Optimizing Solar Integration and Power Flow Analysis for Enhanced Grid Performance in Sulaimani City

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Abstract

The integration of renewable energy sources, particularly solar power, into existing electrical grids is critical for developing a reliable and efficient power system. This study analyzes power flow in Peshazi substation in sulaimani city which feeds a distribution network by about a 60 MW and optimizes the placement of solar sources. The analysis is based on data from Directorate of electricity distribution of Sulaimani city that encompassing 15 distribution feeders with varying loads, power generation, and line lengths, aiming to enhance efficiency, stability, and reliability. The integration of solar energy, driven by its decreasing costs and abundant availability, poses unique challenges due to its variability. The paper outlines methodologies for optimal placement and sizing of solar PV systems to address these challenges study the power system simulation for Engineering (PSSE) software is utilized to simulate and evaluate the integration the solar source to existing grid. Key findings demonstrate significant voltage drops and power losses in certain distribution feeders, emphasizing the need for strategic solar PV installation to improve voltage stability and reduce transmission losses.

Keywords: Solar Integration, DG, Power Flow Analysis, PSSE

1. Introduction

The growing demand for electricity and the urgent need to transition to sustainable energy sources have driven significant advancements in the field of power systems engineering. A recent report by the International Energy Agency (IEA) highlights the global surge in electricity demand, projected to reach 28,400 TWh by 2050, emphasizing the critical role of renewables in meeting future needs [1]. Among these advancements, the integration of renewable energy sources, particularly solar power, into existing electrical grids stands out as a crucial step toward achieving a more resilient and environmentally friendly energy landscape. Solar energy, due to its abundant availability and decreasing costs, has become one of the most promising renewable energy sources. Studies by Lazard show a significant decline in solar energy costs, with solar photovoltaic (PV) reaching record lows of $0.38/watt DC in 2022 [2]. This trend is expected to continue, making solar an increasingly viable option for large-scale power generation. However, its integration into the power grid presents unique challenges that require sophisticated analysis and optimization techniques.

In both conventional and smart distribution networks, load profiling is an important concept for management and control. Traditional strategies depend upon data retrieved from distribution system databases, while smart grids utilize data received from new monitoring systems. Estimating load profiles is useful for numerous functions that utilities offer, such as satisfying consumers' energy requirements, making sound financial decisions, and improving the operational efficiency of electricity networks.

The integration of solar power into the grid introduces new variables and uncertainties that must be carefully managed. Solar power generation is inherently intermittent and depends on factors such as weather conditions and the time of day. This variability can cause fluctuations in voltage levels and power flows, potentially leading to stability issues if not properly managed. Research by Olivares et al. (2014) investigates the impact of solar variability on power system stability and proposes mitigation strategies [7]. Therefore, determining the optimal placement and sizing of solar PV systems within the network is critical to maximizing their benefits while minimizing potential drawbacks [9].

With the growing demand for reliable and efficient power systems, integrating renewable energy sources such as solar power has become essential.

In this paper, the focus is on the power flow and optimize the placement of solar sources in a network fed by a single 60 MW generator in the Sulaimani system. The selected network is versatile and includes various load types, from residential to commercial and industrial loads. The provided data includes information on active and reactive power generated and consumed, line lengths, voltage levels at load points, and phase angles for 15 distribution feeders. By leveraging this data, we aim to perform a detailed power flow analysis, identify areas with significant losses or voltage stability issues, and propose strategic locations for installing solar PV systems.

2. Related Works

The integration of photovoltaic (PV) systems into power networks has been extensively studied to enhance efficiency, stability, and reliability. Key research focuses on optimal placement and sizing to maximize the benefits of PV systems while mitigating potential issues such as voltage instability and power losses.

Distributed generation (DG), including PV systems, has gained increasing interest due to new opportunities in using renewable energy and improving the environmental situation. The CCGTM (California Climate and Grid Technologies Model) defines DG as any small-scale power source directly connected to the distribution network that supplies electrical power to nearby consumers [10]. National governments are setting high levels of DG and combined heat and power (CHP) to fight climate change and reduce over-dependence on a single type of energy [11]. Global DG capacity has grown steadily over the years, from MW to GW/MW, stabilizing in recent years [12].

