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Effect of PV Integration on Voltage of Distribution System Using Optimal Placement of DG

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Abstract: *Proper allocation of distributed generation (DG) units integrated with a distribution system plays a significant role in improving system performance. The voltage profile is one of the factors considered when determining the reliability and efficiency of power grid operation. This paper presents a methodology based on an analytical approach for optimally allocating (site and size) DG units in radial power distribution networks to minimize real power losses. The proposed method only requires the results of the base case load flow to determine the optimal size of DG units needed at each bus. To achieve this, suitable analytical expressions have been proposed to determine the optimal size of DG units that minimize the total real power loss in a given distribution network, along with their corresponding optimal locations. Results obtained by this proposed method validate the suitability and importance of appropriate DG allocation and the number of DG units in power distribution networks.*

Keywords:- Power Distribution System, Distributed Generation, Sizing, Sitting, Real Power loss minimization.

Introduction

Energy and the utilization of renewable resources are pivotal concerns in the future of power grids. In recent years, there has been a substantial surge in energy demand [1]. In response to global warming, the development of renewable energy sources is imperative to mitigate the harmful emissions associated with conventional fossil power plants [2, 3]. Presently, the primary sources of renewable energy generation include solar, wind power, and hydraulic energy. The confluence of issues such as climate change and increased environmental awareness, coupled with significant deregulation in traditional power systems, has compelled governments to explore alternative energy sources to replace conventional ones [4]. These factors are reshaping the landscape of conventional grids, setting the stage for rapid deregulation and a transformative shift driven by the extensive integration of renewable energy generation, including stochastic sources like photovoltaic (PV) systems and wind power. Solar power, in particular, is gaining increasing appeal [5].

1.1 Photovoltaic (PV)

Solar photovoltaic (PV) energy is widely embraced, both by utility companies and for residential use [6]. PV systems utilize semiconductor technology to convert sunlight into electricity [7]. However, PV generation depends on sufficient sunlight during the day, necessitating integration with other power generation systems to ensure a continuous electricity supply [8]. The PV market is exceptionally promising, playing a significant role in the energy landscape of various countries [9]. For instance, during the previous summer, PV contributed to more than 4% of Spain's electricity demand. The world's largest PV plant is currently situated in the Tengger Desert Solar Park in China, boasting a total capacity of 1500 MW. It is closely followed by the Datong Solar Power Top Runner Base in China and the Kurnool Ultra Mega Solar Park in India, each with a capacity of 1000 MW [10]. These levels of generation are expected to continue growing in the coming years, making power grids more complex. One critical consideration in renewable energy is its inherently stochastic nature and its implications for power grids. Effectively managing this grid replete with highly penetrated renewable generation will be a complex task, necessitating extensive research in various aspects [11].

The impact of large-scale PV-based generation units has become a focal point of strategic research on renewable energy integration [12]. Typically, PV-based power generation units operate in a grid-connected mode. However, unlike conventional generation units, high-capacity PV installations, such as those in the multi-megawatt range, significantly affect the dynamic performance of interconnected power systems and have substantial implications for the reliability and stability of these systems [13]. Consequently, researchers have conducted numerous modeling and control studies to assess the dynamic impact of PV systems and their contribution to grid support and ancillary services in the context of grid-connected operation characteristics of large-scale PV systems [14]

1.2 Distributed generation (DG)

Distributed generation (DG) is a small-scale power generation technology connected to consumers' loads via a power utility's distribution system, delivering electric power closer to customers than central station generation [15]. However, there is no universally accepted standard definition for DG. Several international organizations have proposed various definitions based on DG's location, ratings, purpose, technology, mode of operation, and the area it serves. The penetration of DG units in distribution systems is rapidly increasing due to the high global electricity consumption [16]. Recent technological advancements have enabled DG to contribute significantly to global electricity generation, offering reduced costs and high efficiency. Integrating DG into modern power systems allows consumers to meet their load requirements reliably and efficiently [17].

Advancements in the design and manufacturing of DG components, coupled with changes in consumers' power consumption patterns and the uncertainty in the global petroleum market, have created more opportunities for power utilities to harness renewable energy resources and generate sufficient electricity to meet consumers' load demand [18]. With the ongoing power deregulation, it is widely acknowledged that centralized power systems will gradually transition to decentralized power systems. This shift emphasizes the use of DG units to meet customer load demands [19]. To achieve these goals, more entities must be involved in planning, coordination, and the integration of DG units into power systems [20].

