Impact of Solar PV Integration on Power Quality of the JNEC Campus Distribution Network

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Abstract
The increasing adoption of grid-connected solar photovoltaic (PV) systems has introduced new challenges related to voltage regulation and power quality in low-voltage distribution networks. This study investigates the impact of integrating a 240 kW grid-connected solar PV system into the electrical distribution network of Jigme Namgyel Engineering College (JNEC), Bhutan, using the Electrical Transient Analyzer Program (ETAP). An unbalanced load flow and harmonic analysis were conducted to evaluate the effects of PV integration on bus voltage profiles and total harmonic distortion (THD) under existing operating conditions. In addition, PV penetration studies at 25%, 50%, 75%, and 100% generation levels were performed to assess the network response under varying levels of solar generation. To evaluate future expansion, a 5 MW PV integration scenario was also simulated to examine the operational challenges associated with high PV penetration. The results indicate that the 240 kW PV system significantly improves the undervoltage conditions on the feeder supplied by the 250 kVA transformer while maintaining harmonic distortion well within the limits specified by IEEE 519 and the Bhutan Power Corporation (BPC) Low Voltage Distribution Code. However, the 5 MW scenario resulted in excessive voltage rise that required additional voltage control measures. The implementation of a voltage regulator and Static VAR Compensator (SVC) effectively restored bus voltages to acceptable operating limits. The findings demonstrate that appropriately designed voltage regulation techniques enable reliable integration of distributed solar PV systems while maintaining acceptable power quality and supporting future renewable energy expansion in campus distribution networks.
Key Words: *Solar photovoltaic (PV), ETAP, Load flow analysis, Harmonic analysis, Power quality, Voltage regulation, PV penetration, Campus distribution network, Renewable energy integration.*

1. INTRODUCTION

With the increasing shift towards utilizing renewable energy sources of power around the world, the use of solar photovoltaic (PV) systems is one of the fastest-growing methods of generating electricity. The declining cost of PV system components, the advancements in PV system technologies, and the environmental concerns associated with the conventional methods of generating power have led to the adoption of PV systems by governments, industries, and even educational institutions to help to reduce their dependence on fossil fuel power. While Bhutan currently primarily utilizes hydroelectric power to supply its power to the country's electrical grids, PV systems are one of the methods that has garnered the interest of the country to provide power to its grids and to support its sustainable development goals.

Despite the benefits that are provided to the electrical grids by the integration of PV systems, there are still a few technical challenges related to such integration. PV systems produce power that is intermittent in nature, and the inverters that are often utilized to supply such power to electrical grids can introduce issues into the electrical grids related to voltage levels, power flow, and the quality of the power that is supplied to the electrical consumers. Consequently, prior to the integration of PV systems into existing electrical distribution infrastructures, a technical assessment must be performed of those electrical distribution networks to ensure that the PV systems will comply with the standards of the electrical distribution grids and that the integration of such PV systems will ensure the reliability of those electrical distributions.

A number of studies have been performed into the effects of the integration of distributed PV systems into electrical distribution networks, particularly in relation to voltage levels, harmonics, and the penetration of PV systems into electrical distribution networks. However, the majority of these studies have been performed on electrical distribution networks in urban areas, and few have been performed on electrical distribution networks of campuses in developing countries. Additionally, the majority of the existing studies have examined the impact of the integration of moderate capacity solar PV systems into electrical distribution networks, as well as the future integration of large-scale PV systems into those same electrical distribution networks, and the strategies that can be employed to mitigate the resulting voltage issues.

As part of the renewable energy initiative implemented by Jigme Namgyel Engineering College (JNEC), Bhutan plans to install a 240 kW grid-connected solar PV system. Bhutan plans to integrate the grid-connected system into low-voltage campus distribution networks. Before the system is installed, the probable effects PV integration on the campus distribution networks' safe, reliable operation and compliance with the Bhutan Power Corporation (BPC) Low Voltage Distribution Code, and the IEEE 519 standard for harmonics and voltage regulation, are evaluated.

