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Transient response of a megawatt-scale solar photovoltaic in an electric distribution utility

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ABSTRACT

There is an increasing trend among customers of an electrical distribution utility to adopt grid-tied solar photovoltaic systems. This shift offers multiple benefits to consumers, including lower monthly electricity bills and a contribution to the development of green energy. For the electrical distribution utility, various impacts may arise due to varying levels of solar energy penetration. This study investigates the effects of integrating varying levels of solar photovoltaic penetration into the commercial consumer network of Cagayan de Oro Electric Power and Light Company (CEPALCO) in the Philippines. Utilizing PowerWorld simulator, the research evaluates 11 different scenarios with solar penetration levels adjusted according to the percentage of load demand. Key findings include alterations in solar megavolt ampere of reactive power output, bus voltage levels, transformer power loading, and transmission line ampacity, with frequency levels remaining stable across scenarios. The optimal solar penetration level was identified at 70%, balancing the benefits of solar energy integration with the need to maintain grid stability and operational limits. This optimal level ensures the effective utilization of renewable energy sources without compromising the performance of CEPALCO's electrical infrastructure. The research concludes with recommendations for maintaining grid stability and operational limits at the optimal solar penetration limits.

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1. INTRODUCTION

The global perspective on renewable energy has been significantly shaped by the need to shift away from fossil fuels, particularly coal, due to pressing environmental concerns [1]. This shift is driven by the urgent need to reduce greenhouse gas emissions and mitigate the impacts of climate change. In recent years, there has been a remarkable growth in renewable energy sources worldwide, with solar power experiencing a substantial surge. Renewable energy sources (RES) serve as alternative methods for energy generation aimed at decreasing greenhouse gas emissions [2]–[9]. The increasing affordability and efficiency of solar photovoltaic (PV) technology have positioned it as a leader in the renewable energy sector. Statistics indicate a steady increase in solar energy adoption globally, reflecting both technological advancements and policy-driven support. This trend is not only reshaping the energy landscape but also signaling a transformative move towards more sustainable and environmentally friendly energy systems worldwide [10].

Renewable energy in the Philippines has gained momentum as part of the country's commitment to reducing its carbon footprint and enhancing energy security [11]. The Philippines, endowed with abundant natural resources, has focused on harnessing renewable energy sources such as solar, wind, hydro, and geothermal power. Solar energy, in particular, has seen a rapid increase in adoption due to the country's geographical location, which offers substantial solar potential [12]. Government policies and initiatives have been instrumental in promoting renewable energy, with incentives and programs designed to encourage investment in this sector as per the Republic Act or the Renewable Energy Act of 2008 of the Philippines (RA9513). This shift towards renewables is not only pivotal for environmental sustainability but also crucial for the nation's energy independence and economic development [13].

The adoption of renewable energy sources in the Philippines, particularly solar power, however late compared to its neighboring and developed countries, has laid the groundwork for innovative approaches to energy distribution and consumption. One such development is the integration of grid-connected photovoltaic systems (GCPS) [14]. This technology synergizes with the country's renewable energy initiatives, bridging the gap between individual solar energy producers and the larger electric grid [15]. The usage of GCPS is beneficial to both the consumers and the electric utility. On the side of the consumers, it may help lessen the electricity bill and fill up their load demands. During special occasions when the solar PV's output is very low, consumers can use the main distribution grid as the supply [15], [16]. On the electric utility's side, the remainder output of the grid-tied solar PV can help compensate for the load demand of the electric utility given a specific period. In general, grid-connected PV systems are installed to enhance the performance of the electrical distribution network [17], [18]. PV arrays provide energy at the load side of the distribution system, reducing the feeder's active power loading hence improving the voltage profile. Through this method, the PV system can delay the operational operations of the shunt capacitors and series voltage regulators, thus enhancing their lifetime. However, integrating a high penetration level of small-scale grid-connected PV systems into the low voltage distribution network (LVDN) could cause operational problems [19]–[22]. Several distribution utilities in the Philippines do not integrate solar PV systems due to concerns about high solar PV penetration [23].

According to [23], electric distribution utilities encounter several specific challenges. Some of the specific challenges include voltage and frequency variations in the distribution network. This can result in voltage instability and potentially damage sensitive electrical equipment connected to the grid. Moreover, the intermittent nature of solar power generation can create difficulties in maintaining grid stability, particularly during sudden changes in weather and cloudy days. Power from solar systems during these hours results in a lower load for the utility, decreasing the need for economical 24-hour base load power and increasing the need for more expensive intermediate and peaking power during the rest of the day.

One study that is the closest to this present research is the analysis and evaluation of the effects of high PV penetration concerning the total installed power generation capacity of PV power plants in a microgrid (MG) [24]. The research presents a coordinated voltage control solution to maintain the voltage limits within certain standards, such as those outlined by the ANSI. It employs an approach, including simulations based on real data from Los Angeles, California, such as weather conditions and commercial building data, using the IEEE 123-node test feeder as a model. This provides valuable insights into managing voltage regulation in the context of high PV penetration levels, which is relevant to our study of the Cagayan Electric Power and Light Company (CEPALCO) power grid [24].

However, the closest prior study mentioned focused on the effects of high solar PV penetration in power systems, each has their specific deficiencies or challenges that should be considered. The study on "high PV penetration effects in a microgrid" which proposed a coordinated voltage control solution for managing high PV penetration in microgrids, presents several potential deficiencies: i) model limitations: the study is based on a modified version of the IEEE 123-node test feeder and incorporates real data from Los Angeles. While this provides a realistic framework, the findings might not be directly applicable to different geographical locations or grid configurations, such as those in Cagayan de Oro City, Philippines. The specific conditions and characteristics of each location (e.g., existing grid infrastructure) significantly influence the integration and impact of PV systems and ii) scenario limitations: the scenarios considered in the study might not encompass all possible variations in solar PV penetration levels and their impacts on the grid. As solar energy generation can be highly variable and influenced by numerous factors, the scenarios may not fully capture the range of challenges that can occur in real-world applications;

In this closest prior art, a clear boundary for how much solar energy can be safely integrated into the existing power grid at any given time was not established. The supposed identification of the threshold offers critical insights into the sustainable integration capacity of solar energy, which is essential for the strategic planning and optimization of renewable resource utilization. In this prior art, examining how energy demand, voltage, and frequency stability are affected under different levels of solar photovoltaic penetration were not provided. These factors are critical when evaluating the impact of solar photovoltaic on a larger-scale power system. This ensures the power grid's reliability and stability remain intact while embracing renewable energy solutions [25].

This study aims to identify the highest permissible level of solar photovoltaic (PV) system penetration contributed by commercial users within the existing distribution network of the Cagayan Electric Power and Light Company (CEPALCO) in Cagayan de Oro City, Philippines while adhering to the established operational limits. The focus of this paper is primarily on examining how energy demand, voltage, and frequency stability are affected under different levels of solar PV penetration. The main objective of the study is to investigate what are the possible effects of integrating the grid-tied solar PV system from the commercial consumers to the CEPALCO distribution grid, using a simulation tool. The specific objectives of the study are: i) to analyze the possible effects of connecting grid-tied solar PV systems, under various penetration levels to the energy demand of CEPALCO commercial consumers; ii) to monitor the condition of the voltage and frequency of the distribution grid when subjected to various penetration levels; and iii) to determine the maximum penetration level (threshold) of the solar PV system without compromising the operation of the existing distribution utility.

