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PERFORMANCE EVALUATION WITH LARGE-SCALE SOLAR PV INTEGRATION TO GRID: A CASE STUDY OF NEPALESE TRANSMISSION NETWORKS

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Abstract

To mitigate carbon footprints and meet growing energy demands, Nepal is increasingly focusing on the development of clean and renewable energy sources. Currently, the nation primarily relies on hydropower for electricity generation, supplemented by a few solar photovoltaic (PV) projects. As outlined in the Energy Development Roadmap 2081, Nepal aims to install a total electric capacity of 28,500 MW and export 15,000 MW to neighboring countries by 2035. To achieve these goals, the government is planning to integrate solar PV power plants into the national grid alongside hydropower. In alignment with this strategy, the Nepal Electricity Authority (NEA) has recently issued Letters of Intent (LOI) for grid connections of solar power plants in various regions. This study investigates the impact of integrating Photovoltaic power plants into the existing 33 kV and 132 kV transmission networks in the Parasi and Nawalpur districts, located in the mid-southern region of Nepal. Utilizing the ETAP platform, comprehensive analyses, including load flow, flicker, short circuit, and transient frequency studies, were conducted to evaluate the effects of PV penetration at multiple grid locations. The findings offer valuable insights into the impacts on grid performance and present concrete recommendations to ensure grid stability and reliability during the transition to a more renewable energy mix.

Keywords: Photovoltaic, Nepal electricity authority, ETAP, Grid stability

1. Introduction

Electrical energy is an essential necessity for modern human life, and its absence is unimaginable. In the case of Nepal, the total theoretical hydroelectric capacity is 83 GW, with 43 GW being technically and economically achievable (Shrestha, 2017). However, with the increasing energy demand and the limitations of conventional power sources, the need to explore alternative renewable energy solutions has become crucial. Among the various renewable energy sources, solar PV power holds immense potential for Nepal due to its significant solar radiation availability throughout the year. It is estimated that solar PV potential in the country is around 47 GW (Neupane et al., 2022). Investing in high-efficiency photovoltaic (PV) systems can play a vital role in enhancing energy security and sustainability of Nepal national grid. The Integrated Nepal Power System (INPS) owned by NEA is Nepal's national grid and it is responsible for supplying power all across the country (Nepal Electricity Authority, 2024). Till 2080/81 B.S., the total installed capacity connected to the grid has reached to 3164.12 MW, with 183.56 MW generated from Alternative Energy Sources like Micro Hydropower, Photovoltaic, Co-Generation and Thermal Plants. 2980.56 MW is contributed by hydropower (larger than 1 MW) out of which only 106 MW is produced by storage projects while the rest is contributed by ROR/PROR projects (Department of Electricity Development, 2024). By the end of the fiscal year 2080/81 B.S., the total installed capacity of grid substations had reached 13,050 MVA and the transmission line circuit length has reached to 6507 km (Ministry of Energy, Water Resources and Irrigation, 2025). Since most of the plants are ROR/PROR type, Nepal is facing energy deficit in dry seasons. NEA imported 1,895 MU energy in dry season in fiscal year 2080/81 B.S. To meet growing electricity demand involves the establishment and expansion of large centralized power plants, transmission networks,

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and distribution infrastructures. Different researchers have analyzed grid impact assessment of PV into the grid. The study shows that increasing PV capacity affects power flow, voltage variation, short-circuit current and dynamic system behaviors (Wu et al., 2016). According to researchers, during the high penetration of distributed PVs in power system, the sudden change of PV output or transmission line tripping fault can seriously affect the voltage stability of the power system (Zhao et al., 2015). However different mitigation technique has also been employed to minimize the negative effects of PV penetration into the grid. The use of synchronous compensator plays significant role in the event of a voltage dip as they allow a faster recovery of the active power of the photovoltaic power plant, as well as a better response to the dip. Similarly, the use of energy storage along with DVR helps to mitigate the voltage swell and dip problem Jiménez et al., 2023. In Nepal, the integration of renewable energy into the national grid is critical to achieving the country's long-term energy objectives. Solar power generation, with its potential to supplement hydropower during dry seasons, is an essential component of Nepal's energy diversification strategy. However, the deployment of large-scale PV plants presents unique technical challenges that must be addressed to ensure stable and reliable grid operation. PV energy production is intermittent and variable, causing voltage fluctuations in the power system. These fluctuations can affect supply and demand balance, leading to voltage instability Akkur et al., 2023. These challenges are further compounded by potential overloading of grid infrastructure and disruptions to protection coordination. The detailed studies of PV impacts in INPS are still not found in literature. This paper focuses on these impacts and their performances to assess and mitigate of Nepal's national grid in mid-southern region at Nawalpur and Parasi districts. In this paper, a detailed modeled of transmission line network of Nawalpur and Parasi District is modelled and simulations has been carried out to understand the basic model before penetration of PV plant to the grid. Then the study compares the voltage profile, branch loading, line losses, short circuit, and flicker analysis before and after the penetration of PV plant to the grid system.