This research aims to build a precise representation of the JNEC campus distribution network using ETAP and perform unbalanced load flow and harmonics to assess the likely impacts of the planned 240kW PV System. PV penetration to the 25%, 50%, 75%, and 100% thresholds is studied to understand the effects of differing solar generation on campus distribution network operations. A 5 MW PV System is studied to assess the impact of future PV systems on the JNEC campus distribution network. When a significant increase in voltage is observed, the use of a voltage regulator and Static Var Compensator (SVC) are assessed for the control of voltage stability.

This work offers an extensive evaluation of solar PV in an actual campus distribution network modeled in ETAP. Most studies are limited to a specific PV operating condition. In contrast, this study merges several aspects: load flow, harmonics, different PV penetration levels, the prospect of extensive PV integration, and voltage mitigation, all within the framework of a single study. This research offers valuable advice to educational institutions and distribution utilities that are contemplating similar renewable energy integration projects and who wish to maintain a suitable balance of voltage and power quality.

2. LITERATURE REVIEW

The integration of solar photovoltaic (PV) systems into electrical distribution networks has been widely investigated due to the rapid growth of renewable energy deployment and the increasing need for sustainable power generation (International Energy Agency [IEA], 2023; REN21, 2023). Although distributed PV systems provide environmental and economic benefits, their integration into low-voltage distribution systems may introduce technical challenges, including voltage rise, harmonic distortion, reverse power flow, and voltage fluctuations (Farhoodnea et al., 2013; Sharew et al., 2021). Consequently, several researchers have employed power system simulation software to evaluate the impact of PV integration on distribution network performance (Sharew et al., 2021; Gurung et al., 2023).

Studies have shown that moderate PV penetration generally improves feeder voltage profiles by supplying local loads and reducing voltage drops along distribution feeders (Sharew et al., 2021; Darjay et al., 2023). However, as PV penetration increases, excessive active power injection may result in overvoltage conditions, particularly at buses located close to the point of common coupling (Farhoodnea et al., 2013). This issue becomes more significant in radial distribution systems where feeder impedance is relatively high (Subba et al., 2022). Therefore, voltage regulation has become one of the primary technical concerns associated with high-penetration distributed generation (Farhoodnea et al., 2013; Darjay et al., 2023).

Several researchers have also investigated the influence of inverter-based PV systems on power quality. Modern grid-connected inverters generate harmonics due to their switching operations; however, advancements in inverter technology have significantly reduced harmonic emission (Farhoodnea et al., 2013). When designed according to IEEE 519 requirements, contemporary PV inverters generally maintain Total Harmonic Distortion (THD) within acceptable limits (IEEE, 2014). Nevertheless, harmonic assessment remains essential because cumulative harmonic distortion depends not only on inverter characteristics but also on feeder impedance, network topology, and load composition (Farhoodnea et al., 2013; Sharew et al., 2021).

Simulation tools such as Electrical Transient Analyzer Program (ETAP) have become widely adopted for evaluating the technical performance of electrical distribution systems (Operation Technology Inc., 2023). ETAP provides comprehensive capabilities for modelling distribution networks and performing load flow, harmonic, short-circuit, and power quality analyses under various operating conditions (Operation Technology Inc., 2023). Its integrated analysis environment enables engineers to assess the operational impacts of renewable energy sources before their physical implementation, making it an effective tool for planning distributed generation projects (Operation Technology Inc., 2023; Gurung et al., 2023).

Although previous studies have significantly contributed to understanding PV integration in electrical networks, most investigations focus on urban feeders, industrial facilities, or utility-scale distribution systems (Sharew et al., 2021; Darjay et al., 2023). Comparatively fewer studies have examined campus-scale electrical distribution networks, where load diversity, radial feeder configuration, and transformer loading characteristics differ considerably from conventional utility systems (Gurung et al., 2023). In addition, many existing studies evaluate only a single PV installation scenario and do not investigate how varying penetration levels influence voltage profiles and harmonic performance. Furthermore, limited research simultaneously considers future large-scale PV expansion together with practical voltage mitigation strategies within the same distribution network (Subba et al., 2022; Darjay et al., 2023).