The focus of this paper is primarily on examining how energy demand, voltage, and frequency stability are affected under different levels of solar PV penetration. Additionally, it delves into the analysis of the critical threshold for PV penetration and its potential impacts on the operational dynamics of the distribution utility. The study does not include the impacts on the pricing costs, load generation reliability, concerns regarding protection and coordination, power system solutions and mitigations, and economic evaluation of the costs and benefits of solar PV generation. The study was also limited to the commercial consumers connected to the 13.8 kV and 34.5 kV feeders of CEPALCO. It assumes that all the solar PVs are running in good condition.

PowerWorld simulator is a widely-used software tool in power system engineering for simulating and analyzing electrical power systems. It is particularly useful for its ability to model complex network systems and perform detailed analyses, including load flow, stability, and fault studies. The software's graphical interface and data visualization capabilities make it an effective tool for both educational and professional purposes.

Several articles have utilized PowerWorld for various studies in power system analysis [26]–[32]. For [31], the paper focuses on conducting load flow simulations for the Western grid of the Bangladesh power system using power system analysis toolbox (PSAT), a free and open-source software. The study then compares these results with those obtained from PowerWorld, a well-recognized commercial software. The power system in the study comprises 41 buses and 82 interconnecting lines. In this system, the comparison revealed that the bus voltage magnitudes calculated by the two software packages differed by an average of 1.7525%. Additionally, it was observed that PowerWorld completed the simulation 6.4 times more quickly than PSAT.

Therefore, the PowerWorld simulator emerges as an extremely valuable tool for this study. Its demonstrated efficiency in simulation speed, coupled with its reliable and accurate performance in complex system analyses, makes it particularly suitable for our research needs. The software's advanced capabilities in handling intricate power system models and delivering precise results quickly position it as an indispensable resource in conducting thorough and efficient power system studies [32]–[37].

2. METHOD

This section outlines the specific methods employed to collect data, the criteria for selecting the study parameters, and the tools and techniques used for analysis. In particular, this study focused on the application of the PowerWorld simulator to evaluate various scenarios of solar PV penetration in the CEPALCO distribution network. This section describes the simulations conducted, the criteria for measuring outcomes, and the techniques used to analyze these results. This methodological framework is designed to ensure the accuracy and reliability of the study's findings, contributing significantly to the field of renewable energy integration in power grids.

2.1. Data gathering

Data gathering is one of the most important parts of every study since the type of data obtained determines the procedures used to meet the objectives of the study. In Figure 1, the flowchart splits into two paths, depending on whether the voltage and frequency analysis meets the limits. If it does not meet the limits, the process stops. If it meets the limits, it proceeds to transmission line and transformer power loading analysis. Here, the flowchart checks again to see if it exceeds operational limits. If it does, the process stops. If not, it performs one final check to see if it violates grid operations and limits. If it meets all the requirements, the process ends successfully.

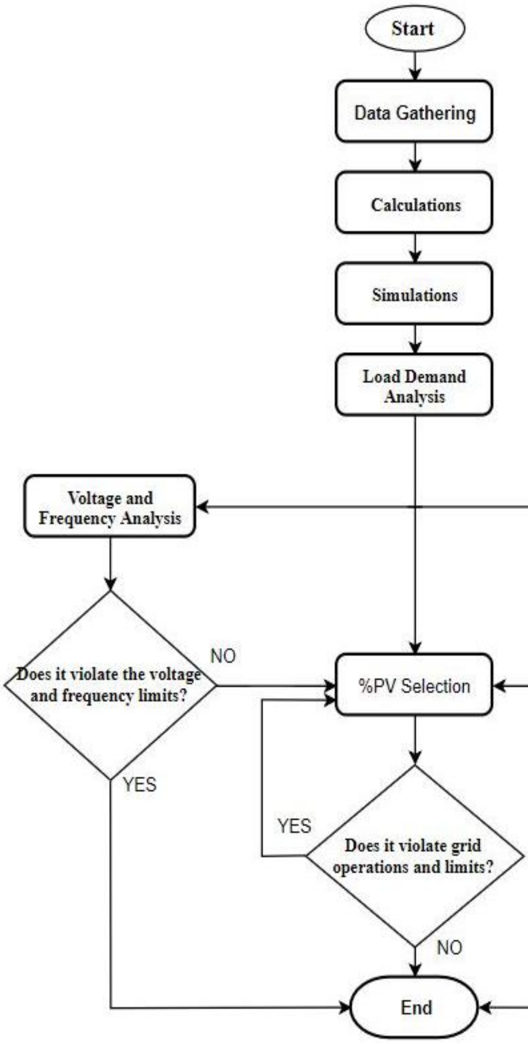


Figure 1. Flow chart of the study which the researcher followed to meet the desired output

The required data and information needed for this study were the following: i) total number of commercial customers per feeder branch, ii) total number of connected residential and commercial consumers per feeder, iii) average daily load consumption of commercial consumers (2017), iv) transformer MVA ratings, and v) Backbone voltage level per distribution feeder branch. Calculations: For this study, a general formula for the injection of both the load and solar PV in a certain bus is used which is given in (1).

$$\%PV + \%\,PL = 100 \tag{1}$$

where $\%PL$ is specific percentage load level and $\%PV$ is solar PV output percentage (penetration level).

In this formula, the total percent injected in a certain bus by both the calculated load value level and solar PV level is equal to 100%. This does not include the other distributed generators that already exist in the PowerWorld diagram. Also by using (1), the uniformity in solving the desired solar PV output throughout the injected buses was attained since there are different feeder load values attached in the CEPALCO grid.

The solar PV output used for the PowerWorld simulation is computed using (2).

$$\%\,(PV) = \frac{PV\ Output\ (kW\ or\ MW)}{Feeder\ Load\ Value\ (kW\ or\ MW)} * 100 \tag{2}$$

Re-arranging (2), the value of the individual solar PV generator output is:

$$PV\ Output = \%PV * Feeder\ Load\ Value\ (MW) \tag{3}$$

From (1), $\%PL$ can be calculated after setting the desired $\%PV$ value. Then multiply the $\%PL$ to the load given in load level per respective feeder, which is (3). The results were used as varying load parameters in PowerWorld simulations.

$$Load\ Value = \%\ PL * Original\ Feeder\ Load\ (MW\ or\ Mvar) \quad (4)$$

For this study, the researcher sets 11 different cases with different solar penetration levels (%PV), starting from 0 to 10%, 20% up to 100%. From these values, the solar PV output is based on the total installed commercial load given.

2.2. Power system software simulations

This study employed the 18th version of the PowerWorld simulator, a sophisticated tool used for analyzing and simulating power systems. Within this simulation environment, specific attention was given to the settings of solar photovoltaic (PV) generators. One critical adjustment made was the activation of the automatic voltage control (AVR) feature within the generator dialog box. The AVR plays a vital role in maintaining the voltage level of the generator within a specified range, ensuring stable operation, and mitigating the risk of voltage-related issues. It is particularly important for solar PV generators due to the variable nature of solar energy. Concurrently, the automatic generation control (AGC) system was deliberately deactivated for these generators. The AGC is typically used to balance supply and demand by adjusting the power output of generators. However, in the context of this study, the decision to deactivate AGC was likely driven by the desire to focus on the impact of voltage control without the complicating factor of generation adjustments. By selectively using these settings, the study aimed to isolate and analyze specific aspects of solar PV generator performance and stability within the power system.

