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Impact Assessment of Grid-Connected Solar Photovoltaic Systems on Power Distribution Grid: A Case Study on a Highly Loaded Feeder in Ulaanbaatar Ger District

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Abstract: Adopting and widely implementing solar photovoltaic (PV) systems are regarded as a promising solution to address energy crises by providing a sustainable and independent electricity supply while significantly reducing greenhouse gas emissions to combat climate change. This encourages households, organizations, and enterprises to install solar PV systems. However, there are many solar PV systems that have been connected to the power distribution grid without following the required procedures. Power distribution grid operators cannot detect the locations of these solar PV systems. Thus, it is necessary to assess the impact of solar PV systems on the power distribution grid in detail, even though there are multiple economic and environmental advantages associated with installing solar PV systems. This study analyzes the changes in an overloaded power distribution grid's power losses and voltage deviations with solar PV systems. There are two main factors considered for assessing the impact of the solar PV system on the power distribution grid: the total installed capacity of the solar PV systems and the location of the connection. Based on a comparison between the measurement results of three feeders with higher loads in the Ulaanbaatar area, the Dambadarjaa feeder, which has the highest load, was selected. The impact of the solar PV systems on the selected feeder was analyzed by connecting eight solar PV systems at four different locations. Their total installed capacities vary between 25 and 80 percent of the highest daily load of the selected feeder. The results show that the power loss of the feeder can be greatly reduced when the total installed capacity of the solar PV systems is selected optimally, and the location of the connection is at the end of the power distribution grid.

Keywords: solar photovoltaic systems; power distribution grid; power loss; voltage deviation

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1. Introduction

The widespread adoption of solar photovoltaic (PV) systems is increasingly being recognized as a transformative solution to address global energy crises while simultaneously mitigating greenhouse gas emissions [1]. As of 2023, the cumulative global installed capacity of solar PV systems exceeded 1400 GW, reflecting a tenfold increase from just over 100 GW in 2012 [2]. This remarkable growth has been driven by advancements in technology, which have reduced solar module prices by approximately 85% since 2010, coupled with supportive policy frameworks such as feed-in tariffs and renewable energy subsidies [3]. In comparison to other renewable energy sources such as wind or hydropower, solar PV systems offer distinct advantages, including scalability, versatility in installation on urban rooftops or rural landscapes, and the absence of location-specific constraints like consistent wind speeds or water availability. These unique attributes make solar PV systems particularly well suited for decentralized energy generation, empowering regions with limited access to traditional grid infrastructure [4].

In line with this global trend, the development of solar PV systems and their associated legal frameworks is expanding beyond highly developed countries to include developing nations [5]. Mongolia, for example, has made significant progress in this area, with several solar power plants of megawatt capacities commissioned over the past decade [6]. Additionally, a large number of small-scale solar PV systems have been successfully connected to the power distribution grid, as reported by the Ulaanbaatar Electricity Distribution Network (UBEDN) state-owned company. To support this growth, Mongolia approved regulations for the interconnection of consumer renewable energy systems to the grid in August 2020, with an updated version released in 2024 [7]. Furthermore, extensive research efforts are being conducted by academic institutions in Mongolia to further advance solar PV systems and their operation [8–11]. As a result of these developments, the number of households, organizations, and enterprises interested in installing solar photovoltaic systems continues to rise steadily.

The integration of solar PV systems into existing power grids, in addition to addressing energy crises and reducing greenhouse gas emissions, has been a focal point of extensive research. A number of studies have explored the impact of solar PV integration on power distribution grids [12–16].

One of the major concerns associated with increased solar PV penetration is its potential effect on voltage quality within the distribution grid. Solar PV generation typically peaks during daylight hours, which can lead to overvoltage when generation surpasses local consumption. This imbalance can result in undesirable consequences such as voltage fluctuations, reverse power flow into the grid, and increased system losses. Several studies have identified these challenges and proposed mitigation strategies to address them [12,13].

For instance, a study using an IEEE 13-bus test case examined the impact of solar PV integration on the distribution grid. By simulating different scenarios with varying levels of PV penetration in the Open Distribution System Simulator (OpenDSS) and interfacing with MATLAB, the study found that higher penetration levels led to more frequent voltage issues and higher system losses. These outcomes necessitated the implementation of corrective actions, such as deploying voltage regulation devices and optimizing inverter settings to mitigate power quality problems [12].

Similarly, an analysis of a real distribution feeder in South Australia revealed that while increasing PV penetration helped reduce instances of undervoltage, it simultaneously caused a significant rise in overvoltage occurrences. This overvoltage led to inverter shutdowns when voltage levels exceeded the maximum limits for inverters. The study also quantified the financial losses resulting from PV curtailment due to overvoltage-induced shutdowns, underlining the importance of considering these financial impacts when planning for greater PV hosting capacity in distribution networks [13].

In addition to voltage issues, the integration of solar PV systems can affect the reliability of distribution systems. A Monte Carlo simulation conducted on the RBTS Bus 2 system assessed how different levels of solar PV integration influence Energy Not Supplied (ENS) during system outages. The results demonstrated that solar PV can significantly reduce ENS, particularly during the day when solar generation is at its peak. This highlights the potential for solar PV to improve the reliability of distribution grids by mitigating energy shortages during outages [14].

Moreover, high levels of rooftop PV penetration can interfere with the operation of voltage-regulating devices, such as tap-changing transformers and reactive power compensators. These devices are designed to maintain voltage levels within acceptable bounds, but the reverse power flow caused by excess PV generation can disrupt their function. The literature suggests that one solution to these challenges is the adoption of smart inverters. These inverters can adjust their output dynamically in response to grid conditions, alleviating many of the voltage-related problems associated with high PV penetration. A review of the impacts of rooftop PV systems highlighted the crucial role of smart inverters in enabling higher levels of PV integration. By providing voltage control and reactive power support, smart inverters reduce the burden on traditional voltage-regulating devices, facilitating smoother integration of solar PV into the distribution grid [15]. Additionally, the complexity of managing solar PV generation is increasing, as it presents more challenges than conventional electricity sources [16].

The high number of households in ger districts, coupled with their sparse distribution, necessitates the construction of extensive power distribution grids. This design leads to issues such as overload and undervoltage, particularly at the end of the lines, as well as higher-than-normal power losses. These challenges are unique to areas like the Ulaanbaatar ger district and may not be fully represented in studies that use more conventional or simplified grid models, such as the 13-bus system or low-voltage systems. Consequently, it is essential to study the impact of solar PV systems on the power distribution grid in these districts in detail. Such research can help address power quality issues in Mongolia, particularly in Ulaanbaatar and other densely populated areas, while also reducing power and electricity losses in distribution lines and substations. Furthermore, understanding the optimal use of small-scale solar PV systems, in compliance with existing regulations, can facilitate the injection of energy into the grid from distributed renewable energy sources owned by consumers. By considering the specific characteristics of overloaded feeders with unevenly distributed loads, this study contributes to optimizing the integration of solar PV systems in areas facing unique grid infrastructure challenges, which are often overlooked in broader studies.