The present study addresses these limitations by investigating the integration of a 240 kW grid-connected solar PV system into the Jigme Namgyel Engineering College (JNEC) campus distribution network using ETAP software. Unbalanced load flow and harmonic analyses are performed under normal operating conditions and at 25%, 50%, 75%, and 100% PV penetration levels. In addition, a 5 MW future expansion scenario is evaluated to examine the technical challenges associated with high PV penetration. Appropriate mitigation measures, including a voltage regulator and a Static VAR Compensator (SVC), are assessed to maintain acceptable voltage levels. By combining practical network modelling, multiple PV penetration scenarios, harmonic assessment, and voltage mitigation within a real campus distribution system, this study provides a comprehensive framework for planning renewable energy integration in educational institutions and similar low-voltage distribution networks.

3. METHODOLOGY

The methodology flow chart in Fig. 1 shows a brief overview of the procedure of the study followed.

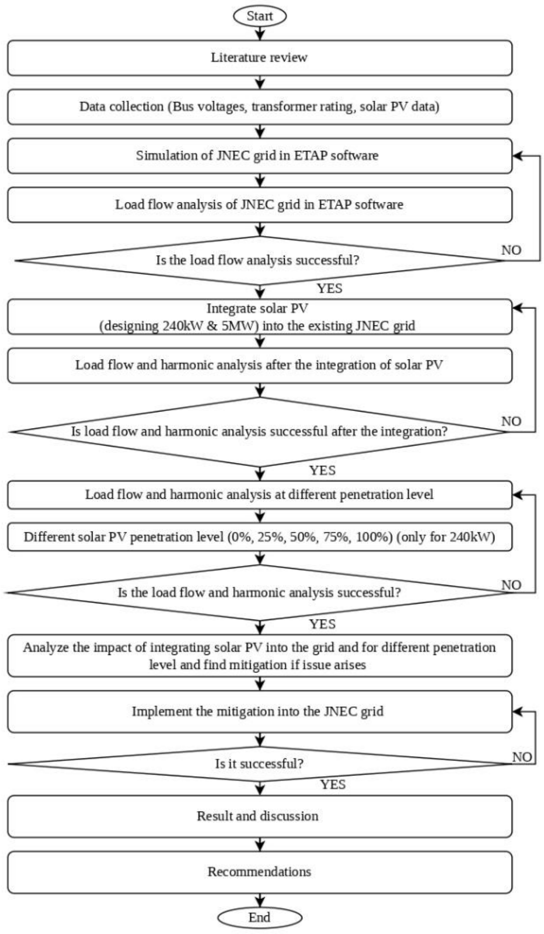

Fig. 1: *Methodology chart*

3.1 JNEC Distribution Network

This study was conducted on the electrical distribution network of Jigme Namgyel Engineering College (JNEC), Bhutan, which is supplied from the Neylang 11 kV distribution feeder through two distribution transformers rated at 500 kVA and 250 kVA, respectively. The 500 kVA transformer supplies the academic buildings, hostels, cafeteria, and staff quarters in the lower campus, while the 250 kVA transformer supplies the upper campus, including residential quarters and student hostels. The total connected load of the campus is approximately 544 kW, distributed between the two transformers according to the existing campus electrical layout. The detailed network configuration was developed from the actual single-line diagram, load inventory, cable routes, and transformer data obtained from the JNEC Estate Office and Electrical Maintenance Unit.

3.2 ETAP Modeling

A detailed model of the campus electrical distribution network was developed using the Electrical Transient Analyzer Program (ETAP). ETAP was selected because it provides an integrated environment for modelling electrical distribution systems and performing load flow, harmonic, and power quality analyses with high accuracy. The simulation model included:

- Incoming 11 kV utility supply
- Distribution transformers
- Low-voltage buses
- Underground distribution cables
- Campus building loads
- Distribution panels
- Grid-connected solar PV system

Actual transformer ratings, cable lengths, conductor types, and connected loads were incorporated into the model to ensure that the simulated network closely represented the existing campus distribution system.