1.3 Solar Radiation

The efficiency of a photovoltaic (PV) device is contingent upon the spectral distribution of solar radiation [21]. The Sun acts as a light source, and its radiation spectrum can be likened to that of a black body at approximately 6000 K. A black body absorbs and emits electromagnetic radiation across all wavelengths [22]. The theoretical distribution of black body radiation wavelengths is described mathematically by Planck's law, which delineates the relationships and dependencies among wavelength (or frequency), temperature, and the spectral distribution of black body radiation [23]. In Figure 1, you can observe the spectral distribution of black body radiation in comparison to extraterrestrial and terrestrial solar radiations

[24]. Studying the impact of solar radiation on PV devices is complex because the sunlight's spectrum on Earth's surface is influenced by variables such as temperature variations on the solar disc and the effects of the atmosphere [25]. In the expanse of outer space, at the average distance between the Sun and the Earth, the solar energy received is approximately 1.353 kW/m². However, on Earth's surface, the irradiance is approximately 1 kW/m² (though it's important to note that the actual irradiance on Earth's surface is subject to various influencing factors).

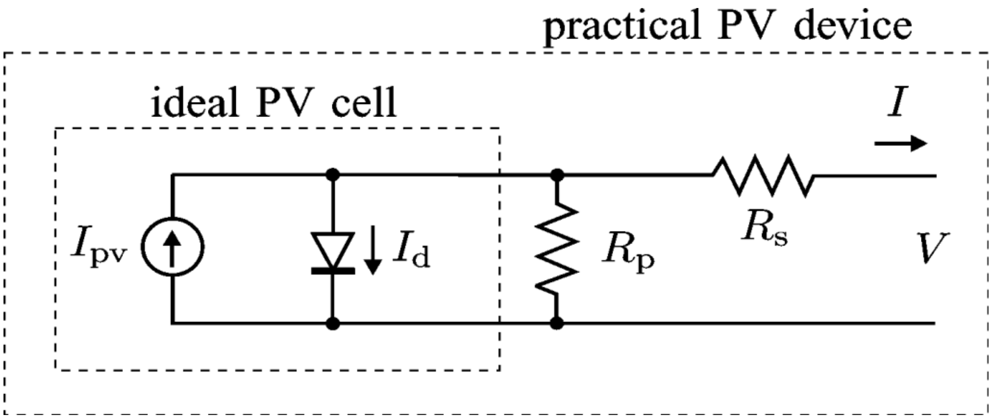

Figure 1: Single-diode model of PV device.

II. Impact of DG on Power System Voltage Stability

Distributed generation technology offers numerous advantages, such as being clean, environmentally friendly, cost-effective, and efficient. It can also enhance the stability and flexibility of the entire power system. In recent years, distributed generation technologies have experienced rapid development, including the implementation of parallel operation [26]. In the past, the various segments of electricity generation, transmission, distribution, and supply were integrated within individual electric utilities, simplifying grid operation because the system operator had full control and knowledge of the grid's status [27]. However, liberalization and deregulation of the industry introduced competition in the generation and supply segments [28]. Transmission and distribution, being natural monopolies, remained subject to network regulation. Electricity possesses unique characteristics, such as non-storability in economic terms, real-time demand variations, low demand elasticity, random real-time failures in generation and transmission, and the need to adhere to physical constraints for reliable network operations [29]. One consequence of liberalization is how the now-separated entities interact with each other. To ensure immediate balance between supply and demand, real-time markets are conducted as centralized markets, even in fully deregulated systems [30]. The system operator acts as a single buyer responsible for regulating supply and demand, often via a bid-based exchange or pool approach. Economic decisions are made independently by market participants, and system-wide reliability is maintained through coordination among different companies. Integrating generators into distribution networks alters the radial design and structure of these networks, where the flow traditionally moves in a single direction, from the substation to the loads. Changing the flow patterns also impacts the voltage profile [31]. Voltage stability in an electrical power system refers to its ability to return to normal operating conditions after experiencing severe disruptions like faults. Various approaches, such as FACTS devices, shunt reactors, capacitors, and DG units, are employed to enhance power system stability [32]. DG units, in particular, can significantly contribute to improving power system stability by increasing the maximum load penetration and expanding the margins of voltage stability.