In Figure 2, it is the equivalent power system grid of Cagayan De Oro, Philippines. The system is inserted with PV generators on their respective feeders. This system is the whole franchise of CEPALCO, with their respective loads and different feeders.

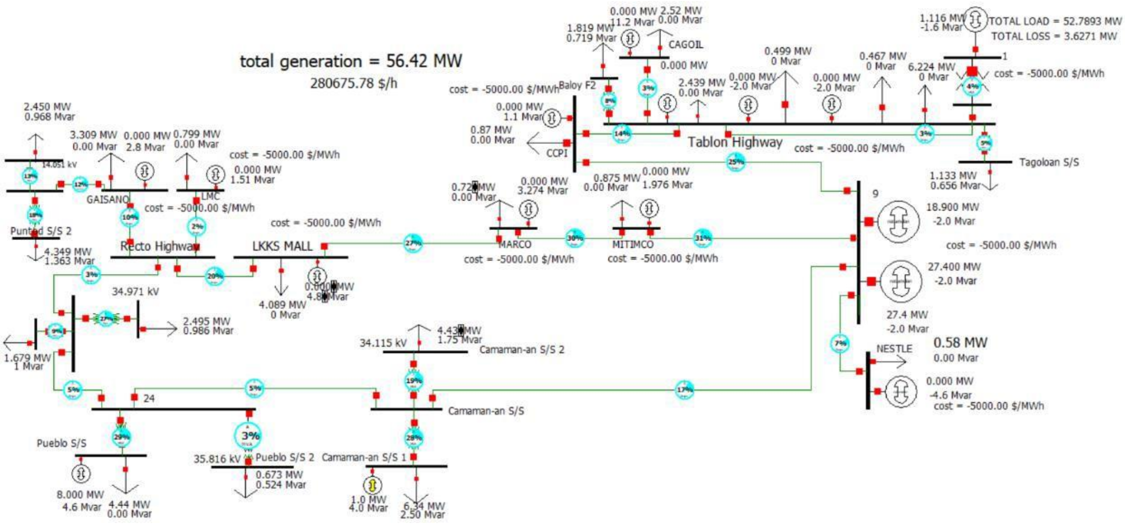


Figure 2. The equivalent power system grid of the electrical distribution utility is inserted by the solar photovoltaic generators on their respective feeders

2.3. Load demand analysis

Load demand analysis explains the changes in the behavior of the load demand of the commercial consumers connected to the 13.8kV and 34.5 kV feeders of CEPALCO when there is a change in the level of injected solar PV. This portion greatly relies on the results obtained in the calculations using (1) and (2). The varying load level justifies the varying actual loads in the real-life scenario.

2.4. Voltage and frequency analysis

The bus voltage level in each bus must be properly monitored to maintain the allowable ±5% changes as prescribed by the grid code. Table 1 shows the minimum and maximum allowable bus voltage level range for the different types of buses in the grid. This range is crucial to ensure the stability and efficiency of the power system. For instance, a transmission bus might have a higher voltage range due to its role in long-distance electricity transmission, whereas a distribution bus, which directly supplies power to consumers, typically operates within a lower voltage range to ensure safety and reliability. The table would detail these specific ranges, reflecting the operational requirements and constraints of each bus type.

Maintaining these voltage levels within the specified ±5% range is essential to prevent equipment damage, minimize energy losses, and ensure consistent power quality for end users. Voltage fluctuations beyond this range can lead to problems like overloading, under-voltage, or even systemic failures in the grid. Therefore, continuous monitoring and regulation of bus voltage levels are performed using sophisticated control systems and regulators. These systems are designed to automatically adjust the voltage, keeping it within acceptable limits, thus ensuring the grid's operational integrity and the safety of both the infrastructure and the consumers it serves. This rigorous monitoring is especially important in grids with a high penetration of renewable energy sources, such as solar PV systems, where voltage levels can be more variable due to the intermittent nature of the energy source. To get the frequency response, the researcher uses the transient stability portion of the power system simulator. To get the desired specific frequency in the power grid, the researcher set the individual bus frequencies to be plotted in the plot designer setting found in the transient stability portion.

Table 1. Minimum and maximum allowable voltage level range

Voltage rating (kV)	Minimum voltage level (kV)	Maximum voltage level (kV)
13.8	12,711	14,049
34.5	32,775	36,225
69	65.55	72.45

2.5. Line ampacity and power loading analysis

The analysis of the behavior of the transmission line ampacity levels and transformer power loading levels attached in the PowerWorld were monitored concerning the changes in the solar PV outputs. Since the analysis of the study is dependent on the results of the PowerWorld, both the line ampacity and power loading levels must not exceed 80% of their nominal rated values as shown in Figures 3 and 4. Since there are different MVA ratings for the transformers and line ampacity tolerance for the transmission lines, a common 80% maximum operational limit was set for the lines and transformers not to get congested, burned, or damaged.

