu
Create_PV_Generation_array i.e
PV_gen_array = np.array ([[0,0]])
For bus_number = bus_number_arr}
    If  bus_type_arr[bus_index] = "wye"
        PV_gen_array=np.append (PV_bus_index_array,bus_number_arr, bus_Vm_pu_ arr,axis = 0)
END If
END For
    For PV_bus_index = PV_bus_index_ array}
        Pandapower Create and place PV generation on Load bus
\\for 20 DGs OF 0.03 mw
            Pandapower.create_sgen(net,int(pv_gen_array[pv_bus_index][0]),p_mw=0.03)
\\for 8 DGs of 0.08 mw
            Pandapower.create_sgen(net,int(PV_gen_array[PV_bus_index][0]),p mw=0.08)
\\ Assign the value of P_mw and Q_mw for PV
            print(PV_bus_index,int(PV_gen_array[PV_bus_index][0]),PV\_gen\_array[PV bus number][1])
END For
Repeat the process by generating different random samples
Again assign the value of P_mw and Q_mw for CASE 2 AND CASE 3 and so on
```

4 Results And Discussions

The case study focused at various scenarios for integrating dispersed PV generation to explore the behavior and capabilities of the Gulshan-e-Iqbal feeder in carrying the maximum PV. To determine the point with limited hosting capacity, the results of all four conceivable scenarios are plotted and compared with the reference case scenarios using the PandaPower Matplotlib module.

4.1. Analysis of Voltage Violation

According to the Distribution Grid Code of Pakistan [22], " Under normal conditions, voltage fluctuations of 5% of the nominal voltage shall be authorised" implying that the voltage level should be between (0.95-1.05) pu. The graphical representation is used to assess the impact of distributed generation on buses that cause voltage violations in the network. Fig 7 depicts the voltage profiles of the Gulshan-e-Iqbal Feeder in four different scenarios. The purple bars reflects the voltage profile when no DG-PV is installed and the voltage limit is set to Vmax = 1.02 pu. This profile is considered as base case scenario. At the first glance voltages on all the buses lies within the envelope set by Distribution Grid Code i.e (0.95 -1.05) pu.

The voltage magnitude of Case 1 when 28 PV units were placed on the low voltage side can be observed in red bars. There is a large increase in voltage magnitude on bus numbers 134, 249, and 250, but we hardly notice a change in voltage magnitude on bus 31 and 32. Bus numbers 196, 201, 206, 245, 249, and 250 are the most vulnerable buses in Case 1, as their voltage levels are much greater than 1.05 pu, potentially causing the system to become unstable. In Case 1, there are 11 buses with voltage magnitudes that are within the 1.05 pu standard limit, Adding additional PV to those buses can result in a significant rise in the voltage magnitude.

In comparison to the Base Case, the green colored bar indicates how voltage levels vary in Case 2 when 40 PV units are connected to the feeder. In this situation, there is a considerable shift in voltage on buses 262 and 263; on the contrary, there is just a fractional change in voltage magnitude on buses 31 and 32. The critical nodes of Case 3 are 276 and 277, Any Small changes in the capacity of the PV units on these buses can have a big influence on the power system, putting the existing system in danger.

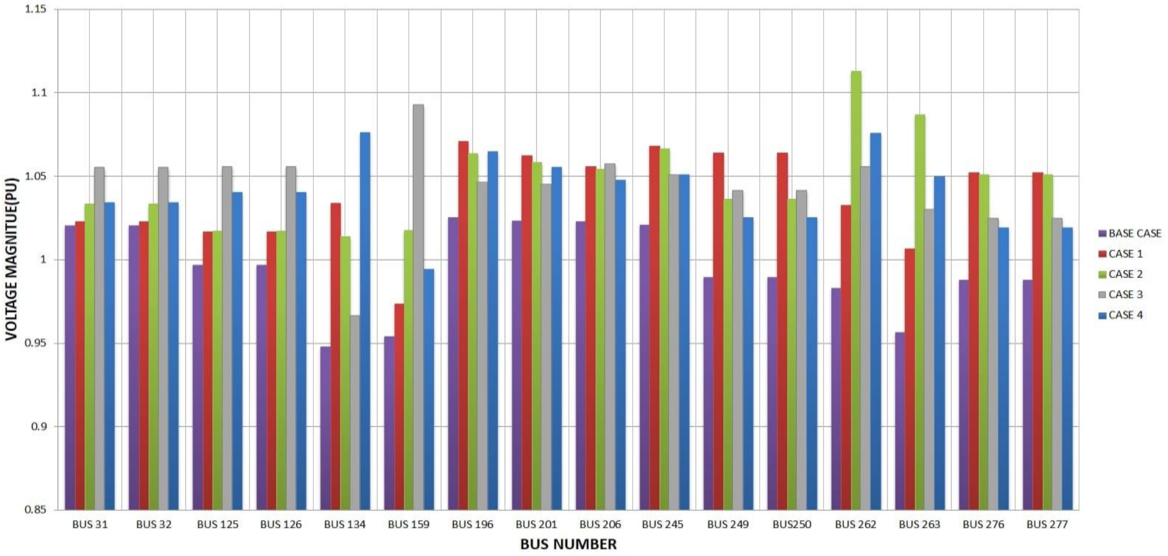

Fig. 7. Analysis of Voltage Violation

The grey bar in Fig 7 illustrates the voltages after the placement of 50 PV units of 0.02MW on each load bus resulting in a growing voltage magnitude. It can be seen from the bar that the buses having voltages greater than 1.05 pu are 13, 32, 125, 126, 159, 206 and 262 while the voltage rise on other buses are merely few decimal in comparison to Base

Case. However, we can detect a fairly large voltage difference on bus 159, which makes it the most hazardous node of this case as it cannot handle any more increases in PV capacity.