This study examines the impact of solar PV systems on the power distribution grid by analyzing changes in power losses and voltage deviations under various scenarios. Two primary factors are considered in the assessment: the installed capacity of the solar PV systems and the location of their connection to the grid. Among three heavily loaded feeders in the Ulaanbaatar area, the Dambadarjaa feeder with the highest load was selected for detailed analysis. The robustness of the methodology was assessed by evaluating eight distinct scenarios, with solar PV systems connected at four primary locations: the beginning, middle, end, and evenly distributed throughout the grid. The installed capacities of the solar PV systems range from 25% to 80% of the feeder's highest daily load. The results consistently demonstrated that power loss reduction is most significant when the total installed capacity of the solar PV systems is 75% of the feeder's highest daily load and the systems are connected at the end of the power distribution grid. While additional scenarios with slight variations could be considered, the differences in outcomes are expected to be minimal due to the comprehensive nature of the analyzed cases. This consistency across multiple scenarios highlights the robustness of the methodology, ensuring its reliability under varying operating conditions.

This study demonstrates that strategic placement and sizing of solar PV systems can significantly enhance grid reliability, reduce power losses, and support higher penetration levels of solar PV systems within acceptable ranges. These insights not only inform grid policy and planning but also contribute to the development of a more sustainable and efficient energy infrastructure.

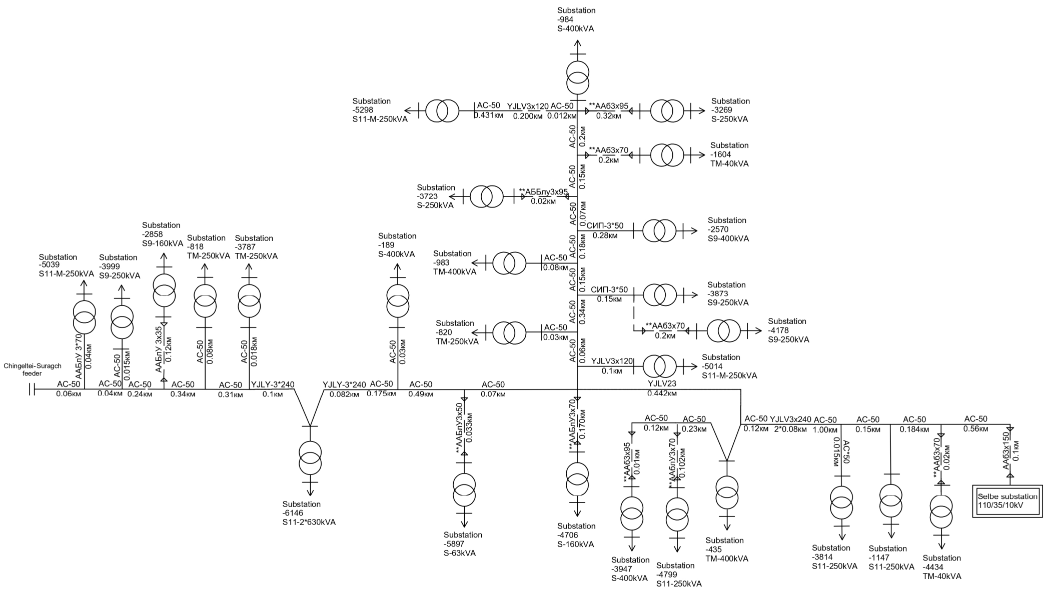
2. Power Distribution Grid and Solar PV Systems

2.1. Power Distribution Grid

The power distribution grid owned by the UBEDN state-owned company is analyzed for the selection of feeders. The following feeders have the most significant number of consumers connected to them and show the highest loads based on the load measurement data. This includes the following:

- The Chingeltei feeder;
- The Sogoot feeder;
- The Dambadarjaa feeder.

Especially during the high load period in the winter, the Chingeltei, Sogoot, and Dambadarjaa feeders supplied up to 2573 kW, 1934 kW, and 3149 kW, respectively. Figure 1 shows the equivalent schemes of these feeders. Thus, the Dambadarjaa feeder was selected as it has the highest load among the other feeders. Figure 2 shows the measured load of the selected feeder for a year on a monthly basis. It can be seen that the peak load occurred between November and February, varying in a range of 2 MW to 3 MW. The load is reduced between June and August, supplying 0.5 MW to 1.5 MW.



(**a**)

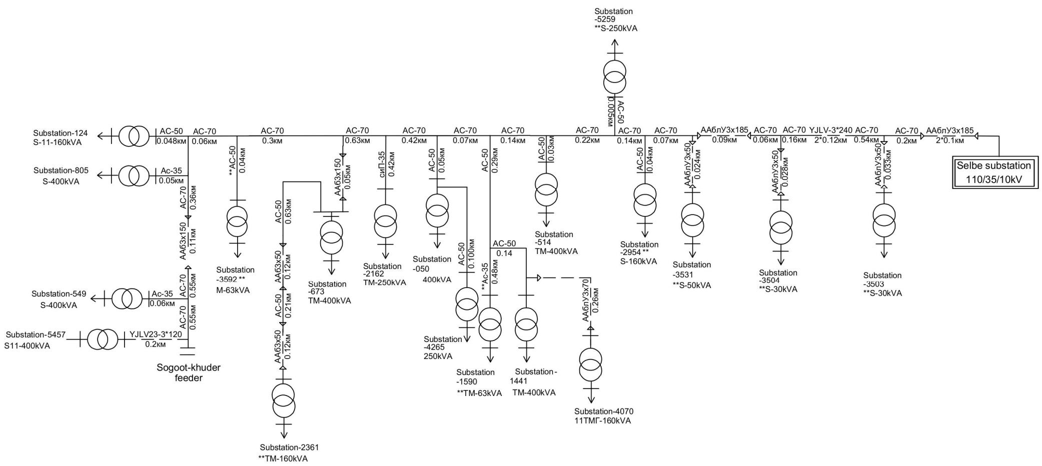


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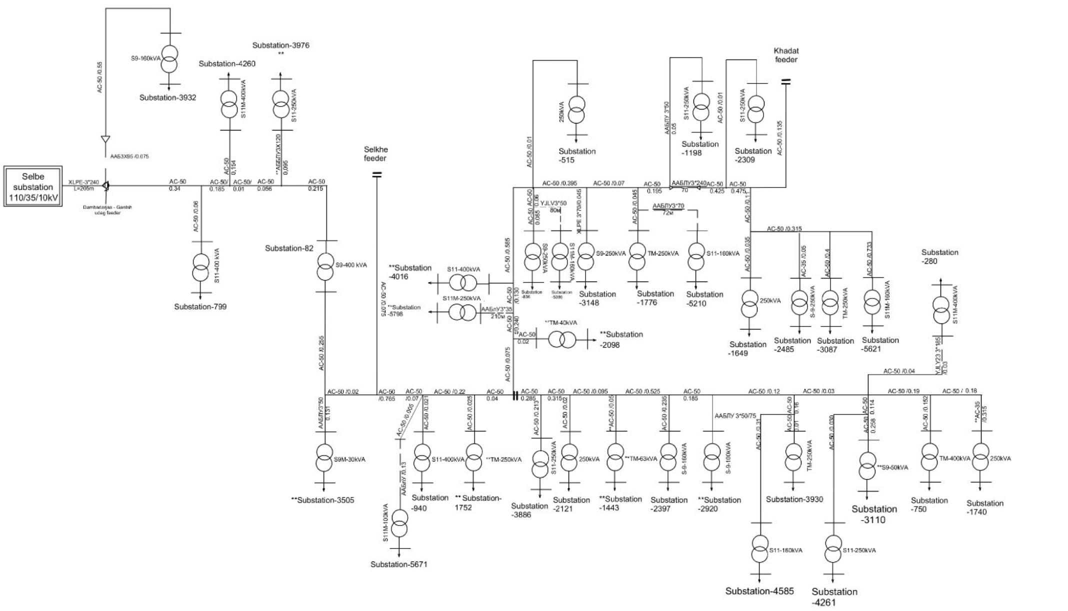
Figure 1. *Cont.*



(**c**)

Figure 1. Equivalent schemes of the feeders with the highest loads in 110/35/10 kV Selbe substation: (**a**) Chingeltei feeder; (**b**) Sogoot feeder; (**c**) Dambadarjaa feeder, where symbol "/" expresses the nominal cross-section of the cable.