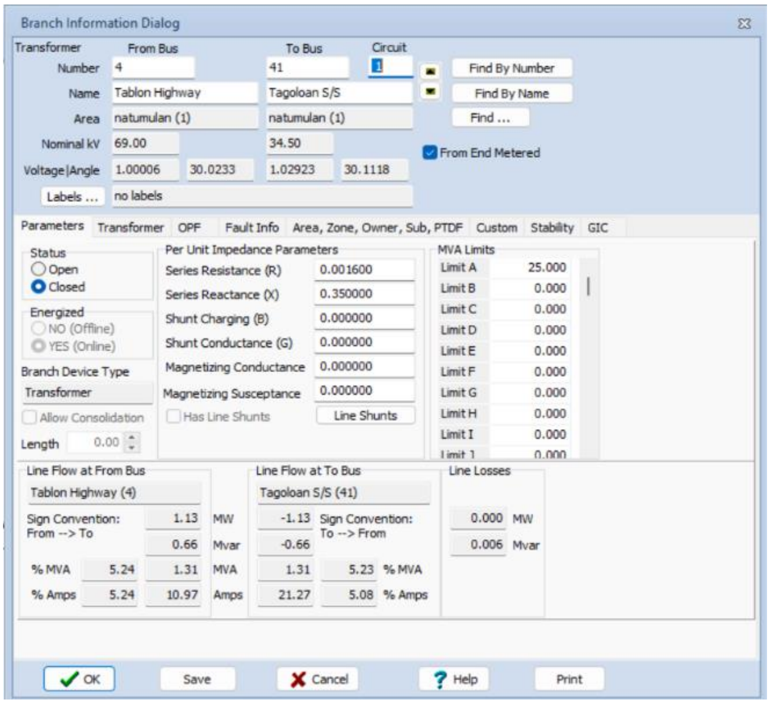


Figure 3. Example of transformer MVA and ampacity levels

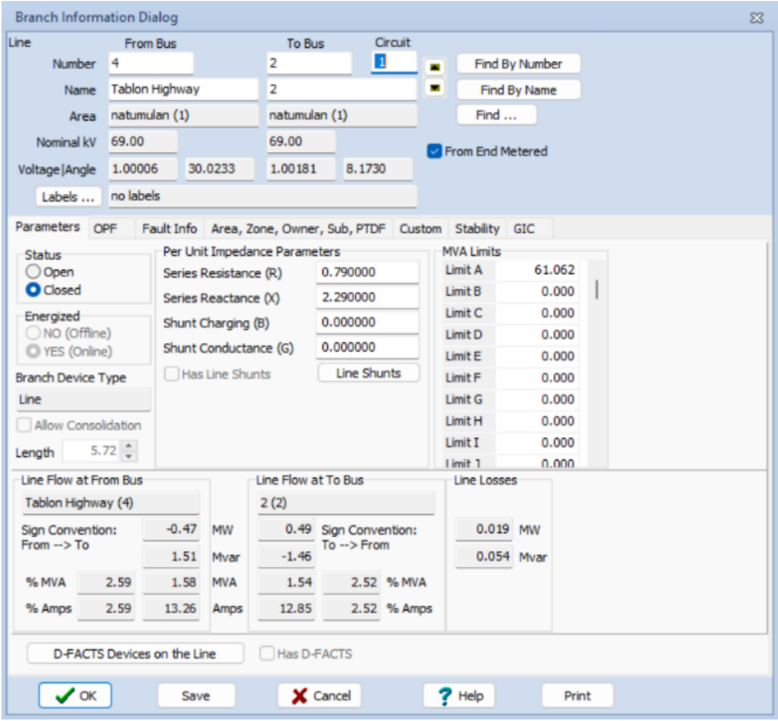


Figure 4. Example of transmission line MVA and ampacity levels

3. RESULTS AND DISCUSSION

The focal point of this chapter is to present our study's major findings about the grid integration of solar photovoltaic (PV) system into the distribution network of Cagayan Electric Power and Light Company (CEPALCO). This research therefore indicates how renewable energy sources like solar PV can be harmonized with conventional electrical infrastructure. One key objective of this study was to investigate the effects of different levels of solar PV penetration on electricity consumption patterns for CEPALCO's commercial customers. Therefore, through simulations using various scenarios for integrating solar PV we could easily determine changes in power demand as well as Power, Voltage and Frequency reliability associated with these systems. This aspect is vital in assessing solar energy that can supplement traditional energy sources and its implications on the overall energy consumption patterns of commercial and industrial entities.

3.1. Data gathering summary

Tables 2 and 3 summarize the acquired data and information obtained from the electrical distribution utility. Table 2 presents a list of different feeder lines, categorized by their respective bus names and voltages. For each feeder line, the transformer rating is provided in mega volt amps (MVA). This data is essential for understanding the capacity and load-handling capabilities of each transformer within the utility's distribution network. The table shows a mix of feeder lines operating at different voltage levels, namely 13.8 kV and 34.5 kV, with transformer ratings primarily hovering around 20 to 25 MVA. Such information is critical for power flow analysis and ensuring that transformers are adequately rated for the expected load.

Table 2. Transformer ratings per feeder lines

Bus name	Transformer ratings (MVA)
Baloy F2 (34.5 kV)	25
Camaman-an F1 (13.8 kV)	20
Camaman-an F2 (34.5 kV)	25
Carmen F1 (13.8 kV)	20
Carmen F2 (34.5 kV)	25
Pueblo de Oro F2 (34.5 kV)	25
Puntod F1 (13.8 kV)	20
Puntod F2 (34.5 kV)	25
Tagoloan (34.5 kV)	25

Table 3. Number of registered commercial customers of CEPALCO's 13.8- and 34.5-kV feeders

CEPALCO feeders with commercial customers	Total registered commercial consumer counts	Total registered consumers counts	Percentage (%)
1. Baloy Feeder 2 (34.5 kV)	2029	17359	11.69
2. Camaman-an Feeder 1 (13.8 kV)	2,934	11,316	29.928
3. Camaman-an Feeder 2 (34.5 kV)	1,363	8,275	16.4713
4. Carmen Feeder 1 (13.8 kV)	2,363	18,455	12.8
5. Carmen Feeder 2 (34.5 kV)	3,201	29,566	10.827
6. Pueblo de Oro Feeder (34.5 kV)	546	4,765	11.459
7. Pueblo de Oro Feeder 2 (34.5kV)	643	11,936	5.387
8. Puntod Feeder 1 (13.8 kV)	215	1,188	18.1
9. Puntod Feeder 2 (34.5 kV)	164	997	16.45
10. Tagoloan Feeder 1 (34.5 kV)	2,801	38,994	7.78

3.2. Calculations results summary

This section provides a summary of the results of the analysis on the transient response of the megawatt scale solar PV system integrated into an electric distribution utility through various cases ranging from 0% to 100% solar PV penetration. There were 11 various cases intended for the calculations. The representative tables show the summary of the hand calculations done using (1)-(4). The core of the analysis revolves around understanding how varying levels of solar energy integration impact the grid, specifically focusing on the balance between the power supplied by solar PV (PV output) and the conventional load demand (PL). This relationship is crucial for maintaining grid stability and operational efficiency.

The analysis begins with case 1, setting a baseline with 0% PV penetration, where all power requirements are met by conventional sources, illustrating the grid's dependency on non-renewable energy. Subsequently, from case 2 to case 11, solar PV penetration increases in increments of 10%, gradually replacing the conventional power load. This step-wise increase allows for a detailed observation of how incremental solar PV integration affects the grid's performance metrics, such as load demand and reactive power output (MVAR). A key observation from the various cases is the inverse relationship between the percentage of power load (PL) and solar PV penetration (PV). As PV penetration increases, there is a corresponding decrease in PL, signifying a shift towards renewable sources for meeting the grid's energy demand. This shift not only emphasizes the potential for renewable energy integration but also highlights the changing dynamics of load management within the grid. A key outcome of this research revealed that during Case 8, characterized by a 30% power load and 70% solar PV penetration, the highest permissible level of solar PV contribution to the grid was achieved. This finding is significant because it establishes a clear boundary for how much solar energy can be safely integrated into the existing power grid at any given time. By identifying this threshold, the study provides valuable insights into the limits of sustainable solar energy integration, which is crucial for planning and optimizing the use of renewable resources without compromising the reliability and stability of the power grid.

In various cases, the most significant aspect in the results of the analysis is the behavior of solar MVAR output relative to solar MW output and the commercial load MVAR. The integration of solar PV influences not just the real power (MW) but also the reactive power (MVAR) within the grid. Initially, as solar PV penetration increases up to 40%, there is a noted decrease in total solar MVAR output, attributed to the reduction in commercial load MVAR. Beyond 40% PV penetration, however, solar MVAR output begins to increase, compensating for the decreasing load MVAR and maintaining voltage stability across the grid. This behavior underscores the importance of managing reactive power in ensuring voltage stability and the efficient operation of the grid with high levels of solar PV penetration.