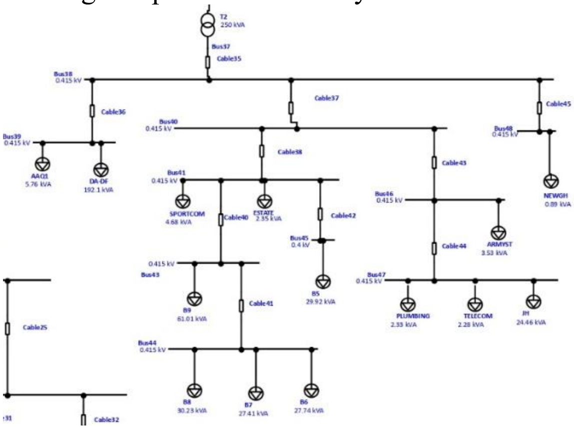

Fig. 2: SLD of upper campus using ETAP Software

3.3 Model Validation

To improve the reliability of the simulation model, the calculated bus voltages obtained from ETAP were compared with measured voltages recorded from the actual JNEC distribution network. Minor adjustments to feeder parameters and connected load values were made until the simulated voltage profile closely matched the measured operating conditions. This validation process increased confidence that the developed model accurately represented the existing electrical network before introducing the solar PV system.

3.4 Solar PV System Modelling

The proposed 240 kW grid-connected solar photovoltaic system was modelled using the actual equipment specifications selected for the JNEC solar project.

The PV system consists of:

- 336 monocrystalline PV modules rated at 720 Wp
- Four 60 kW three-phase grid-connected inverters
- Twenty-four PV strings with fourteen modules connected in series per string
- Total installed capacity of 240 kW

The inverter harmonic characteristics were modelled in accordance with the manufacturer's specifications and IEEE 519 harmonic recommendations. The solar PV system was connected to Bus 38, located on the secondary side of the 250 kVA distribution transformer, which corresponds to the proposed physical installation point of the campus solar project.

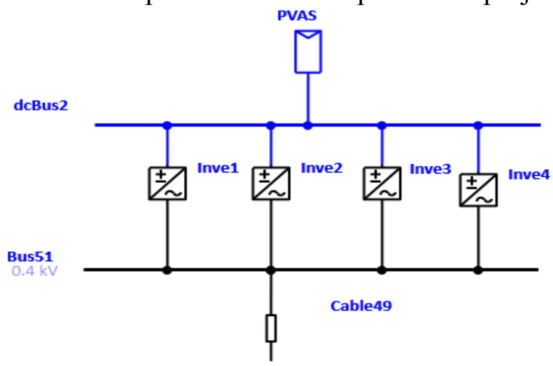

Fig. 3: Solar PV system designed using ETAP

3.5 Load Flow Analysis

An unbalanced three-phase load flow analysis was performed using the Newton–Raphson algorithm implemented in ETAP. The analysis determined the steady-state operating conditions of the campus distribution network, including bus voltage magnitudes, active and reactive power flow, and voltage deviations before and after PV integration. The load flow problem is represented by:

$$P_i = P_i(v, \theta)$$
$$Q_i = Q_i(v, \theta)$$

- $P_i = \text{Active power injection at bus } i,$
- $Q_i = \text{Reactive power injection},$
- $v = \text{Bus voltage magnitude},$
- $\theta = \text{Voltage phase angle}.$

The iterative Newton–Raphson solution was continued until the specified convergence tolerance was achieved.

3.6 Harmonic Analysis

To analyze waveform distortion (Total Harmonic Distortion), harmonic load flow analyses was performed using ETAP software. ETAP executed frequency-sweep calculations across all buses to calculate the Total Harmonic Distortion (THD) for voltage waveforms, governed by the following standard IEEE formula:

$$V_{THD} = \frac{\sqrt{\sum_{h=2}^{N} V_h^2}}{V_1} \times 100\%$$

The calculated results were evaluated against the power quality limits of the BPC standard, which mandates a maximum permissible individual harmonic limit of 3% and Total Harmonic distortion (THD) of 5% for low voltage system.

3.7 Performance Evaluation

The performance of the distribution network was evaluated using the following indicators:

- Bus voltage profile
- Voltage rise
- Total Harmonic Distortion (THD)
- Compliance with IEEE 519
- Compliance with the BPC Low Voltage Distribution Code
- Effectiveness of voltage regulation after PV integration

The results obtained from each operating scenario were compared to identify the technical impact of increasing PV penetration and to determine suitable voltage mitigation measures for reliable operation of the campus distribution network.