III. Related Work

The integration of renewable energy sources, such as solar photovoltaic (PV) generation, into the grid is becoming increasingly vital for the future power network. The level of solar energy penetration varies depending on the location, making it a readily available resource for modern power systems. Solar technologies are environmentally friendly and represent a leading potential source of alternative energy. Furthermore, the cost of PV modules has been consistently declining, with an average reduction of 20% with each doubling of sales. Understanding the available solar radiation in a specific location is a fundamental prerequisite for any solar energy project, whether it involves PV plants, solar thermal systems, or passive solar designs [1].

The incorporation of renewable energy-based distributed generation sources (DGs) into distribution systems offers advantages such as alleviating transmission and distribution capacity issues and enhancing the voltage profile [2]. Practical analyses of the impact of grid-connected DG units on system stability have been presented in [3]. In [4], the authors assessed the impact of DG size and location under changing load conditions due to contingencies in unbalanced distribution systems. Studies have also investigated the effect of DG capacity and location on voltage profile improvements in distribution systems [5].

The rapid growth of distributed PV power generation in recent years has raised challenges due to the stochastic nature of solar power and the presence of clouds, which can lead to supply-demand imbalances. Integrating renewable energy-based distributed PV generation units can influence various aspects of distribution systems, including power quality, stability, voltage profile, protection, power flow, and reliability. While the impacts of DG units are minor at low penetration levels (1%-5%) due to their smaller capacity compared to central power plants, they become more significant as the penetration level increases to the anticipated range of 20%-30% [6].

Voltage instability in distribution systems has been a subject of study for decades, often referred to as load instability. For instance, a voltage instability issue in a distribution network resulted in a major blackout in the S/SE Brazilian system in 1997 [7]. Optimal placement of distributed PV generation units in a power network is crucial for the successful integration of renewable energy. In [8], a method was proposed to optimally allocate DG units to enhance the voltage profile at candidate buses using a voltage collapse index, although it did not consider the impact of line outages. Additionally, in [9], the authors used the findings from [8] to maximize loading under normal and contingency conditions.

Distributed PV generation units should be strategically integrated into optimal locations to relieve the power system. An optimization technique for sizing and allocating renewable energy-based distributed generation on distributed feeders, considering technical and economic constraints, was introduced in [10]. The effects of distributed generation units under both small and substantial disturbances are discussed in [11], while [12] focuses on minimizing voltage instability occurrences when DGs are placed at desirable locations in a power system. Techniques for optimal DG placement considering improvements in voltage profiles and reduced line losses are presented in [13].

Currently, most installed distributed generation operates at unity power factor to avoid interference with voltage regulation devices connected to the system [12] [13]. The proper placement of DG units in distribution networks helps mitigate line congestion and enhances the voltage profile of selected candidate buses in the network. The distribution network considered in this paper comprises solar panels, fossil fuel power plant units, and load demand [14]. This system is linked to the main grid through a tie line with limited capacity. The variations in solar irradiance have been statistically proven to follow a normal probability density function [15].

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)}{2\sigma^2}}$$

The output power of a PV module is dependent on several factors, including the ambient temperature, solar irradiance at the location, and the characteristics of the module itself. It can be calculated using the expression provided in reference [16].

$$P_{say} = N * FF * V_y * I_y$$

IV. Proposed Methodology

This section outlines the solution methodology for the proposed method aimed at minimizing total real power loss through the optimal sizing and placement of DG units in a distribution network. Two scenarios are considered, as described in the following section. The solution algorithm is presented as follows.

4.1 Real power loss minimization by Single DG allocation

The computational steps involved in determining the optimal size and location of DG to minimize total real power loss in a radial power distribution system are as follows:

1. Run the load flow analysis for the base case (without DG) using [28] and calculate the branch currents and total real power loss in the network.
2. Choose the power factor for the DG.
3. Select a bus (one at a time), excluding the source bus, and calculate the DG size in terms of real and reactive components of the injected DG current.
4. Set the bus count as k=2, place the DG at bus k with the corresponding DG size determined in step (3), and calculate the total system real power loss.
5. Verify if the voltage constraint is satisfied. If it is, proceed to the next step; otherwise, discard that particular solution.
6. Store the values of total system real power loss.
7. Check if this is the last bus in the network. If it is, proceed to step (8). If not, increment the bus count by 1 and repeat steps (3) to (6).
8. Finally, sort the stored total system real power loss values in ascending order and select the solution with the lowest loss.
9. The DG size and its corresponding location in the network, which result in the minimum total real power loss, represent the optimal size and location, respectively.