The voltage level variation on Case 4 is illustrated by the blue colored bar in Fig 7. In this case, there is a significant voltage change on buses 134 and 263. and the highest voltage on bus 134 reaches 1.0763 pu, which is above the voltage limit, indicating the weak nodes of the feeder on other buses, however, voltage differences are minor.

4.2. Analysis of Line Loading

Line loading is another key element to consider when looking for a weak point in the feeder where PV cannot be accommodated. The feeder has a total of 240 lines connecting different nodes. Fig 8 shows the details of the lines that are connected to the secondary transformers that go to the load buses. The majority of these lines are Ant type, with current carrying capacities of 0.221 kA. Further examination of the graph reveals that before the penetration of PV lines, the loading percentage of the Gulshan-e-Iqbal feeder is at safe levels and should last for another decade. When PV with varying generating capacities is penetrated into the feeder, the current loading percent fluctuates slightly, but it has no effect on the maximum loading percent. Every line has its own current carrying capability according to its conductor size. When current value hits 30% of total capacity, the cable reaches its thermal limit. The graph below shows that all the lines in all four cases lie blow the limit, which means that the current loading percent is below 30%, indicating sturdy network cables, capable of handling higher currents. This leads to the conclusion that the system's lines do not need to be enhanced and can carry higher currents without causing damage to the feeder.

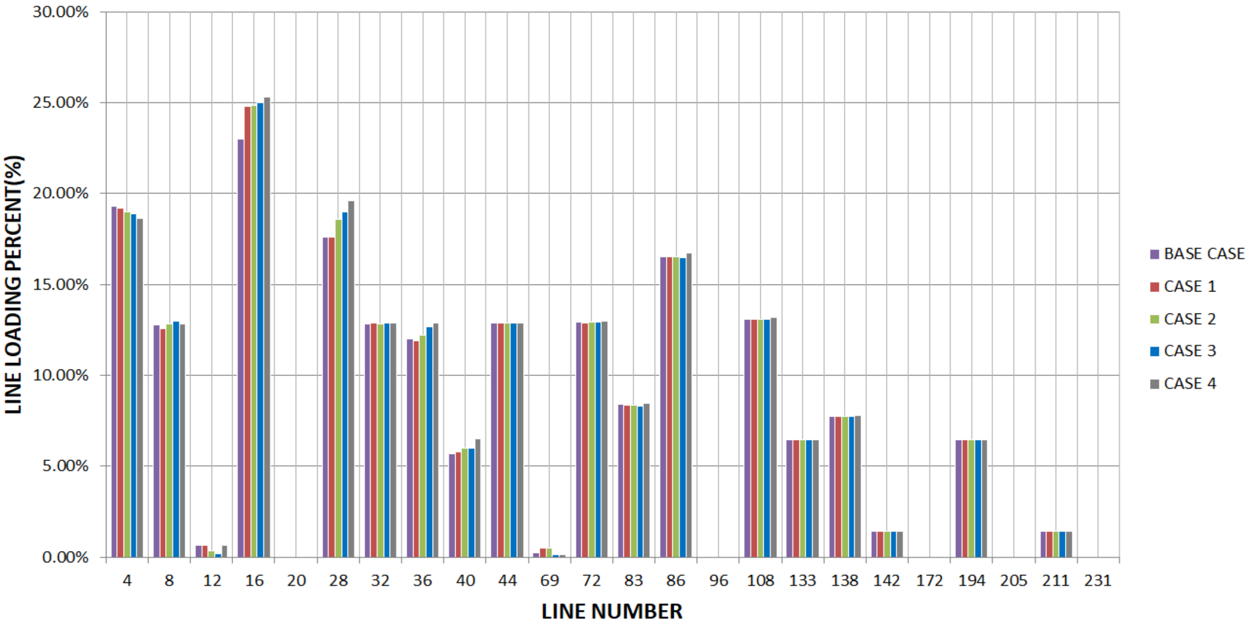

Fig. 8. **Analysis of Line Loading Percent**

4.3. Analysis of Transformer Loading

There are a total of 60 transformers connected to the Gulshan-e-Iqbal feeder, with some of them currently operating at overloaded capacity. There is a defined limit for transformer loading capacity as described in Grid regulations and Grid design standards [21]. In Fig 9, the impact of DG-PV installation on transformer loading capacity is depicted. The purple color bar shows when no DG-PV is attached to the transformer's low voltage side then the transformer`s maximum loading capacity reaches at 87.9% This overloading will shorten the life of the transformer and potentially trigger it's failure during peak hours. The green, yellow, and red colored bars show PV penetration of 40%, 50%, and 60%, respectively.