3.3. Load demand analysis

Upon the increase of solar PV MW output, there is also a relative decrease in the load level on the respective bus they were injected. The percent increase of the solar PV output and decrease in the load level sums up to 100% at all times, as governed by (1). However, between the total solar MVAR output and total commercial load MVAR, it does not follow the trend line because only the commercial MW load in (1) and the solar MVAR output is freely governed by the AVR setting of PowerWorld simulator.

As shown in Figures 5 and 6, the relationship between the total solar MVAR output and the total commercial load MVAR does not adhere to the expected trend line. This discrepancy arises because only the commercial MW load conforms to (1), while the solar MVAR output is independently regulated by the AVR settings in the PowerWorld simulator. The simulated total solar MVAR output decreases along the 0–40% penetration level and gradually increases starting from 40% until 100%. This behavior is due to the gradual loss of the commercial load MVAR level and to compensate for the needed reactive power to maintain the bus voltages of the injected bus and its neighboring buses. The decrease in the load values means that the lost values were accommodated by the solar PV generators, which were gradually rising. The lost load values are relative to the increase in the solar PV values.

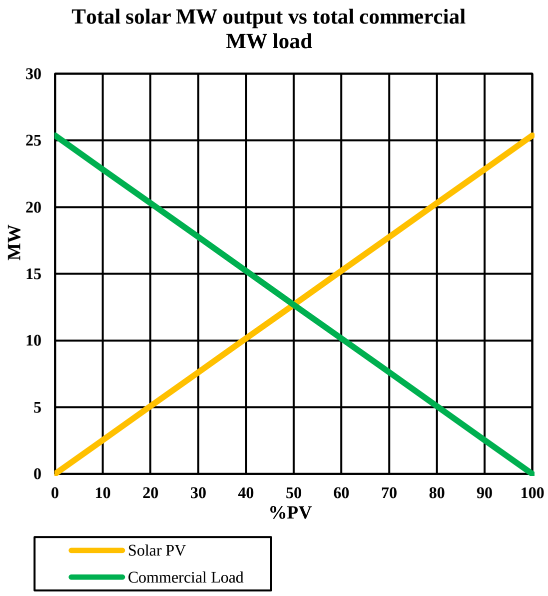


Figure 5. Comparison of total solar MW output and total commercial MW load

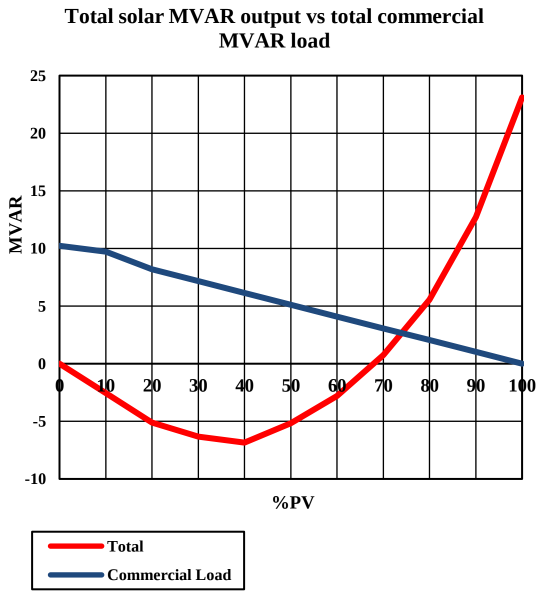


Figure 6. Comparison of total solar MVAR output and total commercial MVAR load

3.4. Simulation results

The PowerWorld simulator's automatic voltage control (AVC) substantially impacts the behavior of solar generators' MVAR output. In contrast to a fixed MVAR output, AVC fluctuates according to two main factors including changes in load level and solar MW output. This ensures that voltage levels are kept consistent on the connected bus.

When there is an increase in the load level on the bus, solar generators' AVC system automatically injects reactive power (positive MVAR) into the grid. In so doing, this counters the voltage dip occasioned by increased loads thereby upholding voltage stability. On the other hand, if there is decrease in load level, the AVC system reduces negative MVAR outputs so as to prevent overvoltage due to busbar.

Likewise, variations in MVAR are triggered whenever there is change in solar MW produced. While daily fluctuations in solar irradiance persistently occur, such variation is witnessed within MWs generated by these machines. These fluctuations are compensated for by the AVC system which ensures that despite how much MW comes from any given generator of a solar at any time, its voltage at a connected bus will be constant throughout. This helps keep power quality stable and maintain grid stability for other loads on this same busbar.

Figure 7 depicts the system condition during case 1 of the study. This case is significant because it sets the baseline for the research by illustrating the initial state of the power system grid before the integration of solar PV generators. Specifically, it shows how the grid operates with conventional power sources, before any solar PV injection. This baseline scenario is crucial for understanding the subsequent effects of solar PV integration at various levels throughout the study. It provides a reference point against which the impacts of increased solar penetration-such as changes in voltage levels, transformer loadings, and reverse power flow-can be measured and analyzed.

One of the notable changes that happens during the simulations is the reverse power flow happening in the power system grid. This is due to the excess solar generator outputs connected to the buses. Based on the simulation, as early as case 3, there was a reverse power flow happening already between the Carmen 69 kV bus and the Recto Highway bus. As the solar penetration level increases, the greater the manifestation of the reverse power flow is obvious. This phenomenon can bring different threats to the real-world power system grid such as difficulty in voltage regulations, rapid rise of line losses, and increase of total reactive power generated. Figures 8(a) and 8(b) show three of the PowerWorld simulation results. These three are from cases 1, 6, and 11, respectively.