The above algorithm provides the optimal DG size and location for a given load level.

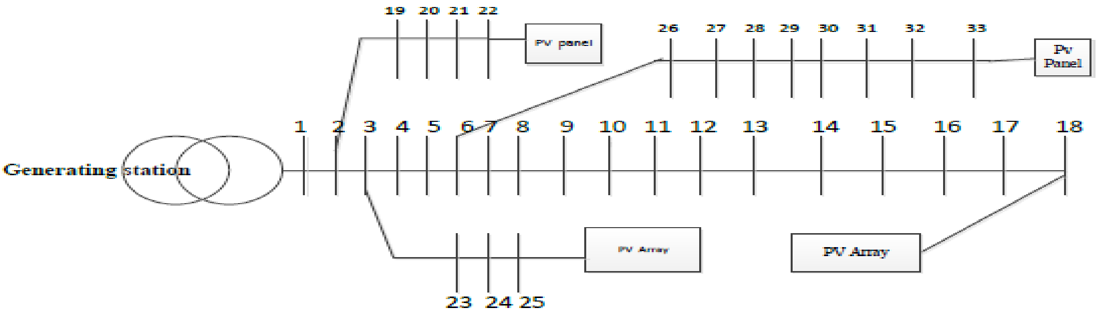

Figure 2: Single line diagram of an existing distribution feeder with PV panel.

In Figure 2, a PV panel is depicted as attached to the distribution system, yet its placement is not optimized but rather based on personal preference. To optimize the positioning of the PV panel, we are employing the Genetic Algorithm with the assistance of Matlab Software. The results obtained after running the Genetic Algorithm will identify the optimal location for the PV Panel. This optimal placement will be the point where losses decrease, and the voltage profile improves, as illustrated in Figure 3. The image in Figure 3 represents the PV panel connected to a specific bus following the results of the proposed method.

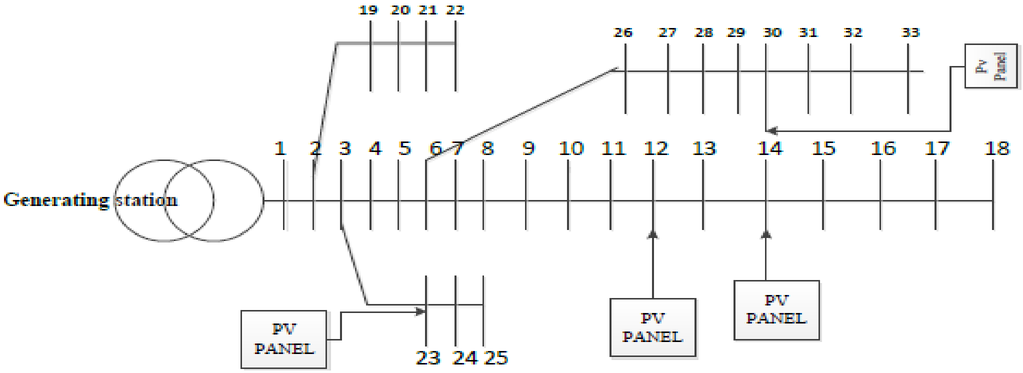

Figure 3: Optimal placement of PV panel.

V. Results & Discussions

An uncomplicated and effective load flow method has been introduced for resolving radial distribution networks. This method fully leverages the radial nature of the distribution network.

5.1 After PV Integration

The integration of PV panels results in an increase in node voltage at the bus. This integration effectively minimizes losses, and by using openDss, we simplify the process. In openDss, there's no need to manually write equations; instead, we write and run a program to obtain our desired results [15].

Table 1: Comparison of losses before & after PV integration.

Parameters	**Before PV Integration**	**After PV Integration**
Line Losses	147.1 Kw	135.6 Kw
Transformer Losses	0.0 Kw	0.0 Kw
Total Losses	147.1 Kw	135.6 Kw
Total Load Power	3362.2 Kw	3374.8 Kw
Percent Losses for Circuit	4.38%	4.02 %

Table 1 provides a comparison of different losses before and after the integration of PV panels. It is evident from the table that following PV integration, all losses have reduced. Figure 4 illustrates that the voltage profile shows improved results after the integration of PV panels.