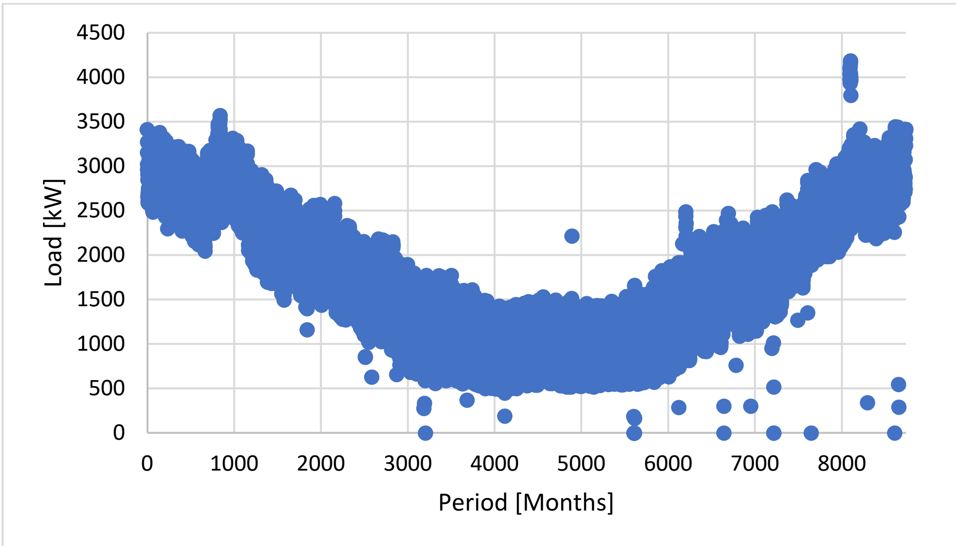


Figure 2. Measured loads of the Dambadarjaa feeder shown on a monthly basis.

2.2. Generation of Solar PV Systems

The average solar irradiation and ambient temperature data are extracted from the Metronorm [17]. Figure 3 shows Ulaanbaatar City's monthly solar irradiance and temperature. Solar irradiance and ambient temperature are highly relevant [18]. In addition, the temperature coefficient of the PV module was taken from the manufacturer's datasheet.

The equation for estimating the output power and performance of a PV module is expressed as

$$P_{estimated} = P_{mp}\Big(1 + \gamma_{coef}(T_{module} - T_{stc})\Big) \cdot G. \quad (1)$$

The total and annual energy generation can be calculated by

$$E_{total} = P_{mp} \cdot PSH \cdot PR \quad (2)$$

and

$$E_{yield} = E_{total} / P_{mp}. \tag{3}$$

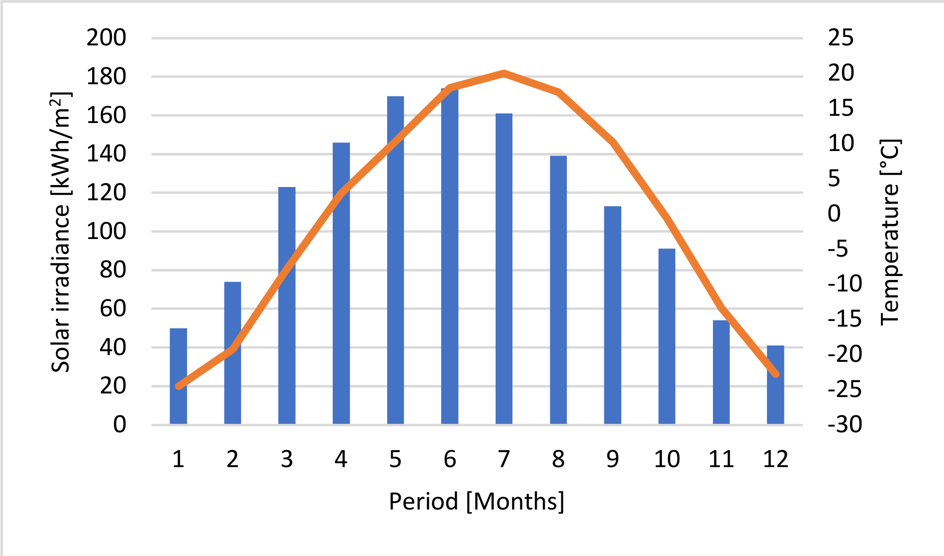


Figure 3. Solar irradiance and ambient temperature in Ulaanbaatar.

2.3. Load Flow of Electric Power System

The active power transferred through a power line generates heat in the core and windings of a transformer, and the reactive power is used to generate magnetic fields in the transformer and line. The power plant generator or source of power supplies an amount of power that not only meets the load of users but also causes the active and reactive power losses in the system [19]. In order to reduce power losses, solar PV systems should be connected near the users. This can reduce the power transmitted through the line.

The state corresponding to each instant of time of the electric power system is called a load flow. The calculation to find the load flow parameters of the system is called load flow analysis. Load flow analysis of the transmission line is multi-step, and each iteration consists of 2 main parts: power balance calculation and voltage balance calculation.

3. Solar PV Systems Connected to Power Distribution Line

In order to assess the impact on voltage deviation and transmission losses when solar PV systems are connected to the Dambadarjaa feeder of the Selbe substation, four different connection points of solar PV systems were studied. The impact of connecting solar PV systems with a capacity of 25 to 80 percent of the feeder's daily load was studied at each connection point. PowerFactory simulation software V.15.1.7 was used in this study. The NU-RC300 solar PV module was chosen for all simulations conducted in this study. The design parameters of the selected PV module are detailed in Table 1.

Figure 4 shows a developed scheme of the Dambadarjaa feeder on the worksheet of the simulation software. The length of the Dambadarjaa feeder line is 6.81 km, and the total length is 11.42 km. In total, 36 units of 10/0.4 kV transformers with different rated powers are connected to the Dambadarjaa feeder. The location of each unit is shown in Figure 5a and the specifications of each unit are listed in Table 2.

Table 1. Design parameters of a solar PV module used in this study.