2. Existing Transmission Line of Nawalpur Nawalparasi District

Figure 1 illustrates the transmission line network within study zone. Nawalpur-Parasi are the mid-southern Terai districts of Nepal. The Bharatpur Substation is situated in the eastern region of Nawalpur district and is connected to Marsyangdi, Damauli and Hetauda Substation to the east. To the west, the Bharatpur Substation is linked to Kawaswoti Substation via a 132 kV transmission line spanning 36 km. The three feeder connect to the Kawaswoti Substation: Mukundapur, Bhojapokhari and Kawaswoti DCS. A transmission extending approximately 34 km leads to Bardaghat Substation located in the eastern part of Parasi District. The Gandak Substation, positioned to the south of the Bardaghat substation, is connected through a 132 kV transmission line. Gandak Hydropower station with an install capacity of 15 MW, currently operating at around 4 MW linked to the Gandak Substation. The Bardaghat Substation, to its western part, is connected through a 132 kV double circuit line to the New-Butwal Substation. The 220 kV transmission line originating from the Kaligandaki-Corridor is stepped down to 132 kV at this substation. The New-Butwal Substation is connected to Sunwal Substation to the west via a 132 kV transmission line of 12 km in length. Additionally, the Sunwal Substation is linked to the Butwal Substation by a 16 km long 132 kV transmission line. The Butwal Substation is linked to three primary areas: Kaligandagi hydropower to the north, Motipur to the west and Mainahiya to the south Nepal Electricity Authority, 2024. The eastern section of Bharatpur Substation, the western section of Butwal Substation, and the southern section of Gandak Substation are modelled as a grid in Simulation.

3. Methodology

This section describes the design and process of the work we have done from preliminary phase to its completion. The existing transmission line and solar PV system is modelled and study is done before and after penetration of PV into the grid.

3.1. Transmission System Network

First, the transmission line, feeder and load data are collected. The transmission line of Nawalpur and Parasi Districts is taken for study. Figure 2 below shows the simulation model of Transmission line network for study. This transmission line network consists of different substations. The PV plant is connected to five major substations: Mukundapur, Gandak, Parasi, New-Butwal and Sunwal Substations. The transmission line parameters, line loading information is extracted from annual report 2080-81 of Nepal Electricity Authority (NEA) Nepal Electricity Authority, 2024.

Table 1 shows the details of transmission line network with information like Voltage level, circuit length, conductor used and circuit configuration.

Table 2 shows the connected load capacity at rated voltage level at different substations.

3.2. Power Flow Study

Load flow study is very crucial to know the circuit performance and to plan for the future expansion as well. It helps to know the different electrical parameters like