5.2 Optimal Placement of PV Panel

This report delves into the investigation of optimal positioning and the appropriate allocation of PV panels to reduce power losses and enhance voltage profiles in distribution systems. The optimization task revolves around minimizing an objective function characterized by three critical parameters: active power losses, reactive power losses, and voltage profile. To achieve this, a genetic algorithm is employed. Power flow analysis is conducted using the backward-forward sweep method, and simulations are executed on a 33-bus test system. The placement of PV panels is seamlessly integrated into the test system.

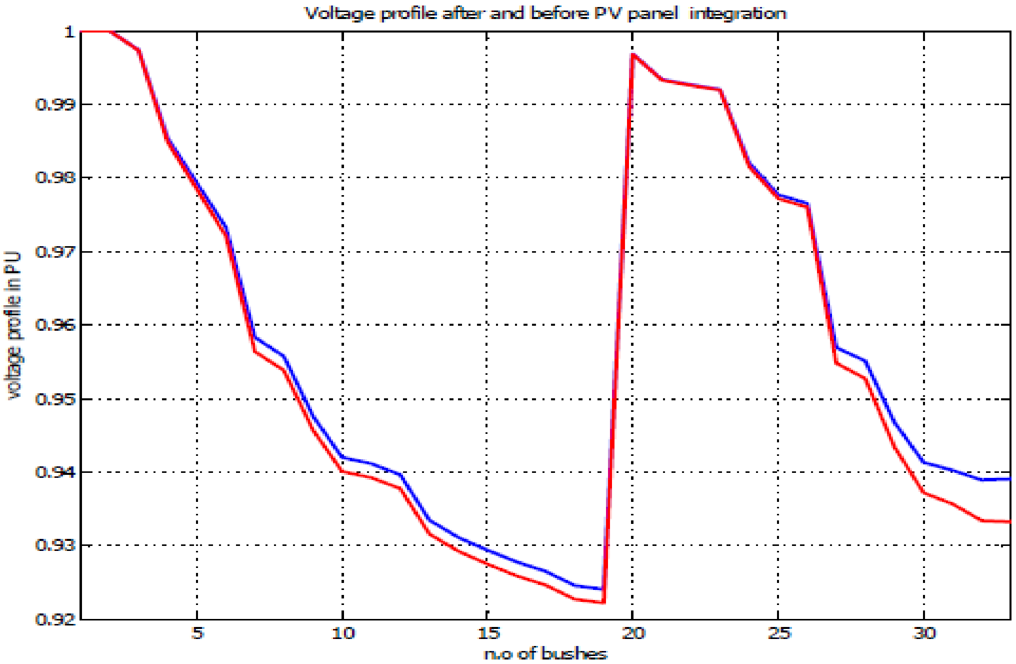

Figure 4: Voltage profile before & after PV Integration.

Results show a significant reduction of losses and improvement of voltage profile with presence of PV panel.

Table 2: Comparison of all losses.

Parameters	**Before PV Integration**	**After PV Integration**	**After optimal PV Integration**
Line Losses (KW)	147.1	135.6	130.2
Transformer Losses (KW)	0.0	0.0	0.0
Total Losses (KW)	147.1	135.6	130.2
Total Load Power (KW)	3362.2	3374.8	3375
Percent Losses for Circuit (%)	4.38	4.02	3.97

Table 2 gives the comparison of various losses before and after PV integration as well as with optimal PV integration. It is clear from the table that after optimal PV integration, all the losses are less.