4. RESULTS AND DISCUSSION

4.1 Base-Case Load Flow Analysis

This section presents the load-flow analyses undertaken on the campus distribution network under normal operation as well as when integrated with photovoltaic sources. An initial simulation study without incorporating solar PV was conducted to obtain a baseline understanding of the operating features of the network. A set of simulations were run using different load configurations and the results have been summarized below.

As shown in Figure 4(a), the simulation under normal operation resulted in a steady state voltage profile of the various nodes fed from the 500kva and 250kva distribution transformer. From the result obtained, we can see that while most of the buses are within their permissible voltages defined in the Bhutan Power Corporation (BPC) Low Voltage Distribution Code, the ones at the farthest ends experience a notable voltage drop attributed mainly to the impedances along the feeders and also the cumulative loading effects.

From figure 4(b), one can note that the highest magnitude of undervoltage occurs on the y-phase of buses 43-44 on 250kva feeder approaching its allowable operational limit. As expected, this kind of phenomenon tends to be common for radial distribution systems due to the increasing influence of the lengths of feeders and corresponding currents flowing through them. It may also be noted that the different magnitudes recorded for each of the three-phases show an indication of load imbalances caused by unevenly spread single-phase loads over the campus network. Also since majority of the loads on the campus are tapped off on the y-phase, hence experiencing greater current flows compared to the other two phases and hence bigger voltage drops. Therefore, there arises the need to perform certain measures aimed at voltage improvements prior to integration with DGs into the system.

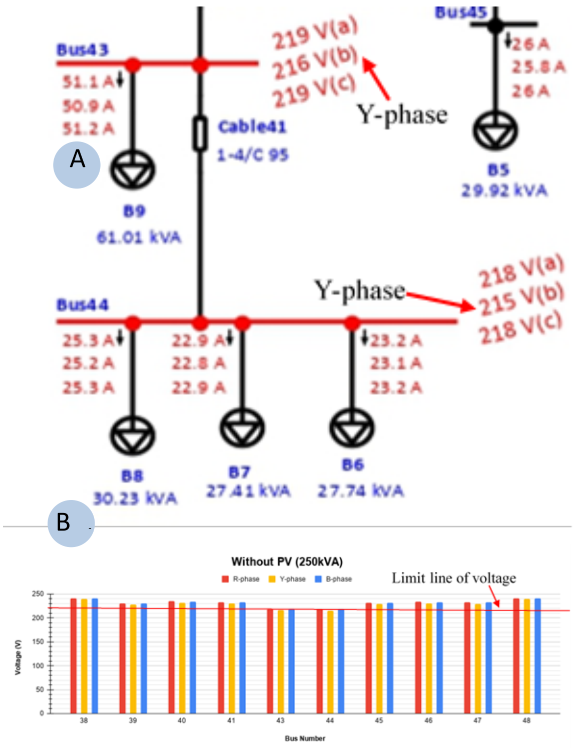

Fig. 4: (a)Voltage at bus 43 and 44 (b) Voltage profiles of Upper Campus Before PV integration

4.2 Impact of 240 kW Solar PV Integration

After checking the model the proposed 240 kW grid-connected solar PV system was added at Bus 38 on the secondary side of the 250 kVA transformer. This is where the actual campus solar project was planned to be installed. The results of the simulation show that the extra power from the PV system greatly improves the voltage of the feeder connected to the 250 kVA transformer. This happens because the local power generation meets some of the demand from the loads downstream which reduces the current in the feeder and minimizes the drops in voltage along the distribution line. As a result the buses that used to have voltage (43 and 44) are now within the acceptable limits.

The voltage profile of the 500 kVA feeder did not change much after the solar PV system was added. This is because the two transformers supply parts of the campus distribution network and the solar power generation was only connected to the 250 kVA transformer. So, the power that was added mainly affected the feeder and did not have a big impact on the rest of the distribution network.