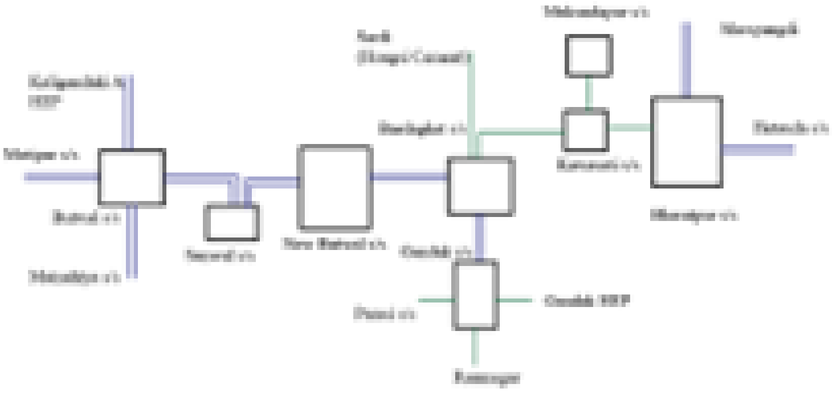

Figure 1. Transmission line of Nawalparasi-Nawalpur Districts

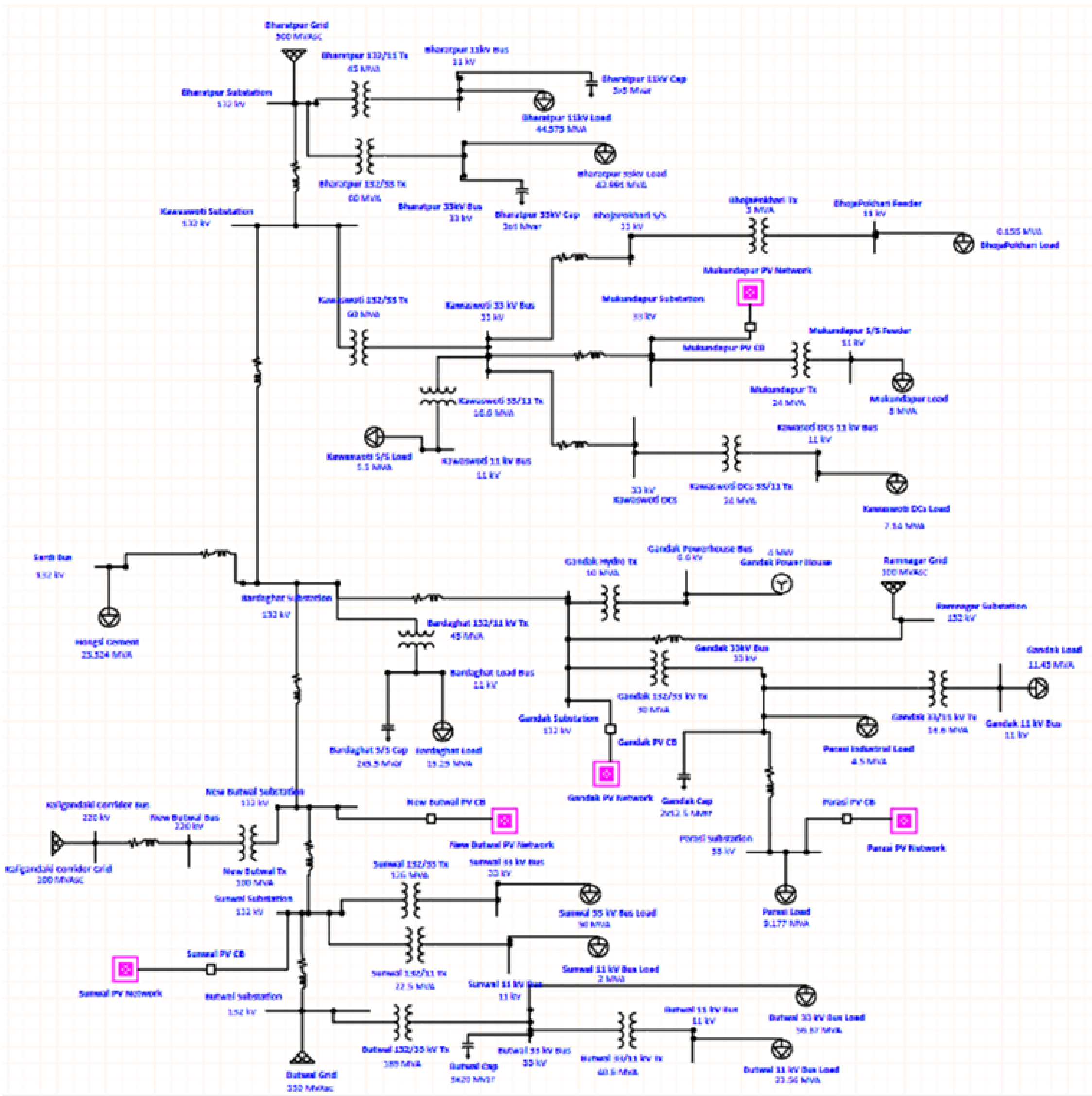

Figure 2. Transmission line with PV model in simulation

Table 1. Transmission line details

S.N	Transmission Line	Voltage (kV)	Length (km)	Conductor	Circuit
1	Bharatpur-Kawaswoti	132	36	Panther	Single
2	Kawaswoti-Bardaghat	132	34	Panther	Single
3	Bardaghat-Gandak	132	14	Panther	Double
4	Gandak-Ramnagar	132	10	Panther	Single
5	Bardaghat-New Butwal	132	14	Bear	Double
6	New Butwal-Sunwal	132	12	Bear	Double
7	Sunwal-Butwal	132	16	Bear	Double
8	Kaligandaki Corridor TL- New Butwal	220	44	ACCC Drake	Double
9	Kawaswoti S/S-Bhojpokhari	66	14	Dog	Single
10	Kawaswoti S/S-Mukundapur	66	14	Dog	Single
11	Kawaswoti S/S-Kawaswoti DCS	66	7	Dog	Single
12	Gandak-Parasi	66	20	Dog	Single
13	Bardaghat-Sardi	132	23	Bear	Single

Table 2. Transformer Details

S.N.	Substations	Voltage Level (kV)	Capacity (MVA)
1	Bharatpur	11	44.575
2	Bharatpur	33	42.991
3	BhojPokhari	11	0.155
4	Mukundapur	11	8
5	Kawaswoti DCS	11	7.14
6	Kawaswoti S/S	11	5.5
7	Sardi	33	23.324
8	Bardaghat S/S	11	15.25
9	Gandak S/S	33	4.5
10	Gandak S/S	11	11.43
11	Parasi S/S	33	9.177
12	Sunwal S/S	33	50
13	Sunwal S/S	11	2
14	Butwal S/S	33	56.87
15	Butwal S/S	11	23.56

voltage, current and power flow at different node and branches. The goal of a power flow study is to obtain complete voltage angle and magnitude information for each bus in a power system for specified load and generator real power and voltage conditions Le Nguyen, 1997.