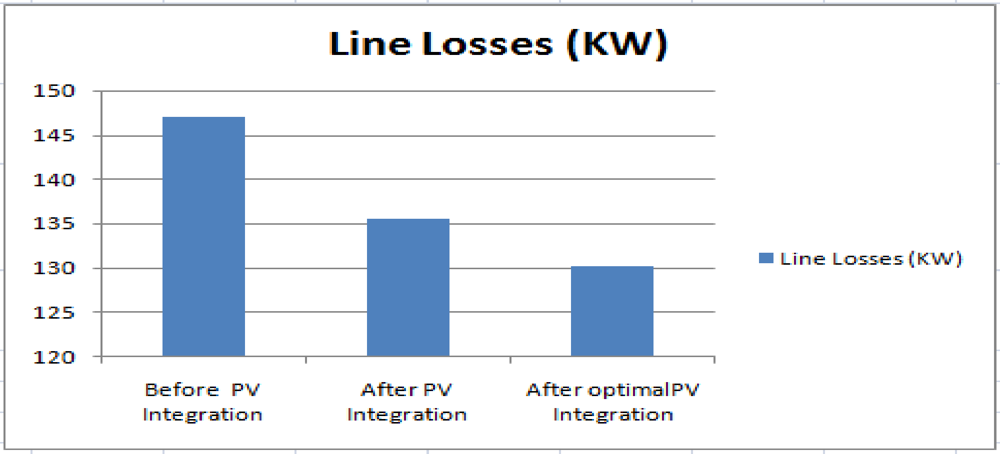

Figure 5: Comparison of Line losses.

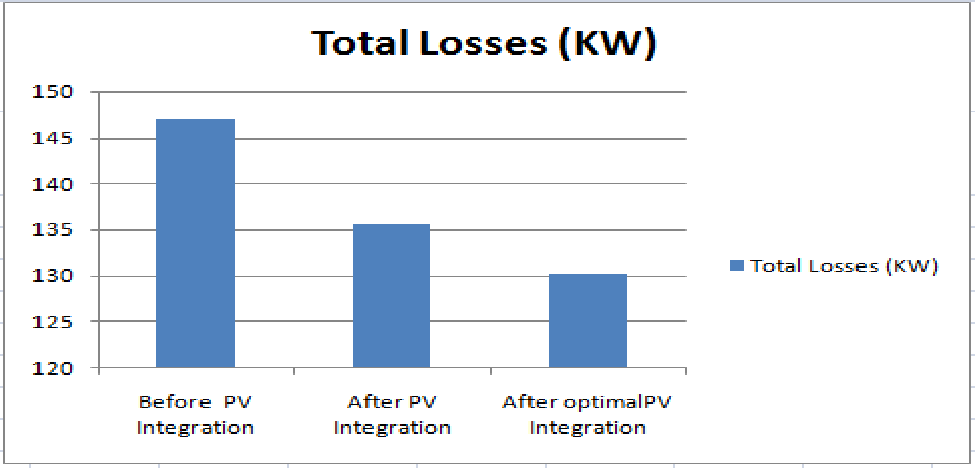

Figure 6: Comparison of Total losses.

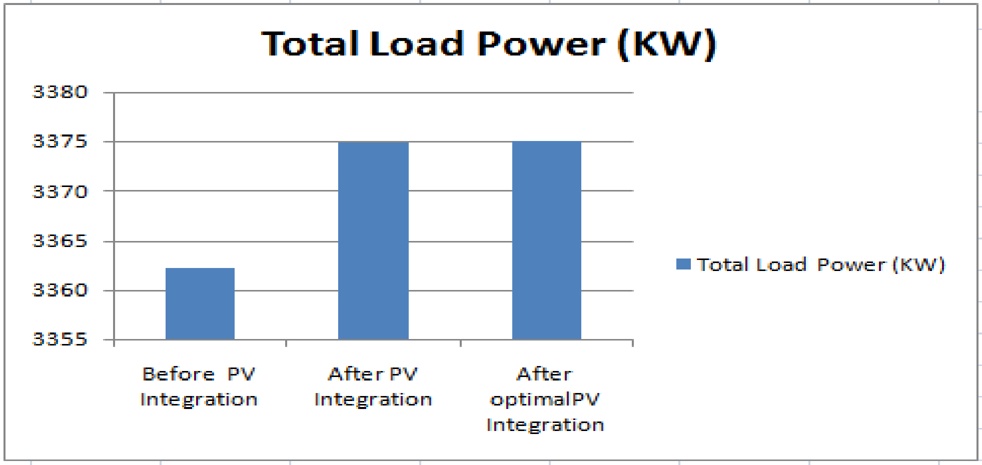

Figure 7: Comparison of Total Load Power.