Design Parameter	Value [Unit]
Module Material	Si monocrystalline
Manufacturer	Sharp
Model No.	NU-RC300
Maximum Power	300 Wp
Voltage at Maximum Power	31.2 V
Current at Maximum Power	9.63 A
Open Circuit Voltage	39.4 V
Short Circuit Current	9.97 A
Module Efficiency	18.3%
Power Tolerance	+5%
Operating Temperature Range	−40~85 °C
Physical Dimension (H/W/D)	1660 × 990 × 50 mm

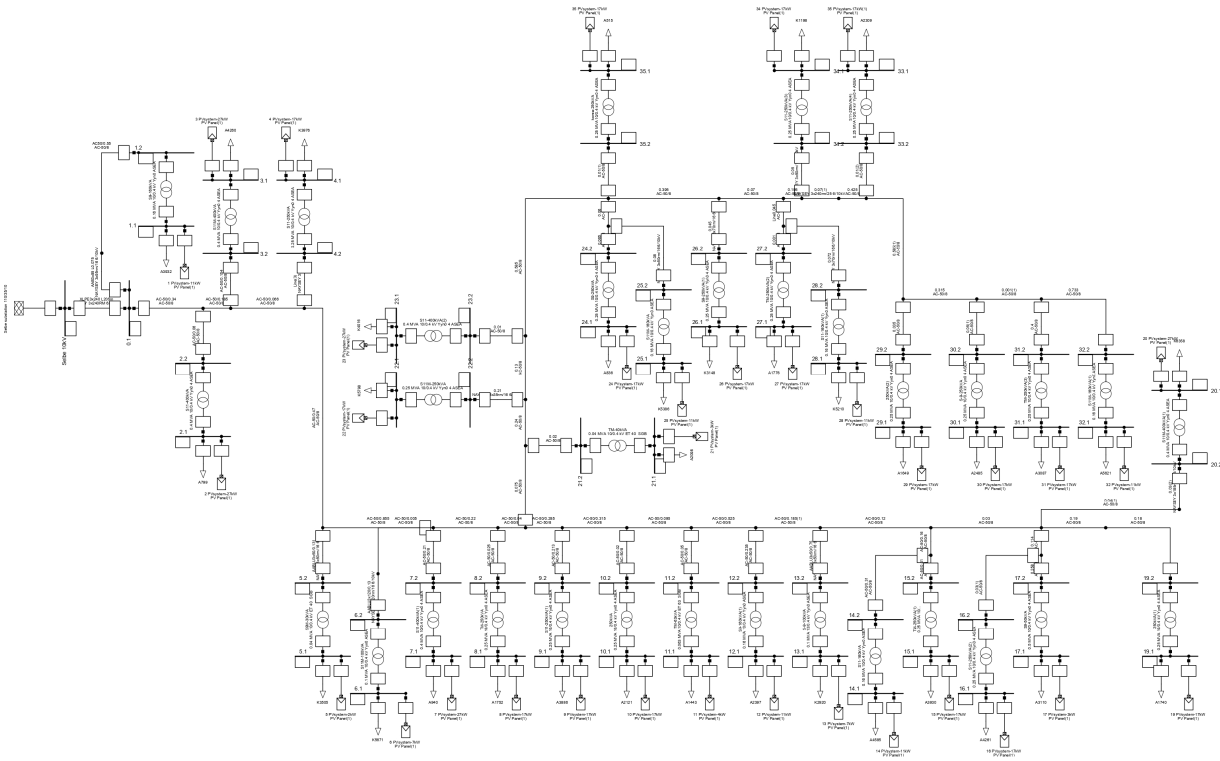
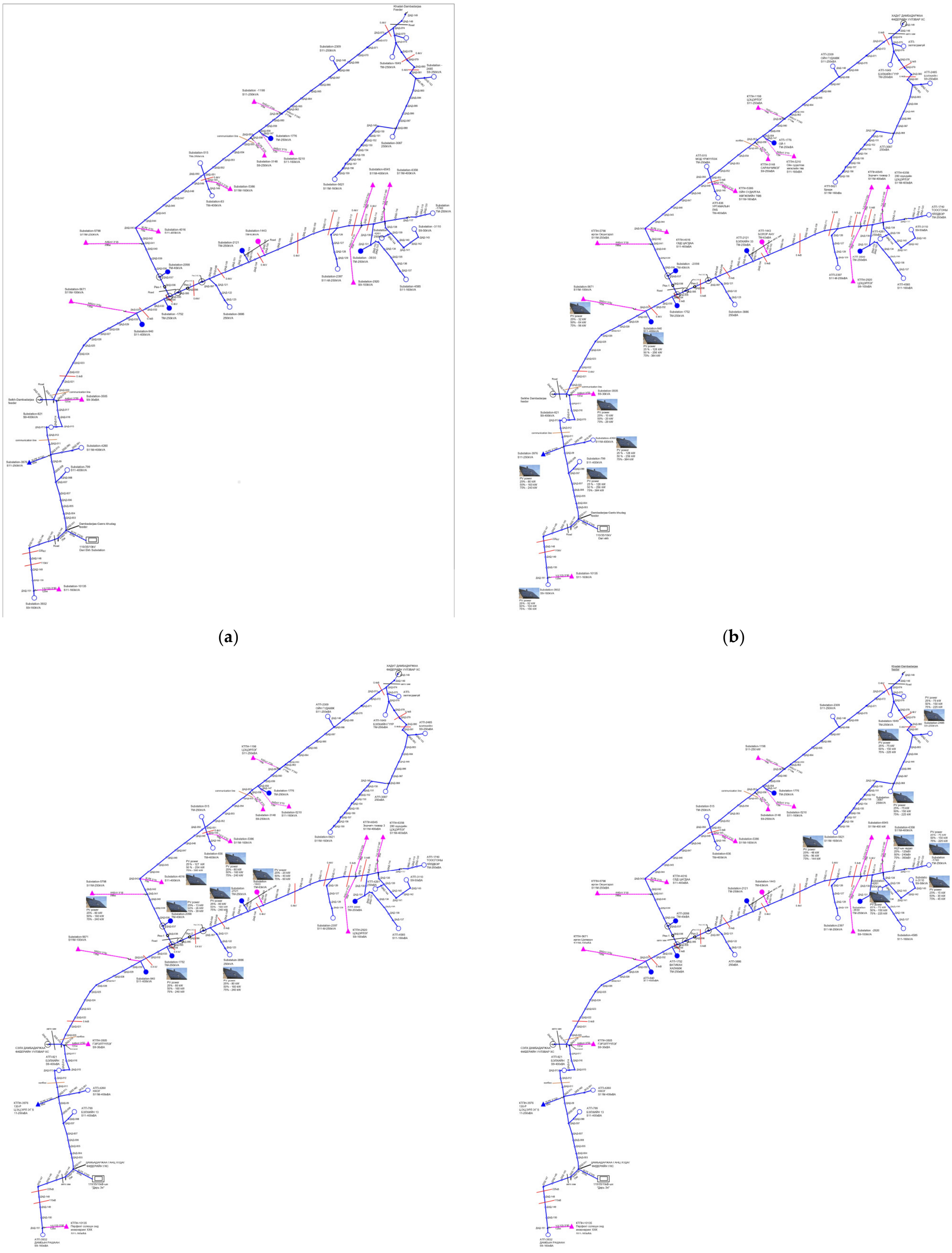


Figure 4. A developed scheme for the Dambadarjaa feeder using the PowerFactory simulation software.