The Y bus can be written as:

$$Y_{\text{Bus}} = \sum_{i=1,\ i\neq k}^{n} Y_{ik} \tag{1}$$

The nodal current is calculated as,

$$I_k = \sum_{\substack{i=1\\ i\neq k}}^{n} Y_{ik}V_k, \quad i = 1, 2, \ldots, n \tag{2}$$

The complex power delivered to bus k is given by,

$$S_i = P_i + jQ_i = V_i \left[\sum_{\substack{i=1\\ i\neq k}}^{n} Y_{ik}V_k \right]^* \tag{3}$$

Separating real and imaginary parts, Power balance equations can be written as,

$$P_i = \sum_{k=1}^{n} |V_i|\,|V_k|\; Y_{ik}\; Cos\;(\theta_{ik} + \delta_k - \delta_i) \tag{4}$$

$$Q_i = -\sum_{k=1}^{n} |V_i|\,|V_k|\; Y_{ik}\; Sin\;(\theta_{ik} + \delta_k - \delta_i) \tag{5}$$

We have,

$$\Delta f = J\Delta X$$

where, J is Jacobian matrix

$$\Delta P_i = P_{i(sp)} - P_{i(cal)} \tag{6}$$

$$\Delta Q_i = Q_{i(sp)} - Q_{i(cal)} \tag{7}$$

Where the subscripts sp and cal refers to specified and calculated value respectively. Then Equation (6) and Equation (7) can be written as,

$$J \begin{bmatrix} \Delta\delta \\ \Delta|V| \end{bmatrix} = \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \tag{8}$$

where J is Jacobian matrix, contain partial derivatives of power equations.

In this way, the change in power angle and change in voltage is determined and power flow solutions of the network is obtained.

3.3. Photovoltaic Power Plant Design

There are altogether 5 solar Plants, which are planned to connect in Parasi and Nawalpur district of Nepal. Nepal Electricity Authority (NEA) has awarded five project at different locations with different capacity. The list of awarded projects are listed in Table 3.

3.3.1 Solar PV Panel and Inverter Specifications

The PV system utilizes Trina Solar panels with a capacity of 715 Wp. The panel's maximum power point voltage (Vmpp) is 41.1 V, and the current at maximum power point (Impp) is 17.40 A. The open-circuit voltage (Voc) is 49.2 V, and the short-circuit current (Isc) is 18.44 A.

The system employs Sungrow inverters (model SG 2500 HV-MV). On the input side, the maximum PV input voltage is 1500 V, and the maximum PV input current is 3508 A. On the output side, the AC output power is 2750 kVA, the maximum output current is 2886 A, and the nominal AC voltage is 550 V.

3.3.2 Layout of Grid Connected PV System with the Central Inverters

The 10 MW PV plant at Mukundapur Substation (Nawalpur) is designed with four PV arrays, each providing 2.5 MW through inverters (SG2500HV-20). Each inverter is connected to 153 parallel strings, with each string comprising 25 solar panels (715 W each). The PV plant has two 5 MVA transformers, each linked to a pair of arrays through separate inverters as shown in Figure 3. The primary sides of the transformers connect to the 11 kV grid bus bar, which is stepped up to either 33 kV or 132 kV, depending on the point of interconnection. The PV plants at another location with different capacities are also designed in similar fashion.

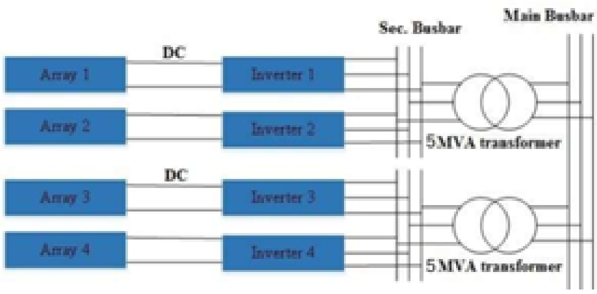

Figure 3. Connection diagram of PV Array into the Grid

3.4. Grid Parameters Impact Study

The integration of distributed energy sources, while offering several advantages, can also negatively impact system parameters. These adverse effects may include voltage swell and dip, increased fault current, harmonic distortions, and grid instability.

3.4.1 Voltage Impact

The inherent variability of solar irradiance, coupled with demand uncertainty and the substantial penetration of PV generators, can induce voltage rises, fluctuations, or imbalances that surpass the acceptable limits outlined in IEEE Standard 1547-2003 (0.95–1.05 p.u.). Consequently, the grid's response to this phenomenon relies on existing voltage control devices, including capacitor banks, reactive power-supportive inverters, and on-load tap-changing transformers Almaktar et al., 2022.

3.4.2 Short Circuit Fault Current

Solar panels remain energized throughout the day due to continuous exposure to sunlight, making it difficult to shut them down during DC-side failures. The higher voltage and current ratings of Solar PV modules increase the likelihood of large fault currents or DC arcs, which can compromise system performance, speed up degradation, and pose fire risks Dhoundiyal et al., 2022.