Several factors have created a new environment for electric power infrastructure, including the privatization or deregulation of the electric utility industry [13], public rejection of new distribution feeders due to environmental concerns [14], and increased environmental consciousness in conventional power generation [15]. The demand for 'green' sources of energy and the risk that DG can help increase the security of supply, particularly for load shaving applications, further drive this trend [16].

Proper positioning of DG is important in an electrical system, as improper positioning results in more system losses, fluctuating voltages, and overall costly impacts [17]. Several methodologies for identifying optimal locations and sizing for DG in power systems have been proposed, including conventional algorithms and artificial intelligence (AI) methods.

PV systems offer several advantages, including reduced transmission losses, enhanced voltage stability, and decreased reliance on conventional fossil fuel-based generation. According to Díaz-González et al. (2012), PV integration can significantly improve the overall efficiency and sustainability of power systems [18].

Optimal placement of PV systems is crucial for maximizing their benefits. Research by Jordehi (2016) highlights various algorithms and methods, such as genetic algorithms, particle swarm optimization, and artificial neural networks, to determine the best locations for PV installations. These methods consider factors such as load demand, line losses, and voltage profiles [19].

Sizing of PV systems involves determining the appropriate capacity to install at each location to meet specific objectives. Zhao et al. (2013) emphasize the importance of accurate sizing to avoid overinvestment and ensure optimal performance. Sizing must balance the initial installation cost, expected energy yield, and potential benefits in loss reduction and voltage support [20].

One of the primary concerns with integrating PV systems is maintaining voltage stability. Studies by Bouzguenda et al. (2010) show that appropriately sized and placed PV systems can enhance voltage profiles, especially in weak grids or areas with significant load variations [21].

PV systems can effectively reduce transmission losses by generating power closer to the load centers. Research by Al-Hadhri et al. (2019) demonstrates that distributed PV generation can lower the burden on distribution feeders, resulting in decreased losses and improved efficiency [22].

3. Unveiling Solar Power's Forecasting

Solar energy is impressively ubiquitous, and perhaps the most daunting task about solar energy is forecasting the unstable output. Instead of the stable cycle seen in burning coal or the more modern natural gas for power plants, solar energy directly interacts with the sun and sways in its rhythm, making it a continually changing source of energy. As we continue to rely on renewable energy sources such as solar energy to supply electrical energy, we must consider the art and science of solar power forecasting to manage the grid effectively.

One crucial factor in this process is the forecasting horizon, the number of periods for which forecasts are provided. The choice of the optimum horizon is context-dependent, requiring a balance between precision and period. Let's delve deeper into the different forecasting horizons and their real-world applications, drawing insights from established research:

Intra-hour (Nowcasting)

Existing in the territory from seconds to an hour, this horizon foresees the immediate future, nowcasting has been christened [23]. For example, picture a conductor of the power grid where it plays a significant role in maintaining or rather balancing the supply and demand. Nowcasting provides crucial insights into:

- **Grid Stability Guardian:** Nowcasting accounts for short-term changes in solar power output, enabling grid operators to fine-tune functions in real-time to ensure quality power and stable grids [24].
- **Spinning Reserve Orchestrator:** It uses “spinning reserves,” which are normal power plants kept on standby for urgent power demands. Nowcasting helps timely deploy these reserves to cover insufficient solar power generation [25].
- **Sub-hourly Market Maestro:** It is particularly helpful in regions with high solar potential but weak power systems, like island states, for bidding in electricity markets. By analyzing daily sunlight patterns, entities can maximize their financial gains [26].

Intra-day

The first horizon with a short-term forecast lasting 1 to 6 hours is used in regulating electricity loads and trading electricity outside the normal grid system [24]. Different hours-based prediction research includes using the NWP dataset for very short-term forecasts (VSTF), while intra-day predictions enhance the accuracy of the NWP by integrating future climatic information [27-29]. Here's how intra-day forecasting benefits the system:

- **Zonal Load Guru:** Electricity grids are segmented into zones based on specific requirements. Intra-day forecasting helps manage fluctuating solar power in a particular region, allowing operators to maintain the supply-demand balance [24].