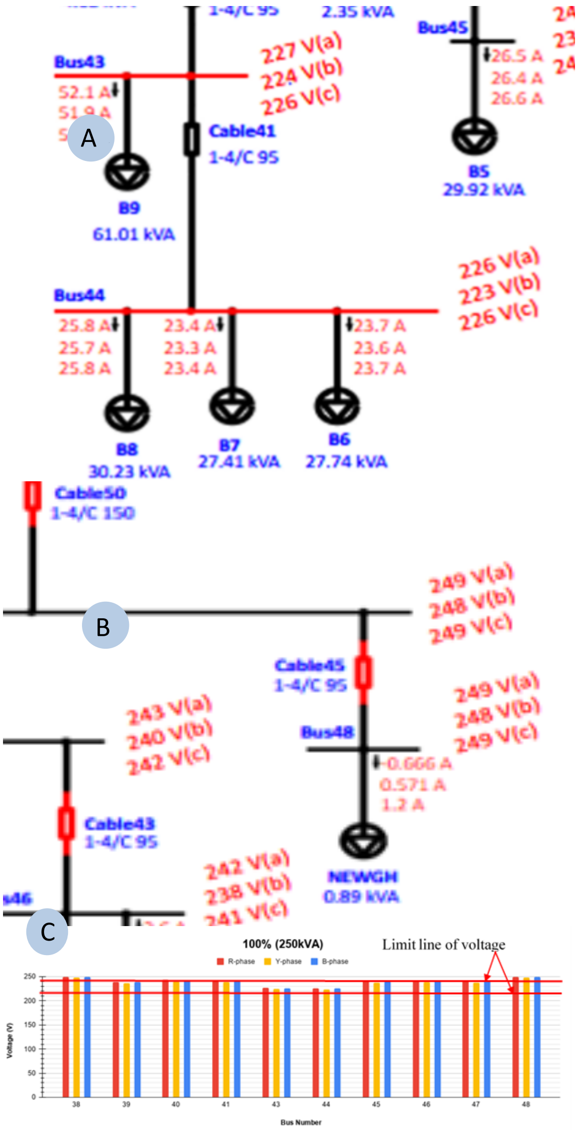

Fig. 5: *(a)Voltage at bus 43 and 44 (b) Voltage at bus 38 and 48 (c) Voltage profiles of Upper Campus after PV integration*

Even though the voltage got better in most of the 250 kVA feeder the buses close to where the solar PV system was connected had an increase in voltage. The highest voltages were seen at Buses 38 and 48 where the power from the PV system was more than the local demand during the peak time. However, the high voltage was not too bad. It shows that adding a moderate amount of solar PV power can really improve the feeder voltage and only needs a little adjustment to the voltage.

4.3 Harmonic Performance after PV Integration

The harmonic analysis was carried out to evaluate the influence of the inverter-based solar PV system on the power quality of the campus distribution network.

The simulation indicates that the harmonic distortion introduced by the PV inverter is relatively small throughout the network. The dominant harmonic components are the 5th, 7th, 11th, and 13th harmonic orders, which are characteristic of modern three-phase grid-connected inverters. However, their magnitudes remain significantly below the allowable limits specified in IEEE 519.

Higher harmonic distortion was observed on buses connected to the 250 kVA feeder because these buses are electrically closer to the PV inverter. Conversely, buses supplied by the 500 kVA transformer exhibit negligible harmonic distortion since they are electrically isolated from the PV connection point. Overall, the results demonstrate that the selected inverter technology maintains excellent power quality while complying with harmonic standards.

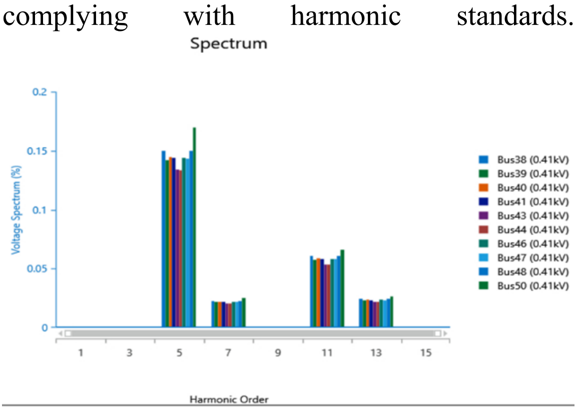

Fig. 6: *Harmonic spectrum of upper campus area after solar PV integration*

4.4 Effect of PV Penetration Levels

To investigate the influence of varying solar generation, additional simulations were performed at 25%, 50%, 75%, and 100% PV penetration levels.