Table 2. The specifications of each 10/04 kV transformer connected to the Dambadarjaa feeder.

No.	No. of Transformers	Rated Power [kVA]
1	1	30
2	1	40
3	1	50
4	1	63
5	2	100
6	6	160
7	17	250
8	7	400



(a) (b) (c) (d)

Figure 5. Dambadarjaa feeder map from 110/35/10 kV Selbe substation with solar PV systems connected at different points: (**a**) Dambadarjaa feeder map from 110/35/10 kV Selbe substation; (**b**) solar PV systems connected at the beginning of the power distribution line; (**c**) solar PV systems connected at the middle of the power distribution line; and (**d**) solar PV systems connected at the end of the power distribution line.

Based on the measurement results, the seasonal load conditions of the selected feeder were determined. Table 3 shows the seasonal lowest and highest loads of the selected feeder, which has a distribution capacity of 2.2 MW. In winter, the lowest and highest loads were equal to 116.89% and 157.47% of the installed capacity of the selected feeder, respectively. It can be seen that the feeder is continuously overloaded during the winter season, resulting in a high temperature and reduced lifetime of the equipment. While the lowest load of the selected feeder was 27.56%, and the highest load was 70.72% in summer. Thus, it can be seen as the load conditions of the power distribution grid strongly depend on the season.

Table 3. The seasonal lowest and highest loads of the Dambadarjaa feeder.

Season	Lowest Load [%]	Highest Load [%]
Winter	116.89	157.47
Spring	64.13	104.96
Summer	27.56	70.72
Autumn	68.61	111.35

3.1. Solar PV Systems Connected at the Beginning of the Power Distribution Line

The power distribution line is divided into three sections: beginning, middle, and end. There are seven transformers connected at the beginning of the power distribution line. These transformers have rated powers of 1 × 30 kVA, 1 × 100 kVA, 1 × 160 kVA, 1 × 250 kVA, and 3 × 400 kVA. The total installed capacity of the solar PV systems was selected to be 25% to 80% of the highest daily load of the feeder, while the installed capacity of each solar PV system was chosen to be up to 75% of the highest load measured on the connected transformer. Figure 5b shows the location of each substation and solar PV system connected at the beginning of the power distribution line. According to the results obtained from the simulation using the PowerFactory software, the daily power losses of the Dambadarjaa feeder were 4319 kWh when there no solar PV systems were connected. This could be reduced by 90 kWh by installing the solar PV systems at the beginning of the feeder. In this case, the total capacity was equal to 25% of the highest daily load of the feeder. The power loss reduction of 90 kWh accounts for 2% of the daily power losses.

Then, the total capacity of the solar PV systems was increased to 50% and 80% of the feeder's highest daily load. The corresponding energy losses were reduced by 3.5% and 4.1%, respectively.

3.2. Solar PV Systems Connected in the Middle of the Power Distribution Line

There are eight transformers connected in the middle of the power distribution line. Their rated powers are 1 × 40 kVA, 1 × 63 kVA, 4 × 250 kVA, and 2 × 400 kVA. The total installed capacity of the solar PV systems was decided in the same way that was used in the previous scenario. Figure 5c shows the location of each transformer and solar PV system connected in the middle of the power distribution line. The losses of the Dambadarjaa feeder were reduced by 224 kWh by installing solar PV systems with a total capacity equal to 25% of the highest daily load of the feeder—the power loss reduction of 224 kWh accounts for 5.1% of the daily power losses.

Like the previous simulation, the total capacity of the solar PV systems was increased to 50% and 80% of the feeder's highest daily load. The corresponding energy losses were reduced by 9.4% and 11.5%, respectively. Thus, it can be seen that the losses could be reduced more when solar PV systems are installed in the middle of the power distribution line.

3.3. Solar PV Systems Connected at the End of the Power Distribution Line

There are also eight transformers connected at the end of the power distribution line. Their rated powers are 1 × 50 kVA, 1 × 160 kVA, 5 × 250 kVA, and 1 × 400 kVA. The sizing of the solar PV systems was completed in the same way as the previous two scenarios. Figure 5d shows the location of each substation and solar PV system at the end of the power distribution line. The losses of the Dambadarjaa feeder were reduced by 258 kWh by installing solar PV systems with a total capacity equal to 25% of the highest daily load of the feeder—the loss reduction of 258 kWh accounts for about 6% of the daily power losses.

As with the previous simulation, the total capacity of the solar PV systems was increased to 50% and 80% of the feeder's highest daily load. The corresponding energy losses were reduced by 10.7% and 12.9%, respectively. The reduction rates of power losses were increased while connecting the solar PV systems at the end of the power distribution line.

3.4. Solar PV Systems Evenly Distributed Along the Power Distribution Line

To assess the effects based on different connection points, solar PV systems distributed evenly along the power distribution line were also examined. Several transformers were systematically chosen along the line until their total installed capacity reached 80% of the feeder's highest daily load. Subsequently, the sizing of the solar PV systems was determined for each selected transformer, varying between 25% and 80% of the feeder's peak daily load.

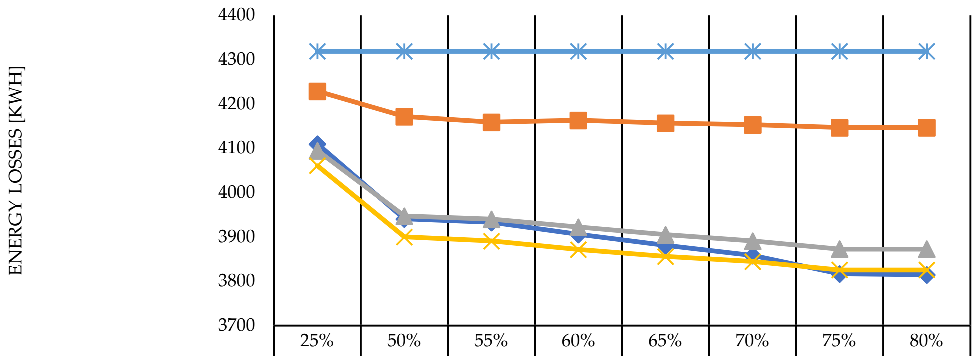
The simulation results from the PowerFactory software showed that the daily power losses of the Dambadarjaa feeder were 4319 kWh when no solar PV systems were connected. With this connection scenario, power losses were reduced by 5%, with the total system capacity set to 25% of the feeder's peak load. As the total capacity of the solar PV systems was increased to 50% and 80% of the feeder's highest daily load, energy losses decreased by 9.5% and 13.2%, respectively.

4. Analyses of Energy Loss Reductions and Voltage Deviations

Figure 6 summarizes energy losses on the feeder depending on the solar PV systems' total installed capacity and connection points. The vertical axis represents energy losses on the feeder. The horizontal axis indicates the ratio of the total installed capacity of the solar PV system and the feeder load by percentage. In order to clearly show the reduction rates of the energy losses, the scenario with no solar PV systems has been added to the existing four scenarios with different connection points. The energy loss has a constant value of 4319 kWh in the scenario with no solar PV systems shown by the light-blue line. The scenarios with solar PV systems connected at the power distribution line's beginning, middle, and end are shown in orange, gray, and amber, respectively. From the comparison shown in Figure 6, it is clear that the associated energy losses could be reduced by the highest percentage when the solar PV systems were connected at the end of the power distribution line until the installed capacity reached 70%. Afterward, the evenly distributed solar PV systems showed lower energy losses when the total installed capacity exceeded 75% of the feeder's highest daily load (for more information, please see the numerical data at the bottom part of Figure 6).