- **Off-grid Electricity Matchmaker:** Intra-day forecasting enables players in the open electricity market to trade electricity outside of the grid. It provides information on short-term solar power contracts, aiding in buying and selling decisions [30].

Day-ahead

This horizon lasts from 6 hours to 48 hours and is useful in utility planning and unit commitment, determining which generating units should be dispatched the following day [31]. Day-ahead reports typically use NWP outputs augmented by weather trend predictions [32]. Here are the advantages of day-ahead forecasting:

- **Resource Allocation Sage:** Day-ahead forecasts help utilities plan resources effectively, avoiding over-reliance on the futures market. They maintain control over power plant schedules to stabilize the grid and operate cost-effectively [33].
- **Unit Commitment Strategist:** Day-ahead forecasts guide operational plans for unit commitment. Utilities identify which power plants to run to ensure adequate generation while minimizing operational expenses [31].

Long-term

Long-term forecasts extend from weekly or daily to monthly or even annual horizons. Though not often used and more prone to large errors due to inherent forecast uncertainties, they are occasionally valuable for long-term planning concerns [34]. Here's a breakdown of the two subcategories:

- **Monthly Forecaster:** Monthly forecasts enhance power production during peak seasons. Utilities can predict high/low generation times, utilizing this to their benefit [35].
- **Yearly Visionary:** Yearly forecasts provide general directions for further planning. Due to the subjective nature of long-term weather forecasts, they should be considered cautiously [34].

4. Methodology

4.1 Data Collection

PSSE software is a powerful tool used for simulating and analyzing the power flow in electrical networks. The steps involved in the power flow analysis are as follows:

1. **Data Input**: Enter the provided data into the PSSE software, ensuring accurate representation of each load, generation point, and transmission line.

2. **Network Modeling**: Model the network configuration, including one slack busbar that connected to the national grid and the 15 distribution feeders with their respective parameters.
3. **Load Flow Calculation**: Perform a load flow calculation to determine the voltage profile, power losses, and phase angles throughout the network.

Table 1. shows load flow results of the system using PSSE software. Power flow at the loads side and at the substation side have been determined as shown.

The data provided includes active and reactive power supplied and consumed, PL/Pg and QL/Qg ratios, line lengths, voltage at load, and phase angles for each of the 15 distribution feeders.

PL/Pg and QL/Qg ratios are: $\left(1-\frac{PL}{Pg}\right)\times 100$ and $\left(1-\frac{QL}{Qg}\right)\times 100$

This information is crucial for performing a power flow analysis using PSSE software.