The results demonstrate a gradual improvement in the voltage profile as PV generation increases. At 25% penetration, only minor voltage improvement is observed, while the undervoltage conditions at the remote buses are still slightly evident. Increasing the penetration level to 50% and 75% further improves the feeder voltage and substantially reduces voltage deviations. At full PV output, the remote buses achieve acceptable voltage levels; however, buses located near the point of common coupling begin to experience slight overvoltage.

These results indicate that moderate PV penetration effectively compensates for feeder voltage drops by supplying local active power. However, excessive power injection increases the risk of voltage rise near the PV connection point. Therefore, the optimum penetration level should balance voltage improvement with the prevention of excessive overvoltage.

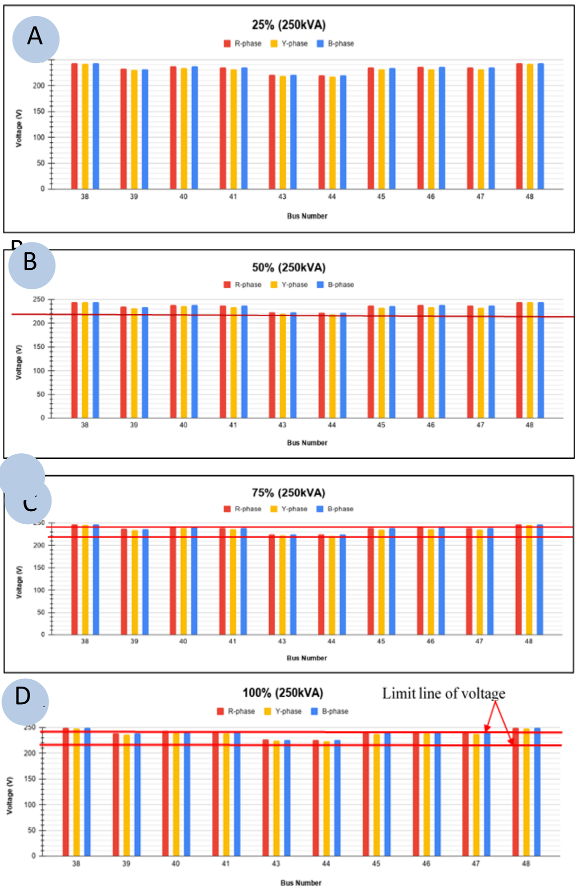

Fig. 7: *Voltage profile of upper campus at solar PV (a) 25% Penetration (b) 50% Penetration (c) 75% Penetration (d) 100% Penetration*

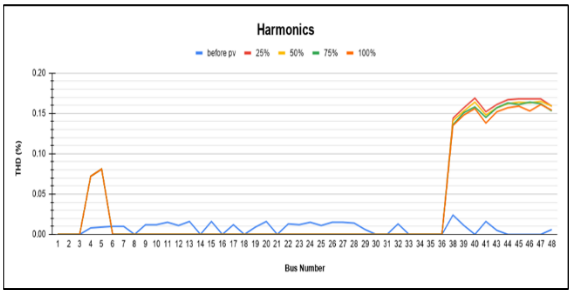

Fig. 8: *THD profile at different Solar PV penetration level*

The harmonic analysis performed for each penetration level shows only minimal variation in Total Harmonic Distortion (THD). Although the buses closest to the inverter consistently exhibit the highest THD values, the overall harmonic distortion remains well below IEEE 519 limits for all operating scenarios. This confirms that the inverter characteristics have a greater influence on harmonic performance than the output power level within the investigated range.

4.5 Performance under the 5 MW PV Scenario

To evaluate the long-term capability of the JNEC distribution network, a hypothetical 5 MW solar PV installation was simulated.

Unlike the 240-kW installation, the 5 MW system injects substantially more active power than the campus load demand. As a result, significant voltage rise occurs throughout the distribution network, particularly at buses located near the PV interconnection point. Under this condition, the network is unable to maintain acceptable voltage limits using its existing configuration.