Figure 7 shows the costs associated with daily energy losses. The costs of daily energy losses are calculated based on the measured energy losses presented in Figure 6. To estimate these costs, the electricity tariff set by the Energy Regulatory Commission of Mongolia in November 2024 was used. The analysis reveals that the largest cost arises from the scenario without any solar PV systems, while the cost of energy losses is significantly reduced in scenarios where solar PV systems are connected to the end of the power distribution grid.

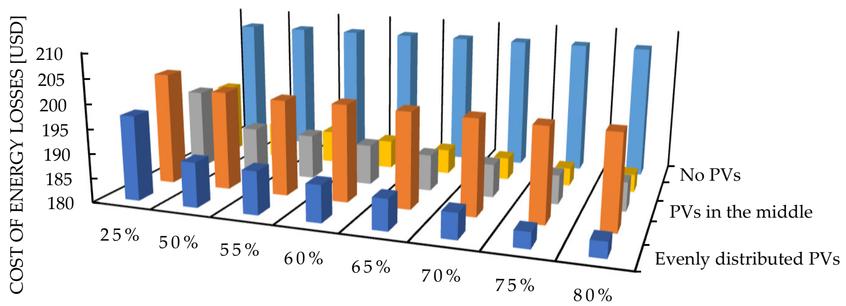
This reduction highlights the potential benefits of integrating solar PV systems into the grid, particularly at strategic locations, to minimize energy losses and associated costs.



	25%	50%	55%	60%	65%	70%	75%	80%
Evenly distributed PVs	4110	3941	3933	3906	3881	3858	3817	3815
PVs at the beginning	4229	4172	4159	4163	4157	4153	4147	4147
PVs in the middle	4095	3947	3940	3922	3905	3891	3873	3873
PVs at the end	4061	3900	3891	3872	3856	3845	3826	3826
No PVs	4319	4319	4319	4319	4319	4319	4319	4319

TOTAL INSTALLED CAPACITY OF SOLAR PV SYSTEMS BY THE PERCENT OF THE DAILY HIGHEST LOAD OF THE FEEDER

Figure 6. Energy losses depend on the total installed capacity and connection points of solar PV systems with regard to the feeder load.



	25%	50%	55%	60%	65%	70%	75%	80%
Evenly distributed PVs	197.28	189.17	188.78	187.49	186.29	185.18	183.22	183.12
PVs at the beginning	202.99	200.26	199.63	199.82	199.54	199.34	199.06	199.06
PVs in the middle	196.56	189.46	189.12	188.26	187.44	186.77	185.90	185.90
PVs at the end	194.93	187.20	186.77	185.86	185.09	184.56	183.65	183.65
No PVs	207.31	207.31	207.31	207.31	207.31	207.31	207.31	207.31

TOTAL INSTALLED CAPACITY OF SOLAR PV SYSTEMS BY THE PERCENT OF THE DAILY HIGHEST LOAD OF THE FEEDER

Figure 7. Costs of energy losses depend on the total installed capacity and connection points of solar PV systems with regard to the feeder load.

In order to analyze the voltage deviations on the selected feeder, voltage probes were placed at the beginning, middle, and end of the power distribution line. As a result of the simulation with no solar PV systems, the probed voltages at the beginning, middle, and end of the power distribution line reached 0.9935 p.u., 0.96368 p.u., and 0.94846 p.u., respectively.

Figure 8 shows the probed voltage deviations at the beginning of the power distribution line depending on the installed location of solar PV systems, where the vertical, primary horizontal, and secondary horizontal axes illustrate the voltage per unit, time in hours, and total installed capacity in the percentage of the highest daily load of the feeder. By installing the solar PV systems at the beginning, middle, and end of, or evenly distributed throughout, the power distribution line, the voltage could be increased to 0.99961 p.u., 0.99961 p.u., 0.99962 p.u., and 0.99961 p.u., respectively. In this case, the closest value to the rated voltage can be obtained with the installation of solar PV systems at the end of the power distribution lines.