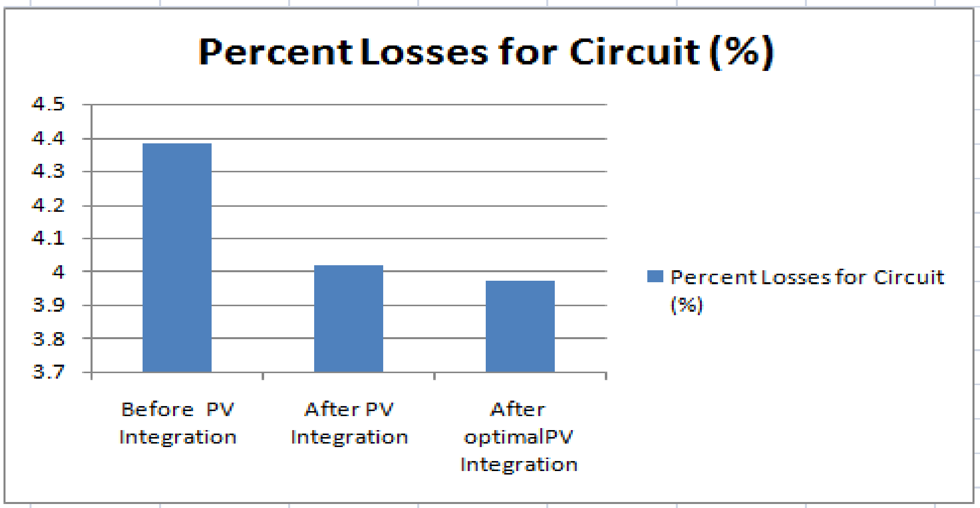

Figure 8: Comparison of circuit losses.

It is clear from the figure 5, figure 6, figure 7, and figure 8 that all types of losses have been minimized when we are proposing optimal PV integration.

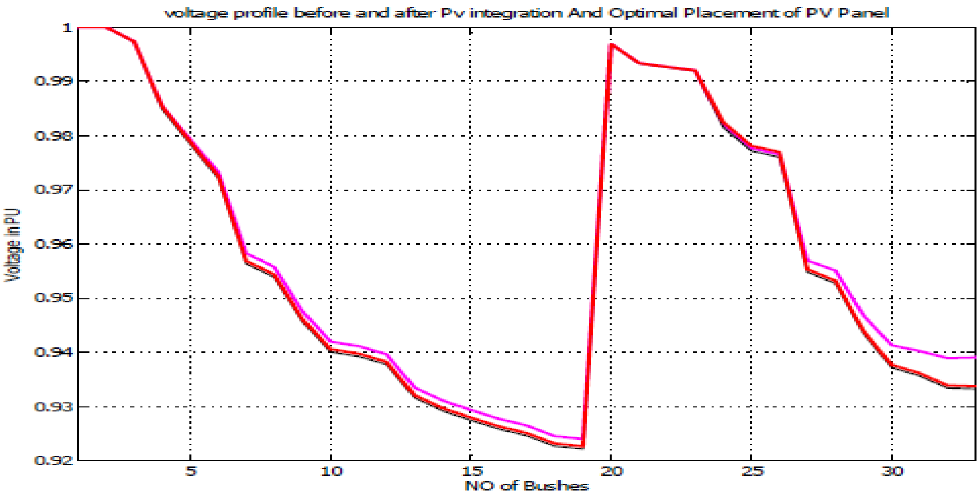

Figure 9: Voltage profile after optimal Placement.

It is shown from the figure 9 that voltage profile is having better results in case of optimal PV integration.

VI. Conclusion

There is a rising trend in integrating various types of distributed generation (DG), particularly photovoltaic (PV) systems, onto the roofs of existing consumers, who then become prosumers. One of the impacts on prosumers is voltage violations, which conventional strategies find challenging to address. However, some prosumers, particularly those with PV systems equipped with inverters in their configurations, can actively participate in voltage optimization. The integration of DG units into existing power distribution systems worldwide is on the rise, and their contribution to the future power system is expected to grow even further. A methodology based on an analytical approach for minimizing real power losses in the power distribution system through the optimal sizing and siting of DG units has been presented. This methodology considers DG units injecting both real and reactive power with a constant power factor set equal to the combined system load power factor. The results obtained by this proposed method show better loss reduction, leading to economic benefits for the utility and improved voltage profiles, contributing to the stable operation of the system.

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