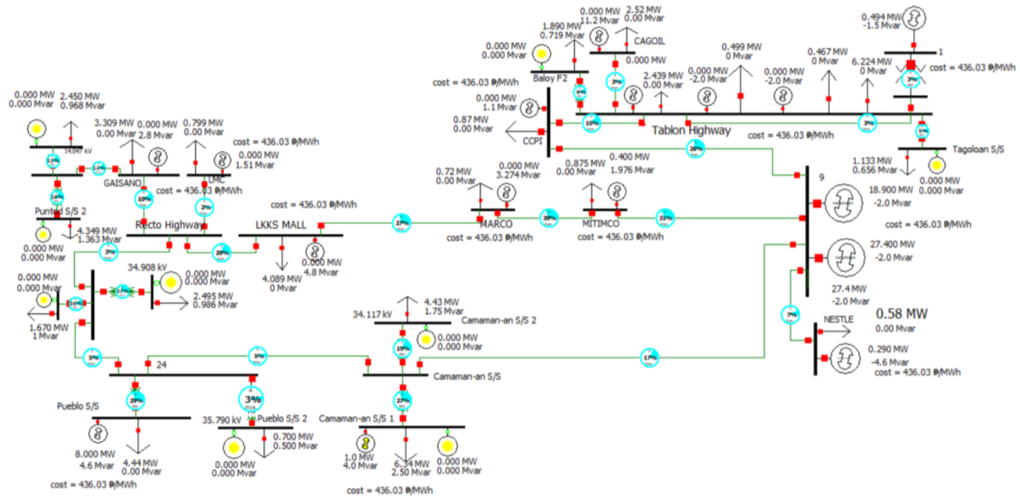
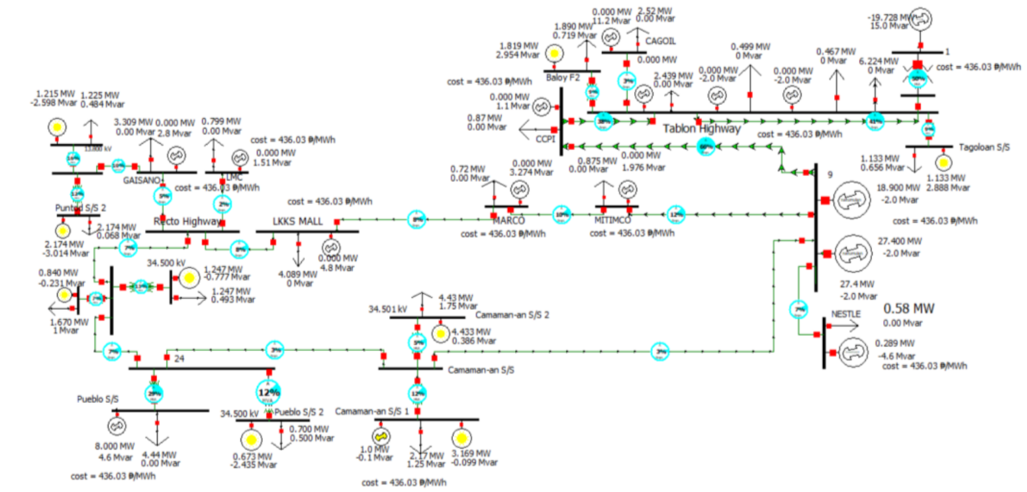
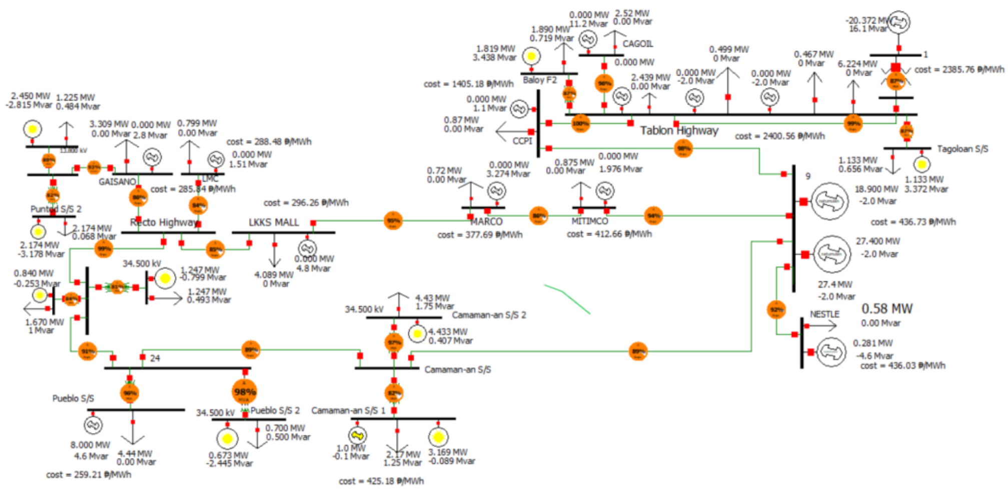


Figure 7. System condition during case 1



(a)



(b)

Figure 8. The three of the PowerWorld simulation results: (a) system condition during case 6 @ 50% solar penetration and (b) system condition during case 11 @100% solar penetration

3.5. Line ampacity and transformer power loading analysis

The changes in the behaviors of both the transmission line and the transformer MVA loading and ampacity ratings were also observed during the simulations. Along with the rise of solar penetration level, several transmission line(s) are also raising their line ampacity level proportional to the increase of %PV. These transmission lines are the transmission lines between bus no. 9 and CCPI bus, Tablon Highway bus and CCPI bus, and bus no. 2 and Tablon Highway. These transmission lines increase their ampacity level until such time that some reach the 80% tolerable level and even exceed it.

For the transformer MVA levels, it was observed that a decrease in the transformer loading happens during the early parts of the various solar PV penetration levels. Transformers at Baloy F2, Camaman-an S/S 1 and 2, Carmen S/S 1 and 2, Puntod S/S 1 and 2, and Tagoloan S/S all decrease their transformer loading from 0-40% penetration level (%PL: 60, %PV: 0-40). The decrease in transformer percent loading is because only a small portion of power was needed for the grid to supply towards the decreasing load values and since the increasing solar PV generators can almost supply the value of the load at the bus they were injected. Figures 9-12 show the behavior of the transmission lines' ampacity under different solar penetration levels.

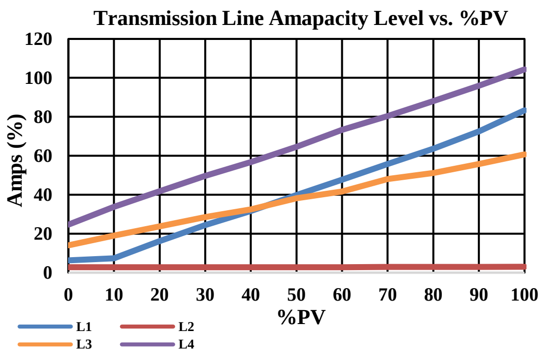


Figure 9. Transmission line % ampacity under various %PV levels for L1 to L4

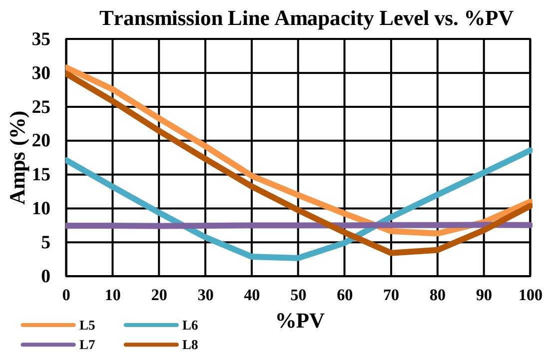


Figure 10. Transmission line % ampacity under various %PV levels for L5 to L8

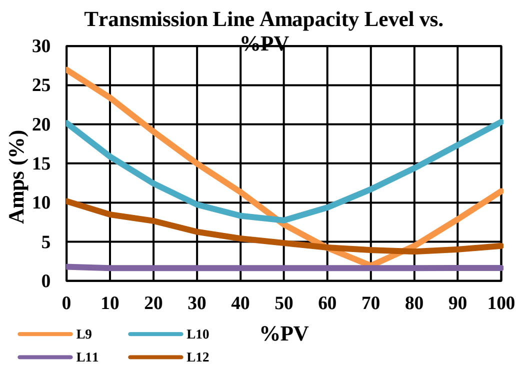


Figure 11. Transmission line % ampacity under various %PV levels for L9 to L12

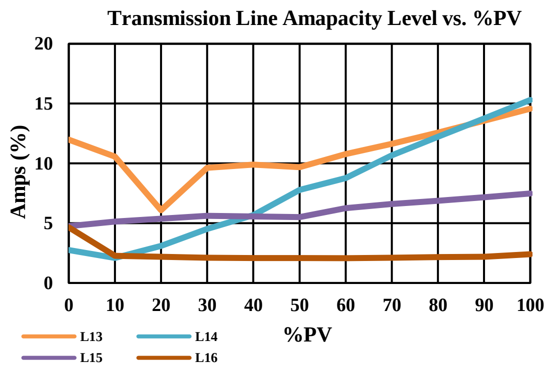


Figure 12. Transmission line % ampacity under various %PV levels for L13 to L16

Upon reaching 50%–60% solar penetration levels, the transformer percent loading started to increase. In the same transformer locations stated above, the gradual rise of MVA percent can be observed. The rise of these values is because the solar PV generator MW output is greater than the load level values. Figures 13-15 show the behavior of the transformer power loading level under different solar penetration levels.