3.4.3 Flicker Issues

Recent studies indicate that the injection of significant inter-harmonic currents into the power system can lead to flicker issues. Due to fluctuations in solar illumination and the use of power electronic devices, grid-connected PV inverters, which convert solar energy into electricity, may also introduce power quality challenges to the system Wei et al., 2016.

4. Results and Discussion

The results are analyzed based on the different scenario. The comparative analysis of grid impact study before and after penetration of PV plants was compared.

4.1. Load Flow Analysis

The load flow is done in ETAP Simulation Software Which uses Adaptive Newton Raphson Method for study. The maximum Iteration is 99 and precision is 0.0001.

4.1.1 Voltage Profile

Figure 4 shows the voltage profile of all the substation point where the PV is penetrated. The voltage profile, upon interconnection of the PV Plant improves. The improvement is observed noticeably in Mukundapur and Parasi Substation with 95.05% and 100.5% of rated value voltage respectively.

Table 3. Different solar projects awarded by NEA in Nawalparasi District

S.N	Proposed Substation	Substation Capacity(MVA)	Voltage Level (kV)	Awarded Capacity (MW)
1	Mukundapur	24	33	10
2	Gandak	93.2	132	25
3	Parasi	40	33	15
4	New Butwal	100	132	15
5	Sunwal	148.5	132	50

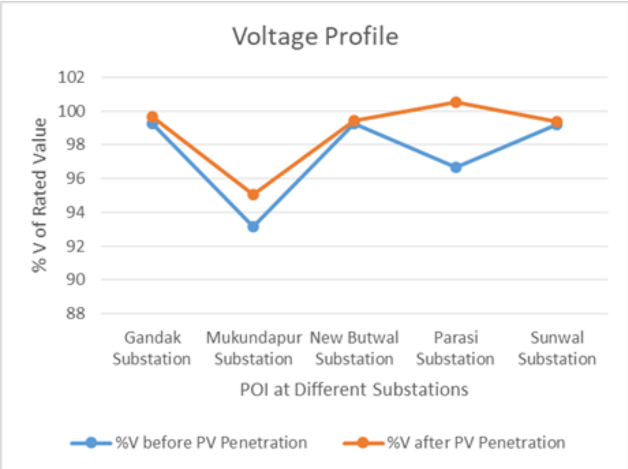

Figure 4. Voltage Profile

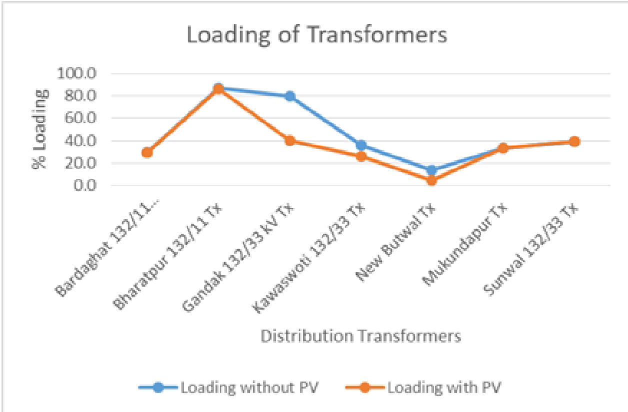

Figure 5. Loading of Transformers

4.1.2 Branch Loading of Transformer

As observed in the Figure 5, Most of the Substations transformers loading is not affected whereas some of the transformer loading has decreased due to penetration of PV Power Plants. The loading of Gandak 132/33 kV transformer has decreased from 80% to 40.1%, Kawaswoti 132/33 kV transformer decreased from 35.8% to 25.8% and New Butwal decreased from 13.7% to 4.9%. Integrating distributed energy sources like PV helps balance local demand, leading to improved branch loading.. Hence the loading of the line improves upon interconnection of the PV System.

4.1.3 Losses in Transmission Line

Integrating distributed energy sources, such as photovoltaic (PV) plants, can significantly reduce these losses. Figure 6 shows losses in line before and after penetration of the PV into the grid. For example, losses in the Kawaswoti-Mukundapur Transmission Line were reduced from 172.8 kW to 106.4 kW. In the New-Butwal to Sunwal Transmission Line, losses dropped from 25.7 kW to 1.0 kW, while the Sunwal-Butwal Transmission Line saw a reduction from 266.1 kW to 48.4 kW. Hence, the losses in the transmission line network reduced significantly upon interconnection of the PV Plant into the grid.