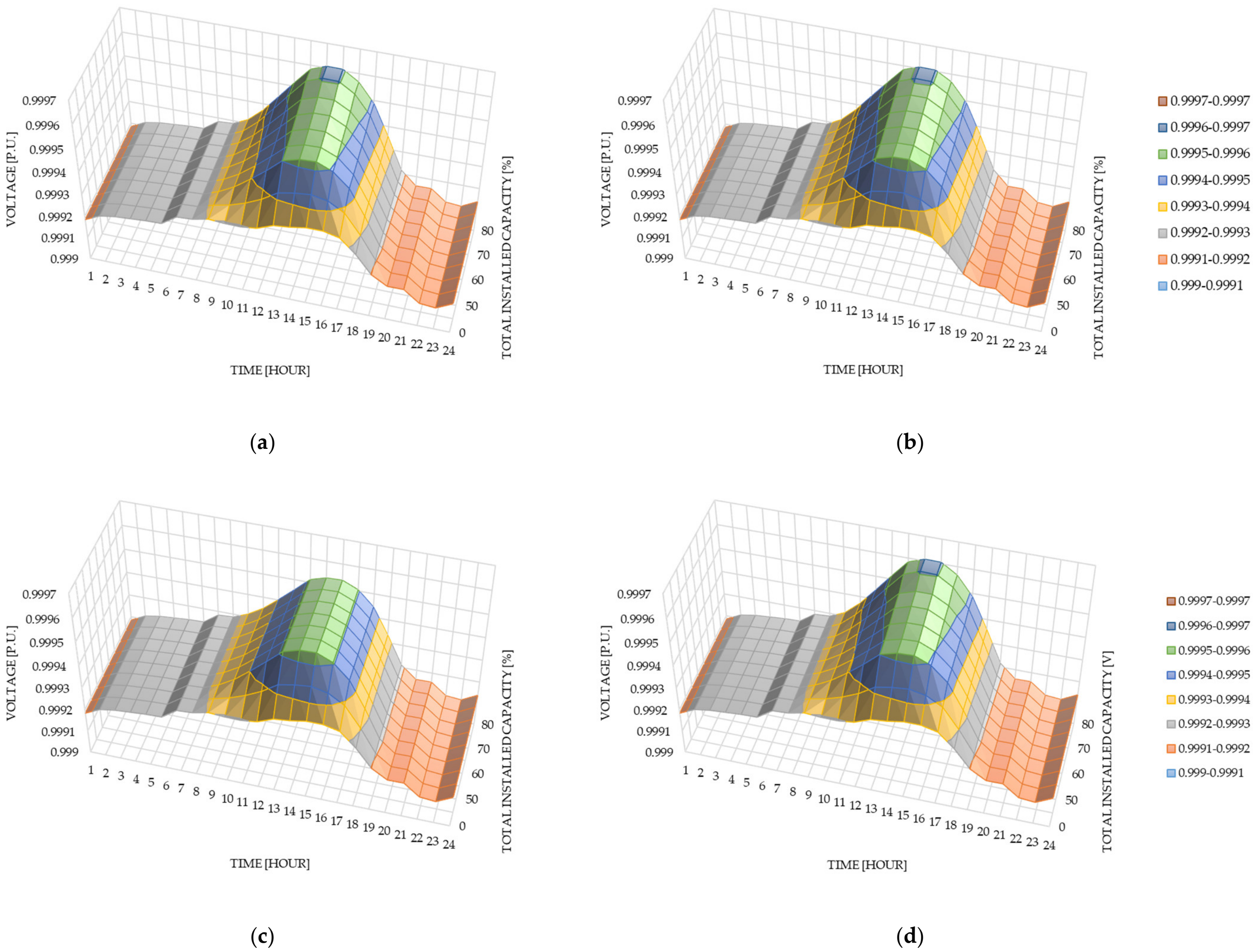


Figure 8. Probed voltage deviation at the beginning of the power distribution line when the solar PV systems are connected (**a**) at the beginning, (**b**) in the middle, (**c**) at the end, and (**d**) evenly distributed throughout the power distribution line.

Figure 9 shows the probed voltage deviations in the middle of the power distribution line depending on the installed location of the solar PV systems. The voltage increases to 0.97240 p.u., 0.98481 p.u., 0.98572 p.u., and 0.98158 p.u. when the solar PV systems are installed at the beginning, middle, and end, or evenly distributed throughout the power distribution line, respectively. In this scenario, the closest value to the rated voltage is achieved when the solar PV systems are also installed at the end of the distribution lines.

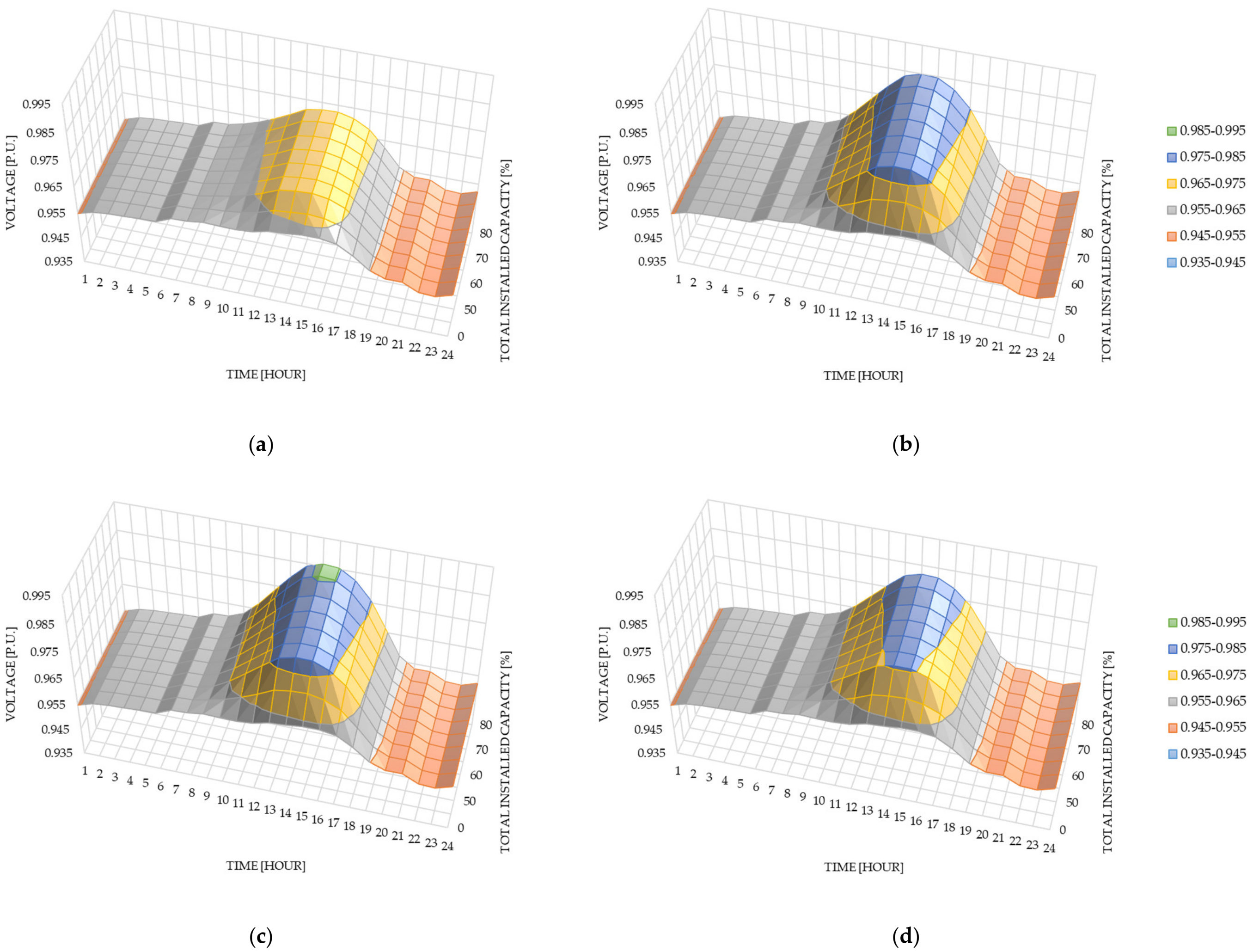


Figure 9. Probed voltage deviation in the middle of the power distribution line when the solar PV systems are connected (**a**) at the beginning, (**b**) in the middle, (**c**) at the end, and (**d**) evenly distributed throughout the power distribution line.

Figure 10 shows the probed voltage deviations at the end of the power distribution line depending on the installed location of solar PV systems. In the scenario with solar PV systems connected at the end of the power distribution line, the voltages increased to 0.95731 p.u., 0.97254 p.u., 0.98632 p.u., and 0.97393 p.u.

Overall, the voltage at the beginning of the power distribution line does not have a noticeable increase regarding the installed location of the solar PV systems, whereas there are significant differences in the voltage in the middle and end of the power distribution line due to the installed locations. This can be seen in the voltage at the end of the power distribution line, which was increased to the highest value when the solar PV systems were installed at the end of the power distribution line.