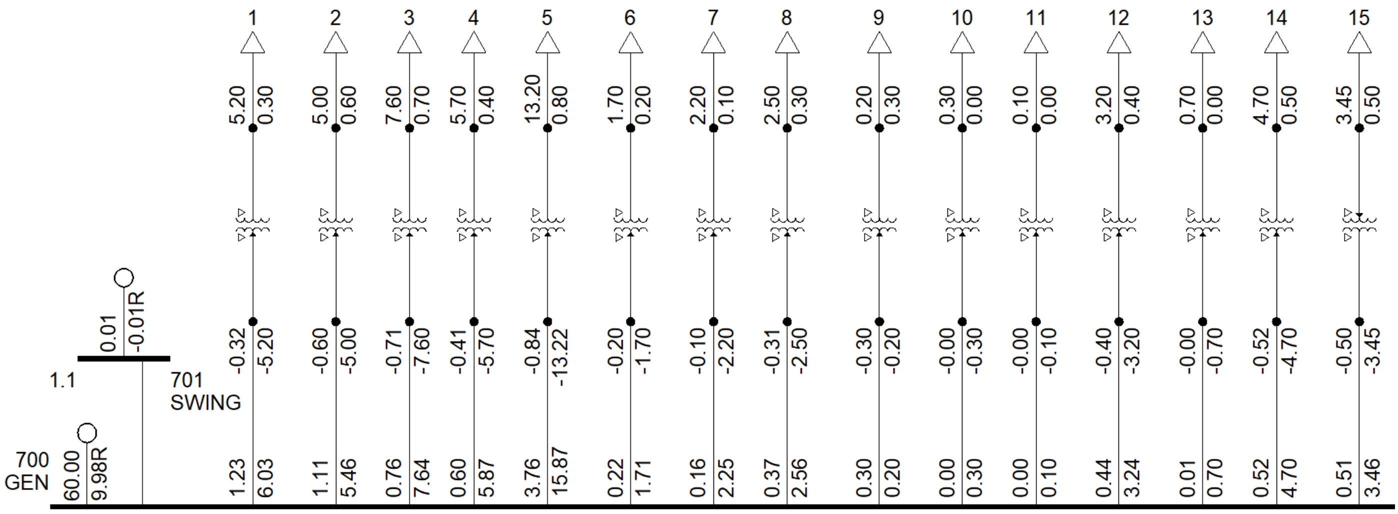

Fig. 1, Peshasazi station power flow with no PV installed

The data used for the simulation are based on the data of feeders of Peshasazi substation in Sulaimani city, and its power system consists of a Sub-station of 60MW feeding 15 branches. Data of the branches and load are shown in table below. Total consumed power on the buses is 60.09MW while total reactive power is 9.99 MVar. However, due to loss on the lines, delivered power to the loads is 55.7 [MW] and 5.1 [MVar] reactive power and total loss on the lines is 7.31% and 48.95%, respectively. As can be seen in Fig. 1.

Table 1: Peshasazi feeder data

Line	P_{BUS}	Q_{BUS}	P_{Load}	Q_{Load}	P_{Load}/P_{BUS} %	Q_{Load}/Q_{BUS} %	$V_{@load}$ pu	$Angle_{@load}$	Length [m]
L01	6.03	1.23	5.2	0.3	13.8	75.6	0.9324	-8.26	3708.746

L02	5.46	1.11	5	0.6	8.4	45.9	0.9962	-4.61	3403.4
L03	7.64	0.76	7.6	0.7	0.5	7.9	1.0958	-0.39	149.997
L04	5.87	0.6	5.7	0.4	2.9	33.3	1.0673	-1.81	8905.488
L05	15.87	3.76	13.2	0.8	16.8	78.7	0.8939	-9.86	5995.567
L06	1.71	0.22	1.7	0.2	0.6	9.1	1.0936	-0.46	265.329
L07	2.25	0.16	2.2	0.1	2.2	37.5	1.0771	-1.37	1983.061
L08	2.56	0.37	2.5	0.3	2.3	18.9	1.0734	-1.38	4041.71
L09	0.2	0.3	0.2	0.3	0.0	0.0	1.0965	0.04	1609.525
L10	0.3	0.0001	0.3	0	0.0	100.0	1.1024	-0.01	3850.792
L11	0.1	0.0001	0.1	0	0.0	100.0	1.1015	-0.05	3575.77
L12	3.24	0.44	3.2	0.4	1.2	9.1	1.0884	-0.66	3965.2
L13	0.7	0.01	0.7	0	0.0	100.0	1.0953	-0.43	31.821
L14	4.7	0.52	4.7	0.5	0.0	3.8	1.1012	-0.22	3282.037
L15	3.46	0.51	3.4	0.5	1.7	2.0	1.1005	-0.12	1352.433
Total	60.09	9.9902	55.7	5.1	7.3	48.9			42751.51