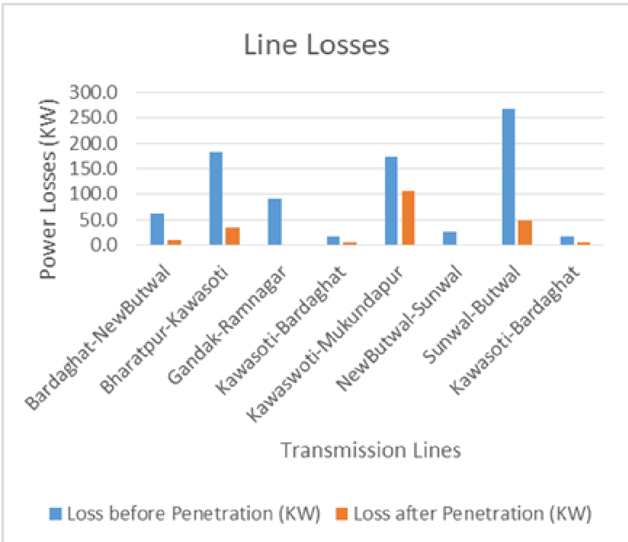

Figure 6. Line Losses

4.2. Short Circuit Analysis

The PV penetration to the grid increases the fault current which may affect the interrupting duty of the Protective device. The three phase fault current has increases slightly upon interconnection of PV Power Plant. The maximum increment is seen in Parasi Substation bus bar with greater than 10% increment. The increment is noticeable in Parasi Substation due to the large PV penetration into the low voltage grid i.e. 33kV. However the short circuit current does not exceed 87.5% of the interrupting capacity of protective devices. So the interconnection of PV Power Plant does not have serious impact on fault duty.

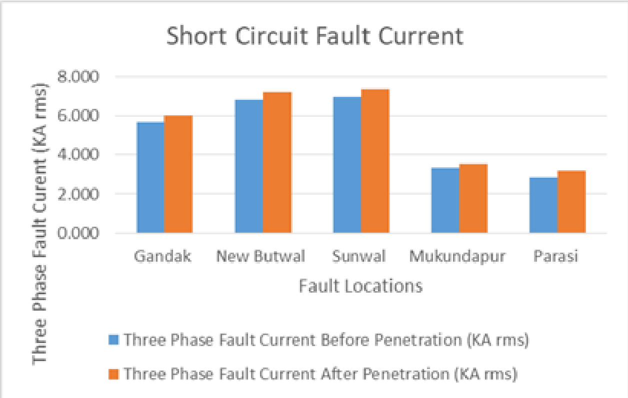

Figure 7. Three phase short circuit current

4.3. Voltage Flicker Analysis

Excessive flicker can cause eye strain and headaches. Most electric device may not work under voltage fluctuations. Since PV Power is intermittent in nature, the voltage Flicker analysis must be done. At point of Interconnection, the Voltage Flicker should not cross 3% Photovoltaics and Storage, 2018.

4.3.1 Voltage Flicker at Mukundapur and Parasi Substation

For voltage flicker analysis, an event was created. For the simulation of 30s, the circuit breaker associated to the PV Plant is disconnected after 5 sec and the voltage deviation is observed.

The voltage variation after the disconnection of PV Plant after 5 sec of simulation time is shown in Figure 8. When the circuit breaker of respective PV Plant opens, the voltage dropped from 31.35 kV to 30.6 kV resulting in 2.39% in Mukundapur and 33.2 kV to 31.5 kV resulting in 5.12% reduction in Parasi Substation at POI. The voltage flicker at Mukundapur Substation is within the range, however the voltage flicker at Parasi Substation is greater than 3%.

4.3.2 Voltage Flicker at Gandak, Sunwal and New-Butwal Substation

After 5 seconds, the circuit breaker of the PV power plant was opened, leading to voltage fluctuations, as shown in Figure 9. The voltage dropped from 131.6 kV to 129.3 kV at Gandak Substation, a 1.75% decrease. At Sunwal Substation, the voltage declined from 131.5 kV to 127.1 kV, resulting in a 3.346% reduction. Meanwhile, at New-Butwal

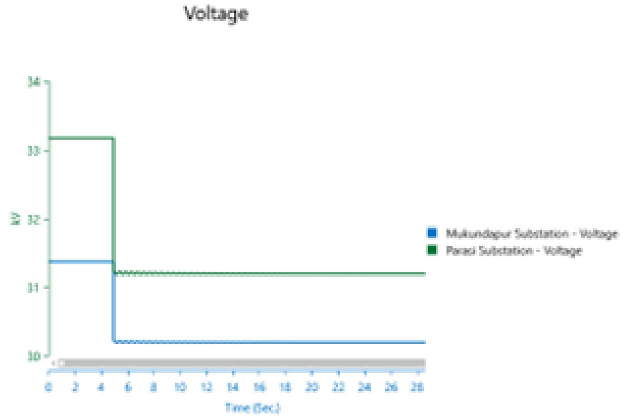

Figure 8. Voltage Flicker at Gandak, Sunwal and New-Butwal Substation

Substation, the voltage decreased from 131.3 kV to 129.8 kV, reflecting a 1.142% drop. The voltage flicker at the Sunwal Substation is significant, exceeding 3%, primarily due to the high capacity of the PV plant, with a 50 MW penetration into the grid. In contrast, voltage flicker at the Gandak and New Butwal Substations remains within acceptable limits.

The substantial capacity of the PV system at Sunwal boosts the voltage at the point of interconnection (POI), but when the PV plant is disconnected, it causes considerable voltage fluctuations.