Here, an excess of solar output is generated and it is sent to the other parts of the grid to meet their needs. In this way, the power flows in reverse directions, as depicted in the previous part of this chapter. As the solar penetration level rises the greater the excess in the solar output be, thus the greater the reverse power transfer in the transformers will take place.

Figures 13 through 15 offer a nuanced understanding of the transformer power loading levels as the penetration of solar photovoltaic (PV) systems escalates from 0% to 100%. This progressive examination is critical, demonstrating how the integration of solar energy affects the operational dynamics of transformers within the power distribution network. Figure 13, focusing on transformers 1 (T1) to T4, demonstrates a varied response in power loading across different transformers as the level of solar PV penetration intensifies. This variation underscores the transformers' capacity to adapt to the shifting energy landscape, accommodating the fluctuating supply of solar power. It is proof of the resilience and flexibility of the power distribution infrastructure, showcasing its ability to handle the integration of renewable energy sources without compromising stability or efficiency. The observed changes in transformer loading percentages reflect the intricate balance between solar energy input and the conventional power grid's demands, highlighting the critical role of transformers in managing and distributing the increased solar power supply across the network.

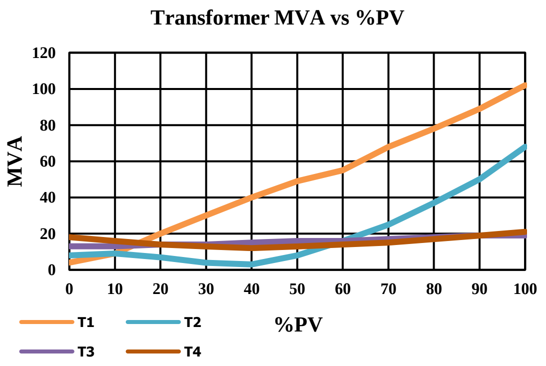


Figure 13. Transformer power loading (%) under various %PV levels for transmission 1 (T1) to T4

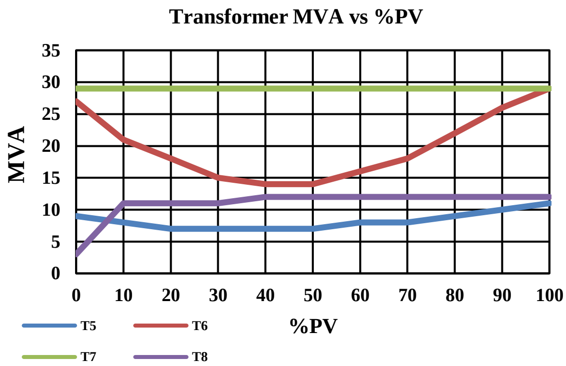


Figure 14. Transformer power loading (%) under various %PV levels for T5 to T8

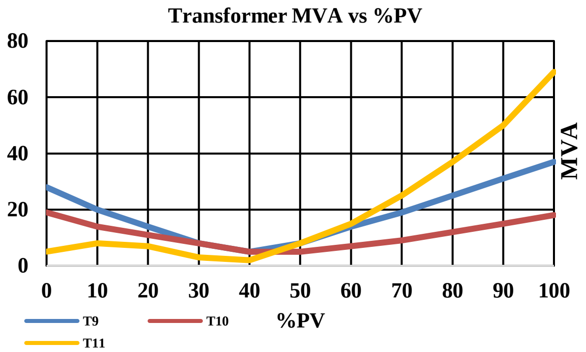


Figure 15. Transformer power loading (%) under various %PV levels for T9 to T11

3.6. Bus voltages level results analysis

The researchers monitored the conditions of the bus voltages and found out that during case 1 (%PV=0), the bus voltages were quite a little higher level than the usual nominal rated bus voltages. Nevertheless, as the injection of solar penetration level increases, the bus voltages relatively decrease its values. As case 11 reaches, bus 2, Tablon Highway bus, and CAGAOIL bus went lower than the critical bus voltage value which is beyond the allowable ±5% described by the Grid Code.

The reduction of the bus voltage levels is due to the decreasing power generation coming from the generators of the CEPALCO power grid. The lower the generated power, the lower the level the bus voltages became. As discussed later, as the excess power is generated rapidly, the slack generator operates like a motor and consumes a large amount of power, leaving the other buses in low power conditions and lowering their bus voltage values. Figures 16-20 show the graph of the bus voltage conditions when subjected to various solar penetration levels. Notice that the majority of the bus voltages are decreasing.

3.7. Frequency response results analysis

Based on the various simulations conducted, the behavior of the frequency of each bus in the PowerWorld diagram did not have significant or big changes or fluctuations. There are relatively small changes in the frequency fluctuations but mostly only range between 59 Hz (minimum) to 61 Hz (maximum). The first fluctuation in the frequency (either rise or fall) usually appears in the first second of the simulation and then several trends follow but the same trends continue further as common trends throughout the time range, thus making it look like the frequency is in a stable state.

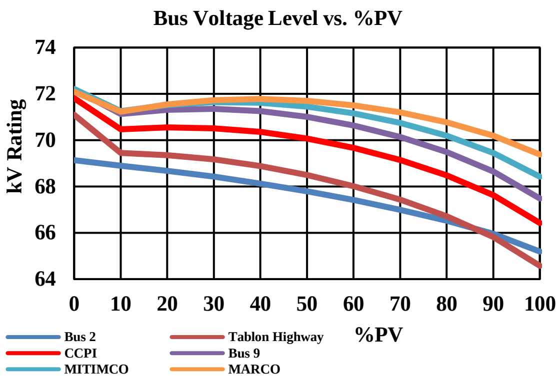


Figure 16. Bus voltages under various %PV levels in Tablon Highway and CCPI

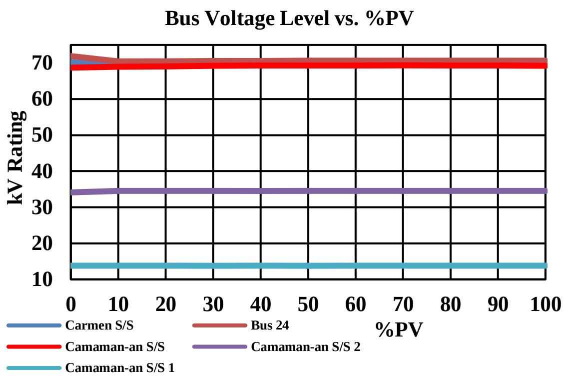


Figure 17. Bus voltages under various %PV levels in Carmen and Camaman-an

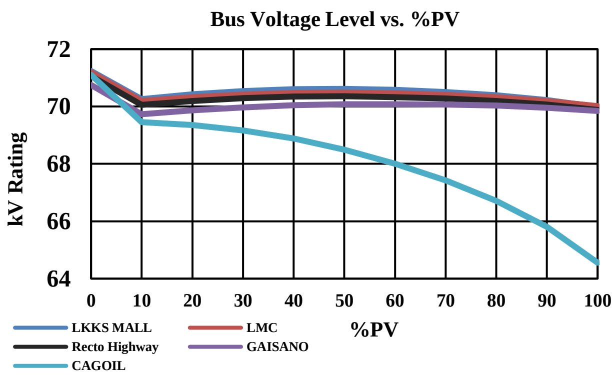


Figure 18. Bus voltages under various %PV levels in LKKS Mall, Recto Highway, CagOil, LMS, and Gaisano