Considering Line L01, the voltage drop at the load is 0.9324 pu, which is significantly below the ideal value of 1 pu. This indicates a substantial voltage drop along the line. This drop in the magnitude can lead to several issues, like inefficient operation of electrical equipment, reduced lifespan of the equipment, and potential instability in the power system [36]. The angle at the load is -8.26°, which is a relatively large negative value. It indicates a high lagging power factor, which is due to inductivity of the load. The high lagging power factor may be a result of either an increased losses in the power system, or reduced capacity of the system to supply active power, or voltage stability issues [37]. This issue has several solutions for instance, reducing the load, increase in the power supply or upgrade the line conductors. In addition, installing voltage regulators, such as tap-changing transformers or voltage stabilizers, maintain the voltage closer to 1 pu, or through using capacitors and synchronous condensers to provide reactive power compensation. However, introducing distributed generation sources (like solar panels and wind turbines) closer to the load will reduce distance of the power has to travel, thereby reducing the voltage drops [38-39].

The next line that warrants is Line L05. This line has a significant load and shows a substantial voltage drop, indicating potential issues that could affect the overall power system stability and efficiency. Line L05 has one of the highest load values in terms of active power (13.2 MW). This high load can significantly impact the voltage stability and power quality on this line as obvious in the data of Table 01. The voltage at the load is 0.8939 pu, which is even lower than that of Line L01. This indicates a severe voltage drop, which will lead to significant operational issues. The angle at the load for Line L05 is -9.86 degrees, which is higher in magnitude compared to Line L01. The total length of all the feeders is 5995.567 meters.

Optimization Criteria

The criteria for optimizing the placement of solar sources include:

1. **Solar Source Placement**: Based on the initial analysis, strategically place solar sources on specific branches to optimize power flow and reduce losses. It is suggested to install PV solar source about 20% of the load [40-41]. The approach to begin with a smaller portion, like 20%, allows for initial assessment and adaptation before committing to larger-scale installations. This strategy helps manage initial costs, allows for performance monitoring, and ensures that any technical or operational issues can be addressed early on.
2. **Improving PL/Pg Ratios**: Place solar sources where PL/Pg ratios are significantly lower than 100%, indicating higher losses.
3. **Voltage Support**: Position solar sources where voltage levels are lower to maintain stability.
4. **Proximity to Loads**: Install solar sources close to higher loads to reduce transmission losses.

Considering above points in placing PV solar sources, it is necessary to choose the lines with the highest loss and have highest voltage drops, which are Line L01 and L05.

5. Result and Discussion

Case 1: L01 is selected with approximately 20% of the total load to be out of PV solar source, i.e. 1.0MW PV solar source. After adding the dedicated power source to line L01 at the load side, the measured data of that line are: P_{load}=5.2MW, Q_{Load}=0.3Mvar, P_{BUS}=4.69MW, Q_{BUS}=-0.1MVar, V_{Load}=1 pu, $Angle_{Load}$= -7.33 deg. Data of all of the lines kept the same.

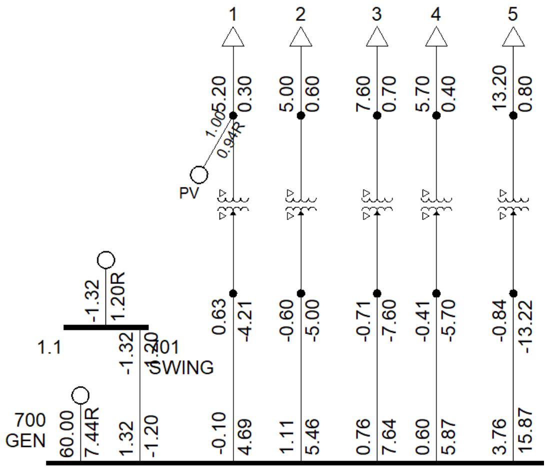

Fig. 2, adding 1.0MW PV solar on Line L01.

The addition of a 1.0MW solar PV system to Line L01 has significantly improved the voltage regulation, power factor, and overall efficiency of the power system. By decreasing both the active and reactive power demands from the grid, the solar PV system has alleviated stress on the main power supply and enhanced the stability and performance of the electrical network. So, adding 1.0MW, makes P_{BUS} lower than before by 1.34MW which is 0.34MW higher than what is required to transfer to the load. Hence, the power source not only reduced by 1.0MW but also reduced by 0.34MW extra which was a loss on the wire transmission. That is approximately 34% benefit on the power plants for the amount installed on L05 load.