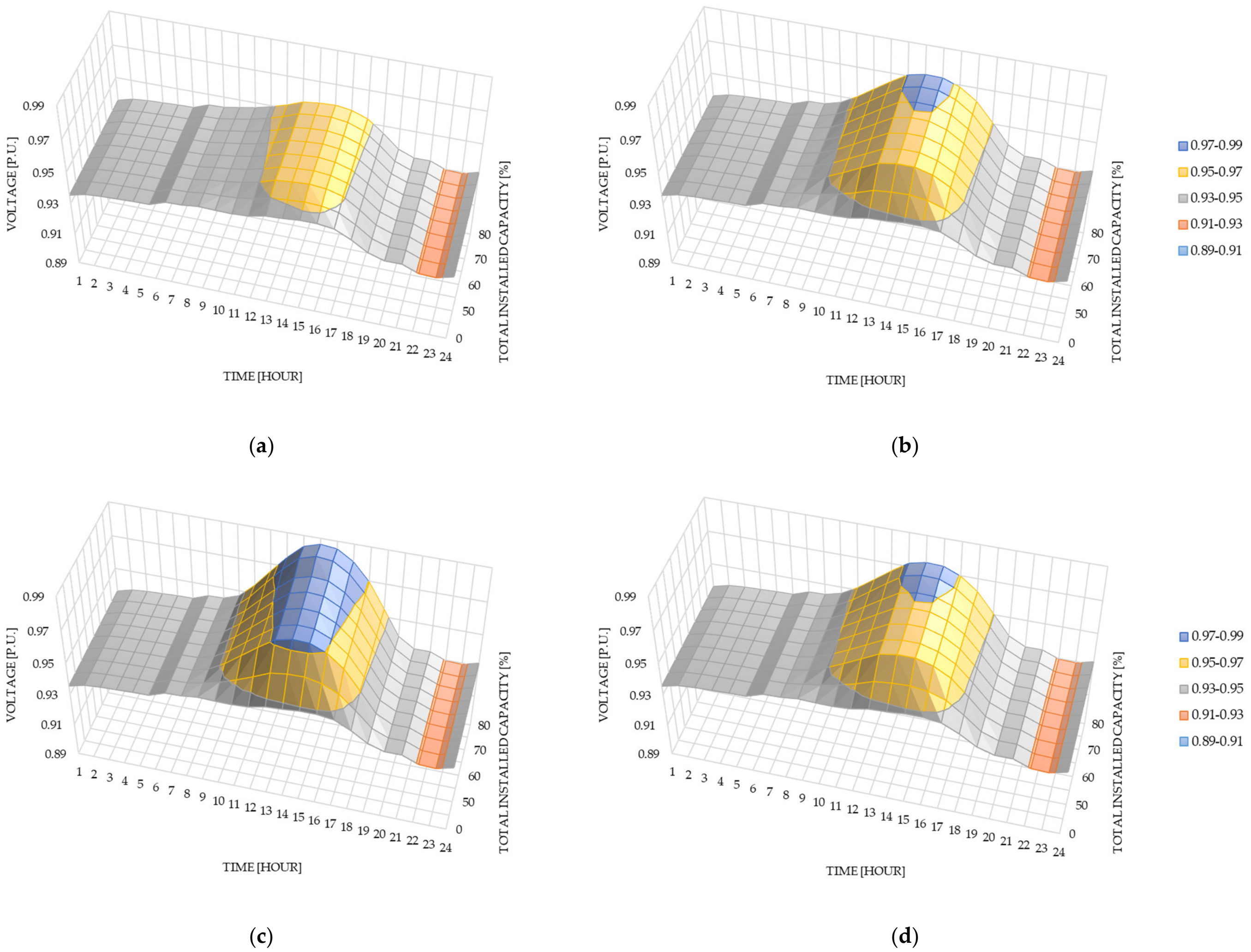


Figure 10. Probed voltage deviation at the end of the power distribution line when the solar PV systems are connected (**a**) at the beginning, (**b**) in the middle, (**c**) at the end, and (**d**) evenly distributed throughout the power distribution line.

5. Comparison with Existing Grid Enhancement Strategies

5.1. Optimization Models for Loss Reduction

A study conducted in Tianjin [20] introduced a combined optimization framework targeting weak points in the distribution network by replacing components such as distribution lines and transformers and implementing reactive power compensation. Their approach employed a cost–benefit ratio to optimize grid enhancements. While this method effectively reduced power losses, it required significant capital investments for infrastructure upgrades. In contrast, the current study focuses on the integration of distributed renewable energy sources, such as solar PV systems, to address power losses and voltage issues. This approach provides a sustainable and cost-effective solution tailored to the specific challenges of ger districts, such as sparse and overloaded feeders.

5.2. Genetic Algorithms (GA) for Optimal DG Placement

Research employing Genetic Algorithms (GA) for optimizing Distributed Generation (DG) placement, such as studies on the IEEE 33 and 69-bus systems, has demonstrated significant reductions in power losses and improvements in voltage profiles. These studies often incorporate the operation of Electric Vehicles (EV) to simulate variable loads [21]. Unlike these methodologies, the present study is grounded in real-world data from the

Ulaanbaatar ger district, focusing on an overloaded feeder with uneven household distribution. While both approaches aim to minimize power losses, this study emphasizes addressing unique regional challenges, such as sparse yet heavily loaded distribution lines, without requiring complex algorithmic models.

5.3. Reactive Power Compensation and Component Replacement

Grid enhancement strategies such as reactive power compensation and component replacement improve grid performance through hardware upgrades. These strategies, though effective, involve substantial financial investment and infrastructure modification [22]. In contrast, the integration of solar PV systems as explored in this study offers comparable improvements in loss reduction and voltage stabilization with minimal infrastructural changes, making it a practical and scalable option for resource-constrained settings like the Ulaanbaatar ger district.

6. Conclusions

In this study, an impact assessment of the grid-connected solar PV systems on the overloaded feeder in Ulaanbaatar ger district was carried out considering the total installed capacity and installation locations. Solar PV systems show the best effect on the undervoltage of the power distribution line when they are connected at the end of the line.

In terms of the loss reduction rate, solar PV systems with a total installed capacity equal to 25% of the daily load of the selected feeder can reduce the associated loss by 2% to 6%, depending on the connection point. The total installed capacity of the solar PV systems was then increased to 50% of the daily load of the selected feeder, resulting in a loss reduction of 3.4% to 9.7%. Afterward, the total installed capacity was increased to 75% of the daily load of the selected feeder. With this capacity specification, the associated loss could be reduced by 4% to 11.4%, suggesting that this scenario is the best one.

In other words, the energy losses are reduced most significantly when solar PV systems are installed at the end of the distribution line, particularly for installed capacities up to 70% of the feeder's highest daily load. This is because end-of-line installations provide localized electricity generation for households farthest from the feeder's source, thereby minimizing the need for long-distance power transmission and reducing resistive losses. However, when the total installed capacity exceeds 75% of the feeder's highest daily load, scenarios with evenly distributed solar PV systems result in lower energy losses. However, the performance on the reduction of the voltage deviation with the evenly distributed solar PV systems could not overcome the scenario when the solar PV systems were installed at the end of the power distribution line.

The findings of this study are primarily based on the power distribution grid in the Ulaanbaatar ger district, where the grid structure is characterized by long feeder lines with high resistance and an uneven distribution of load centers. However, the observed results and underlying principles are applicable to other ger districts or areas with similar power distribution grid structures. In particular, the reduction in energy losses and voltage deviations when solar PV systems are installed at the end of the distribution line is primarily due to localized electricity generation near the households at the feeder's farthest points, which minimizes long-distance power transmission and reduces resistive losses. This behavior is expected to be consistent in other ger districts due to their similar characteristics.

It is entirely feasible to address undervoltage and other technical challenges through the integration of battery energy storage systems with solar PV installations. The findings of this study provide a solid foundation for developing a methodology to determine the optimal installed capacity of solar PV systems at any point along the power distribution line. This methodology will be presented in forthcoming research.

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