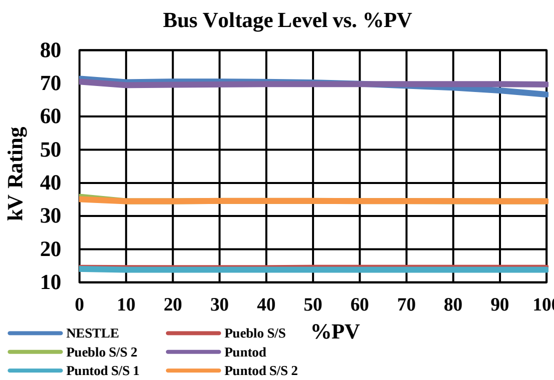


Figure 19. Bus voltages under various %PV levels in Nestle, Puntod, and Pueblo

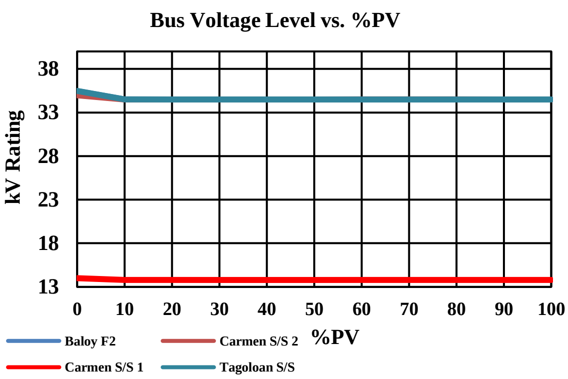


Figure 20. Bus voltages under various %PV levels in Baloy and Carmen

3.8. Selection of maximum solar penetration level

In the study, it was determined what is the maximum that can be achieved in terms of integrating solar energy into a given power grid. Different settings were analyzed, which had different proportions of traditional (%PL) and photovoltaic solar power (PV). Research findings indicated that case 8 with %PL=30% and 70% from PV is an optimum balance. This instance uses up all available capacity without overloading the system. Under this scenario, it emerged from the analysis that the line ampacity of the grid remained within safe operational limits of 80%. In addition, bus voltages critical for maintaining a stable flow of electricity stayed within acceptable limits.

Similarly, frequency response which tells how well a grid can cope with changes in demand for electrical energy was relatively stable under scenario 8. This demonstrates that increased use of solar does not affect the ability of grids to maintain constant frequency, a key element necessary for a reliable supply of electricity. For illustration purposes, Figure 21 in this paper portrays PowerWorld diagram displaying the network configuration in Case 8.

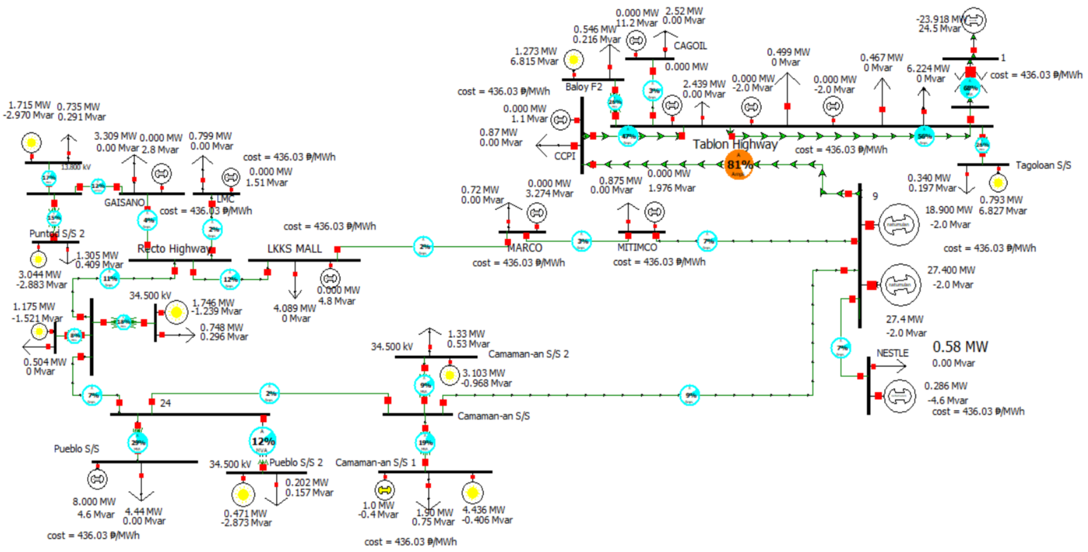


Figure 21. Power grid condition under 70% solar penetration level

4. CONCLUSION

This study arrives at several key conclusions regarding the impact of solar energy penetration on the power grid. Firstly, it was observed that as the solar penetration level increases, the total solar MVAR outputs also rise. However, this excessive increase in total reactive power can adversely affect the power grid, particularly reducing the overall system efficiency, with notable impacts on power transformers. Secondly, a correlation was found between the increased levels of solar penetration and a decrease in the voltage levels of the buses, indicating a direct impact of solar energy integration on bus voltage stability.

Furthermore, the study determined that the interconnection of grid-tied solar photovoltaics (PVs) within the CEPALCO power grid did not result in any violations or changes in bus frequencies, suggesting a stable frequency profile despite solar integration. Additionally, it was noted that both the transmission line ampacity and transformer power loading levels change relative to solar penetration levels. This phenomenon is attributed to the reverse power flow occurring within the power grid.

A significant finding of this study was that at Case 8 (with 30% power load and 70% solar PV penetration), the maximum allowable level of grid-tied solar PV injection was reached. This indicates a threshold for sustainable solar integration without compromising grid stability. Based on these findings, the researcher recommends several avenues for future work. First, acquiring actual and up-to-date data on the load demand of residential, commercial, and industrial consumers of CEPALCO, preferably in the form of a load demand curve, would be beneficial. This would allow for a comparison between the study's results and the latest load demand data. Additionally, experimenting with other power system simulators, such as ETAP or SYNERGY, and comparing the outcomes with those obtained using PowerWorld, could provide further insights. The inclusion of power system solutions, mitigations, and grid protections to address the effects of increased solar photovoltaic penetration levels is also recommended. Lastly, exploring other potential effects on transient and grid impact stability, such as rotor angle stability, under various solar penetration levels, would contribute to a more comprehensive understanding of solar integration's impact on the power grid.

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