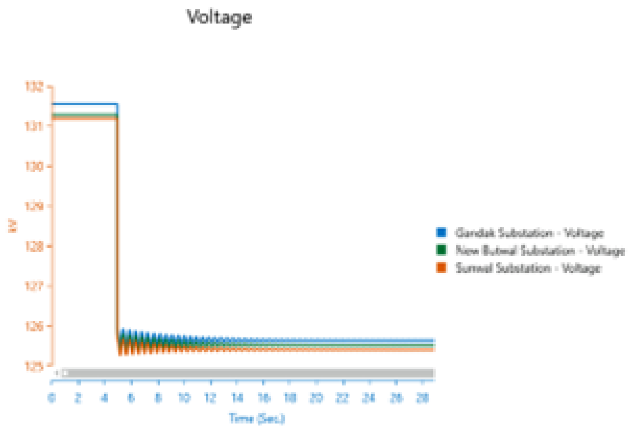

Figure 9. Voltage change in Gandak, Sunwal, and New Butwal Substation

4.4. Transient Frequency Response

The transient frequency was analyzed in the simulation. The PV Plants was made to disconnect in 5 sec and the base model was check whether the system do have capacity to maintain the frequency within the limit or not.

Figure 10, Figure 11, Figure 12, and Figure 13 show that the transient frequency response of the system is stable. The

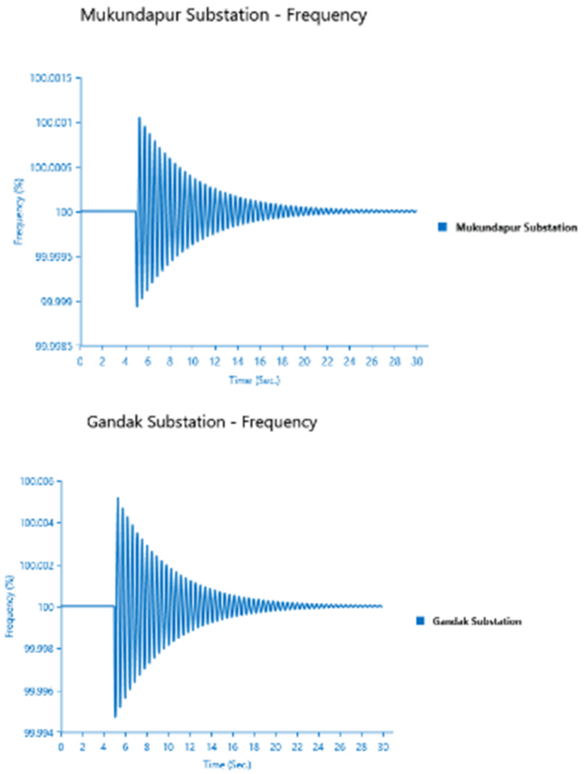

Figure 10. Frequency response of Mukundapur and Gandak substation

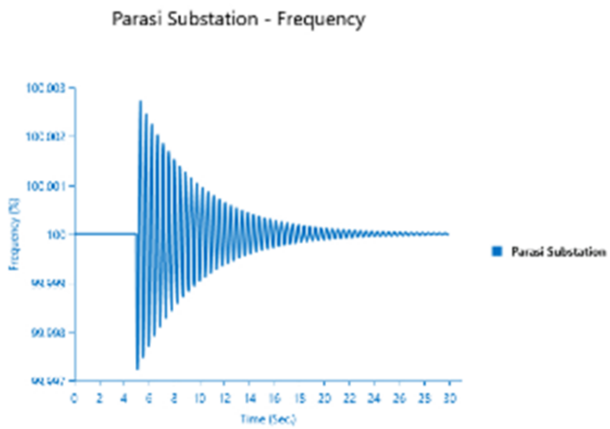

Figure 11. Frequency response of Sunwal substation

system can maintain the frequency within the limit upon disconnection of the PV Power Plants. It concludes that the large grid can easily maintain the transient frequency of the system even when the PV Power plants are disconnected during operation.

5. Conclusion

The system was analyzed before and after the integration of the Photovoltaic (PV) power plants. During the load