These findings indicate that the existing campus distribution infrastructure is not designed to accommodate utility-scale PV generation without additional voltage regulation measures. The study therefore demonstrates that future expansion of distributed generation requires coordinated voltage control strategies to ensure reliable network operation.

4.6 Voltage Regulation Using a Voltage Regulator and SVC

To mitigate the voltage rise observed under high PV penetration, a voltage regulator and a Static VAR Compensator (SVC) were incorporated into the ETAP model.

The voltage regulator effectively controlled feeder voltage by adjusting the downstream operating voltage during periods of high PV generation. As a result, the excessive voltage rise produced by the PV system was significantly reduced, restoring the majority of buses to acceptable operating limits.

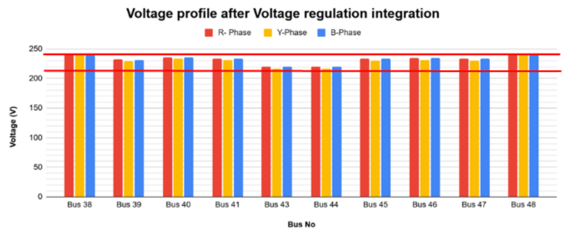

Fig. 9: *Voltage profile of upper campus after voltage regulator implementation*

For the 5 MW scenario, additional reactive power compensation was provided by the SVC. The coordinated operation of the voltage regulator and SVC further improved voltage stability by dynamically regulating reactive power and minimizing voltage deviations across the distribution network.

These results demonstrate that conventional voltage regulation devices remain effective solutions for integrating higher levels of distributed solar PV into exist.

Fig. 10: *(a) Voltage profile of upper Campus with 5MW PV system (b)Voltage profile of upper campus after SVC implementation*

5. CONCLUSION

This study evaluated the technical impact of integrating a 240 kW grid-connected solar photovoltaic (PV) system into the existing electrical distribution network of Jigme Namgyel Engineering College (JNEC), Bhutan, using ETAP simulation software. Unbalanced load flow and harmonic analyses were performed to assess the effects of PV integration on voltage profile and power quality under existing network conditions. In addition, PV penetration studies at 25%, 50%, 75%, and 100% generation levels were carried out to investigate the influence of increasing solar generation on distribution network performance. A 5 MW future expansion scenario was also evaluated to examine the operational challenges associated with large-scale PV integration.

The simulation results demonstrated that the proposed 240 kW PV system improved the voltage profile of the feeder supplied by the 250 kVA transformer by reducing feeder voltage drops and restoring previously undervoltage buses to acceptable operating limits. In contrast, the 500 kVA feeder showed minimal voltage variation because it operates independently of the PV connection point. Harmonic analysis further confirmed that the Total Harmonic Distortion (THD) remained well within the limits specified by IEEE 519 and the Bhutan Power Corporation (BPC) Low Voltage Distribution Code, indicating that the selected inverter technology maintains satisfactory power quality.

The PV penetration analysis showed that increasing PV generation progressively improved feeder voltage; however, higher penetration levels also resulted in localized voltage rise near the point of common coupling. Under the hypothetical 5 MW PV integration scenario, the existing campus distribution network experienced excessive overvoltage that exceeded acceptable operating limits. The implementation of a voltage regulator and Static VAR Compensator (SVC) effectively mitigated these voltage deviations and restored the network to stable operating conditions.

Overall, the findings demonstrate that the planned 240 kW solar PV installation can be successfully integrated into the JNEC campus distribution network without adversely affecting voltage regulation or power quality. The study also highlights the importance of incorporating appropriate voltage control strategies when planning future high-penetration PV installations. The developed ETAP model provides a practical framework for assessing distributed renewable energy integration in campus-scale electrical distribution systems and can support planning studies for similar educational institutions and low-voltage distribution networks.

This study is limited to simulation-based analysis using the available network configuration and operating conditions. Future research may include field validation after PV installation, assessment of seasonal load and solar generation variations, real-time monitoring of power quality, and evaluation of advanced smart inverter control strategies for enhancing voltage regulation under higher renewable energy penetration.

6. ACKNOWLEDGEMENT

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