The X-axis of Fig 9 depicts the visualisation of transformer numbers that reflect crucial nodes where secondary transformer capacity is severely low and replacement of such transformers with high loading capacities are required. When a PV generator is mounted on the secondary side of a transformer, the DG will give additional power to the load, reducing the transformer's maximum capacity and decreasing the current that passes in the transformer. As a result, the heat on the transformer windings will be reduced, and losses will be reduced.

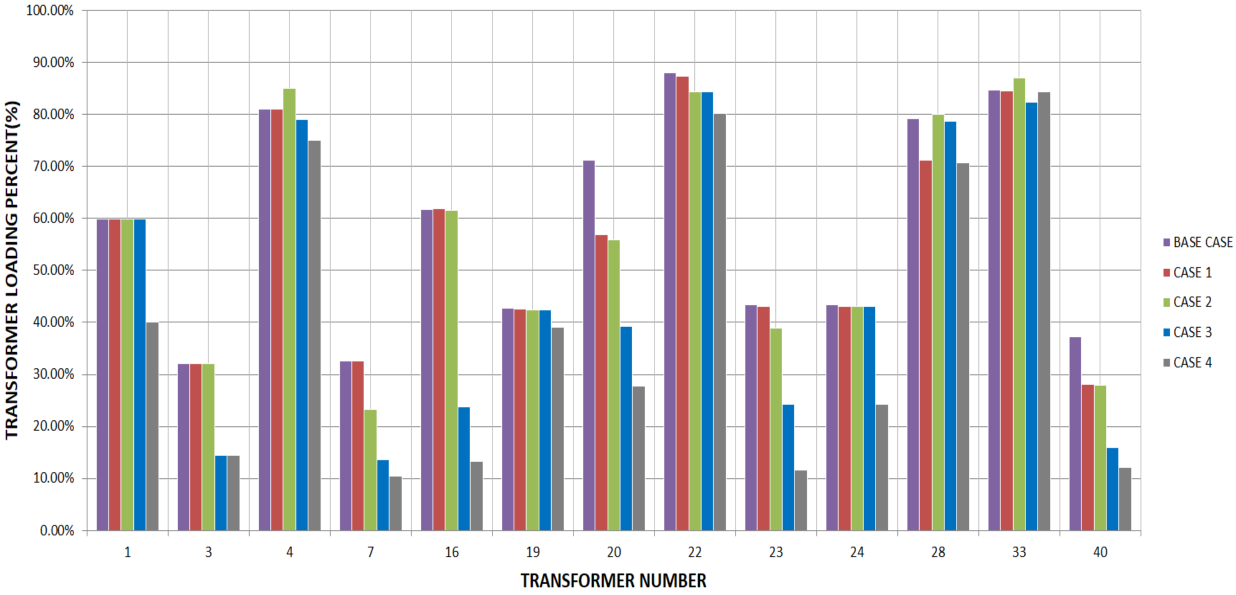

Fig. 9. Analysis of Transformer Over loading

In Case 2, the green colored bar depicts that adding 40 PV units to the Gulshan-e-Iqbal feeder results in considerable changes in the loading percent of transformer number 7, 22, 23, and 51 which are not alarming in these bus nodes. Similarly, the blue bar representing Case 3 reveals that by increasing the number of PV up to 50 units, there is a significant shift in the loading % on transformers 3, 16, and 40. Finally, the grey colored bar in Case 4, illustrates that installing 100 PV units in the system can reduce the system's maximum loading capacity from 87.91 percent to 80 percent at transformer number 22.