Case 2: adding a 20% PV solar source on line L05 load, i.e. 2.64MW on line L05. The measured data became: P_{Load}=13.2MW, Q_{Load}=3.85MVar, P_{BUS}=12.04MW, Q_{BUS}=-1.41MVar, V_{Load}=1 p.u., Q_{Load}= -9.04 deg. Data of all other lines kept the same.

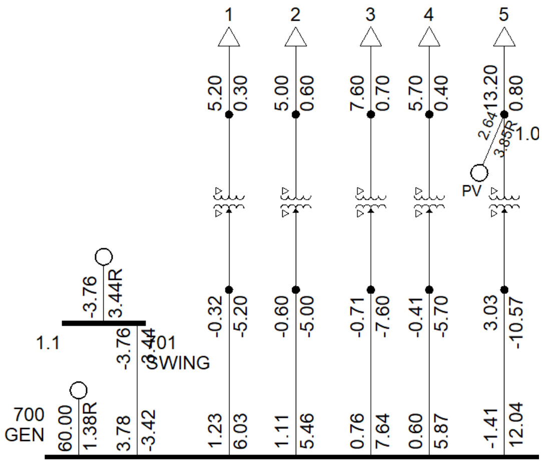

Fig. 3, adding 2.64MW PV solar on Line L05.

By the same way as the improvement done on line L01 when the PV solar source was added, the same results obtained on line L05 as well. So, adding 2.64MW to the load reduces the necessary power from the generated power on the Bus and it became 12.04MW instead of 16.8MW as before, which is a reduction of approximately 16.8-2.64=14.16MW. Hence a reduction of approximately of 2.12MW lower than before which is about 3.5% less generation than without installing PV Solar source.

Same procedure can be applied on line L02 by adding a 1MW PV solar system to overcome the loss on that line.

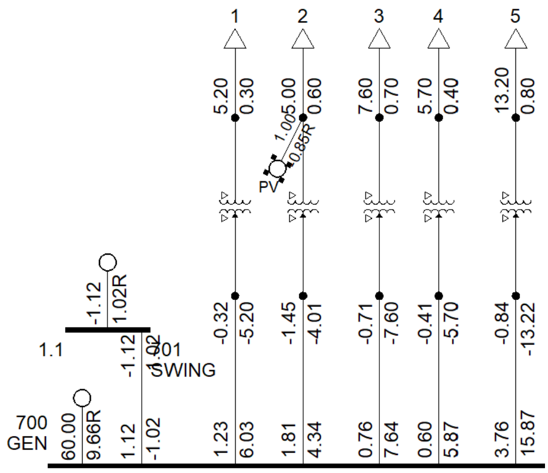

Fig. 4, adding 1.0MW PV solar on Line L02.

6. Conclusions

This study highlights the critical role of solar power integration into existing electrical grids as a solution to meet the increasing electricity demand and facilitate the transition towards more sustainable energy sources. Utilizing PSSE software, we performed an in-depth power flow analysis on a network supplied by approximately 60 MW, pinpointing key areas that experience significant voltage drops and power losses. Through this analysis, we identified optimal locations and sizing for solar PV systems by taking into account factors such as power generation capacity, voltage stability, and proximity to major load centers.

Our results demonstrate that the strategic placement of solar PV systems can effectively alleviate voltage instability issues and significantly reduce transmission losses, leading to a more efficient power distribution. This optimization not only improves the operational efficiency of the grid but also enhances its resilience against fluctuations in demand and supply, fostering a more reliable and sustainable energy infrastructure.

The findings underscore the importance of incorporating renewable energy sources as part of long-term energy planning, particularly in areas prone to grid instability. Moving forward, future research should explore real-time monitoring and adaptive control mechanisms to further streamline the integration of renewable energy into the grid. By focusing on dynamic adjustments and intelligent grid management, there is potential to greatly improve the efficiency and sustainability of modern power systems, ensuring they can meet both current and future energy needs.

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