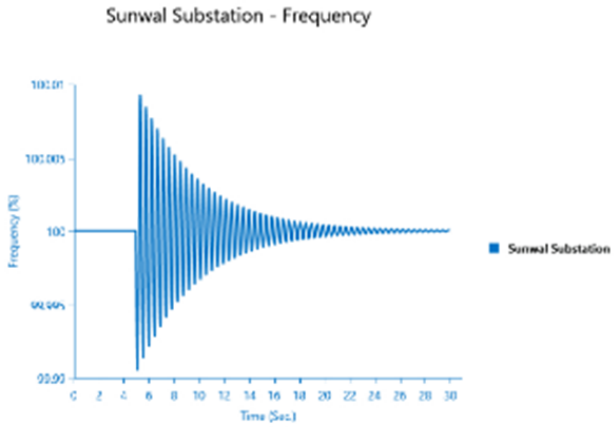

Figure 12. Frequency response of Parasi substation

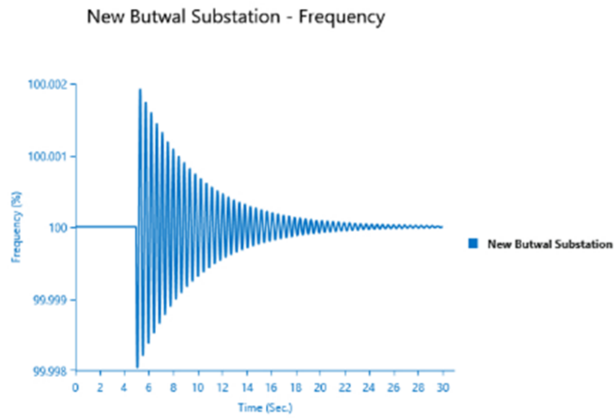

Figure 13. Frequency response of New-Butwal substation

flow analysis, it was noted that the voltage profile at the point of interconnection (POI) improved, while transformer loading and transmission line losses decreased following the interconnection of the PV Power Plants. Although PV penetration increased the fault current within the system, the increment remained within 10% threshold, with the exception of the Parasi Substation. Notably the fault current at the Parasi Substation is less than 87.5% of the rating of the protective equipment. When the PV power plants were disconnected, the voltage fluctuations at Muknundapur, Gandak and New-Butwal Substations were below 3% at POI, except for the Parasi and Sunwal Substations, which experienced fluctuations slightly above 3%. To address issues related to voltage flicker, it is recommended that the PV plants at Parasi and Sunwal operate with a non-unity power factor. The transient frequency response of the system remained stable upon the shutdown of PV power plants. As a result, the grid parameters are stable following the interconnection of these plants. This study was conducted considering peak load conditions, however the utility should remain vigilant for potential violations that may arise during integration of PV plants under varying loading conditions.

References

Akkur, M. S., Singh, S., Gill, A., & Kapse, V. M. (2023). The consequences and barriers of power system voltage stability in the integration of solar and wind energy: An in-depth analysis. *Multidisciplinary Reviews*, *6*.

Almaktar, M., Falah, A., Hasan, Z., Elbreki, A., & Mohamed, F. (2022). Power quality assessment of karabuk university's grid-connected microgrid under high penetration of pv generation. *2022 International Symposium on Multidisciplinary Studies and Innovative Technologies (ISMSIT)*, 472–477.

Department of Electricity Development. (2024). 31st anniversary souvenir - 2081.

Dhoundiyal, P., Kumar, Y., Negi, S., & Barthwal, A. (2022). Fault detection and classification in solar photovoltaic array. *2022 IEEE Global Conference on Computing, Power and Communication Technologies (GlobConPT)*, 1–6.

Jiménez, R. P., Platero, C. A., Sánchez, M. E., & Barneto, E. R. (2023). Synchronous condenser for european grid code compliance: A case study of a pv power plant in spain. *IEEE Access*, *11*, 54713–54723.

Le Nguyen, H. (1997). Newton-raphson method in complex form [power system load flow analysis]. *IEEE transactions on power systems*, *12*(3), 1355–1359.

Ministry of Energy, Water Resources and Irrigation. (2025). *Energy development roadmap, 2081* (tech. rep.). Ministry of Energy, Water Resources and Irrigation. Kathmandu, Nepal.

Nepal Electricity Authority. (2024). *Nepal electricity authority: A year in fiscal year 2023/24* (tech. rep.). Nepal Electricity Authority. Kathmandu, Nepal.

Neupane, D., Kafle, S., Karki, K. R., Kim, D. H., & Pradhan, P. (2022). Solar and wind energy potential assessment at provincial level in nepal: Geospatial and economic analysis. *Renewable Energy*, *181*, 278–291.

Photovoltaics, D. G., & Storage, E. (2018). Ieee standard for interconnection and interoperability of distributed energy resources with associated electric power systems interfaces. *IEEE std*, *1547*(1547), 2018.

Shrestha, H. M. (2017). Facts and figures about hydropower development in nepal. *Hydro Nepal: Journal of Water, Energy and Environment*, *20*, 1–5.

Wei, D., Jingsheng, H., Fei, Z., & Xiaolin, Z. (2016). A flicker assessment method for pv plants considering solar radiation condition. *2016 China International Conference on Electricity Distribution (CICED)*, 1–5.

Wu, Y.-K., Ye, G.-T., & Shaaban, M. (2016). Analysis of impact of integration of large pv generation capacity and optimization of pv capacity: Case studies in taiwan. *IEEE Transactions on Industry Applications*, *52*(6), 4535–4548.

Zhao, W., Shi, X., Guo, Q., Sun, H., Xu, F., Li, Z., Niu, T., & Wang, B. (2015). Voltage security analysis with high pvs penetration considering the interaction of transmission and distribution grids: Case studies. *2015 IEEE PES Asia-Pacific Power and Energy Engineering Conference (APPEEC)*, 1–5.

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