Keeping in mind that the system still represents its maximum loading limit of 80% on transformer 22, this can deteriorate or even ignite the transformer windings, implying that any increase in load will cause the system to be permanently damaged or shorten its life duration. Such issues should be addressed by the company, as they would cause the system to change dramatically after PV installation. If the loads required per day is provided by the distribution firm, load shifting or peak shearing studies may be beneficial.

4.4. EVALUATION OF HOSTING CAPACITY

Hosting capacity is defined as the amount of PV that a feeder location can host without compromising its power quality, system reliability and safety concern [23]. The primary concept behind evaluating the Gulshan-e-Iqbal feeder's hosting capacity is to assess the influence of PV installation on the voltage profile, line loading, and transformer loading, considering the planning principals. The overall hosting capacity of the Gulshan-e-Iqbal feeder is compared in Fig 10 for all four cases.

The pie chart in Fig 10 shows that increasing the amount of PV in the low voltage distribution feeder improves the overall voltage profile of the buses. The overall voltage violation of Gulshan-e-Iqbal feeder when 46% of PV units are installed is 15%. Similarly, by increasing number of PV units to 66% and 83% reduces overall voltage violations in the feeder to 12% and 15% respectively. Finally, when we increase the number of PV units more than 150% on the load bus, the voltage violation drops to 5%. The sensitive nodes identified in the preceding section are considered as the points where the hosting capacity of Gulshan-e-Iqbal feeder is weak, and PV hosting at these points should be avoided for maintaining acceptable voltage profile.

High solar photovoltaic penetration, on the other hand, might result in reverse power flows that increase the thermal loading limits of line. Although the loading percent of the line increases from Case 1 to Case 4, but it is not dangerous for the feeder; even after adding 100 PV units of 0.01 MW, the overall loading percent of the Gulshan-e-Iqbal feeder remains below the limit.

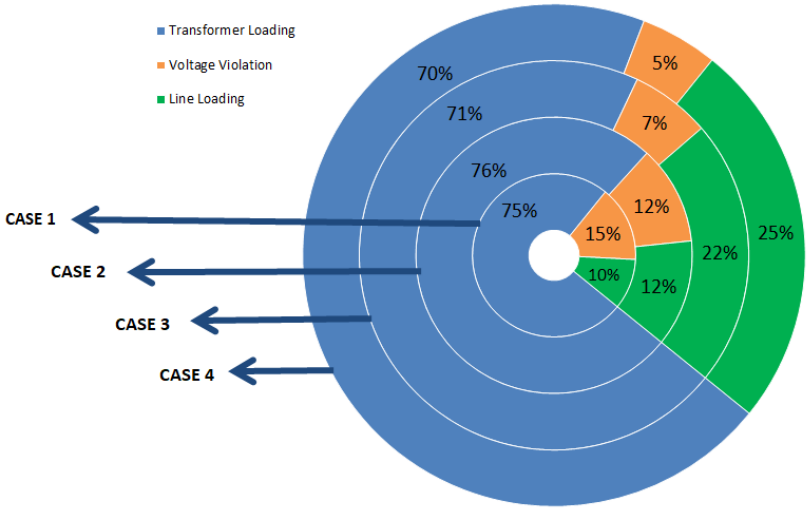

Fig. 10. Evaluation of Hosting Capacity

Although the proposed solution decreases transformer overloading of the feeder, the transformers utilised by the LESCO are quite old, reducing overall transformer efficiency, serviceability, and life span. The company should focus on the upkeep of a transformer with a high loading percentage.

5. Conclusion

The thumb-rule of 1 MW PV penetration per feeder can lead to identified problems in network operations. Although proposed probabilistic PV placement procedure is generic, its usefulness in determining performance of the Gulshan-e-Iqbal feeder is demonstrated. While keeping total PV penetration at 1 MW, if roof top PV units of low(high) capacity are assumed, then grid voltage violation is minimum (maximum). Moreover, since the early part of the lateral is stronger than the end of the feeder, concentrating PV on this section may result in the least voltage variation. Voltage analysis demonstrates that the bus number 245 is the most sensitive bus, as the voltage value climbs above 1.05 in all four cases, indicating the point of weak hosting capacity.

The line conductors of the Gulshan-e-Iqbal feeder are found to have sufficient capacity in all explored cases of stochastic PV growth. However, transformer loading exceeds the 80% loading criterion for some transformers, and this can jeopardize reliable system operation In this study, nodes that breach the voltage constraints and transformers that reach loading constraints have been highlighted. The proposed stochastic PV growth exploration procedure determines nodes where roof-top PV connection requests of consumers can or cannot be entertained to maintain desirable grid performance.

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