Analyzing the Integration of 17.38 MW Sephu Solar PV Plant into the Western Grid of Bhutan

Sonam Wangmo[1], Tshering Choden[2], Lok Bahadur Gurung[3], Chenga Dorji[4*], and Tshewang Rinzin[5]

[1-5]*Department of Electrical Engineering, Jigme Namgyel Engineering College, Royal University of Bhutan*
[*]*Corresponding author: chengadorji.jnec@rub.edu.bt*

Published: February 2025

Abstract

This report involves integrating Sephu Solar PV system's distributed generation into Bhutan's Western grid to examine and assess how the grid performs. Renewable Energy source integration with power systems is a strategic concept of smart grids. It is a beneficial technology as the integration of standardized PV systems into grids optimizes building energy balance, improves the economics of the PV system, reduces operational costs, and provides added value to the consumer and its utility. However, the variability and limited predictability of these sources, have posed significant challenges associated with integration. This report reviews integration of solar systems into electricity grids and highlights challenges faced by the existing grids. Some notable challenges associated with with Solar-Grid integration include problems of voltage stability, frequency stability, and overall power quality. This report will examine the challenges and behavior of the existing Western Grid when integrating Sephu Solar PV into the existing Western grid of Bhutan using PSS/E software.

Keywords— Distributed generation, Solar PV system, Smart grid, Solar Grid integration, Voltage stability

1 Introduction

The energy sector in Bhutan is majorly dominated by electrical energy generated from hydropower projects. The Renewable Energy Management Master Plan (2016) estimates that Bhutan has a potential to produce 12GW of solar and 760MW of wind energy. Solar photovoltaic energy has been implemented in both on- and off-grid settings, all at smaller scales [1]. The proposed 17.38 MW solar power plant site is located at Yongtru village under Sephu gewog of Wangdue Phodrang district. Electricity produced at the Sephu solar power plant will be distributed from the power plant at 33kV and be delivered to the national grid through three existing substations: Lobesa substation and Phobjikha substation to the west of Sephu and Yurmo substation located in the east of Sephu.

Of the existing power lines that connect Sephu to these three substations, BPC has recommended that approximately 29 km are reconducted to facilitate power evacuation in case one of the 33 kV feeders fail. The existing 33 kV line from Sephu running west toward Lobesa and Phobjikha will, therefore be upgraded over a length of about 8 km, by replacing the existing electrical conductor with a conductor of a higher diameter (rabbit to dog conductor) [18]. The aim of this project is to analyze and evaluate the integration of the Sephu Solar PV distributed generation into Bhutans existing western grid using PSSE software. Bhutan faces a significant challenge in integrating renewable resources, particularly solar power, into its existing grid due to the intermittent nature of solar PV generation. This challenge is exacerbated by the traditional one-way flow of electricity and communication within the power system, leading to increased susceptibility to disruptions such as voltage and frequency instability, and power outages. So, the objectives include developing the western grid layout and performing load flow analysis, conducting contingency analysis to simulate grid responses, incorporating Sephu Solar PV to assess its operational behavior, evaluating the effects of DG integration on grid stability, deploying suitable FACTS devices to address voltage and frequency instabilities, and performing post-implementation contingency analysis for grid instability caused by FACTS devices.

2 Literature Review

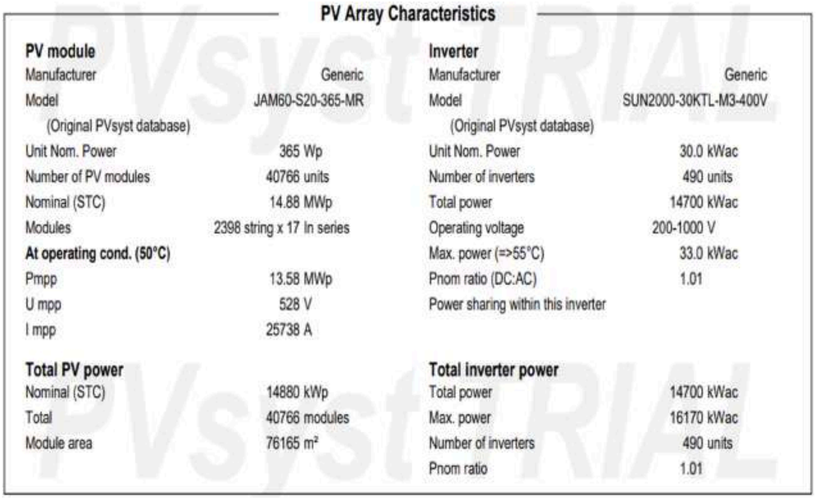
Due to the intermittent nature, several challenges are presented in integrating solar photovoltaic (PV) and wind energy systems into the electrical grids [2]. Wind energy systems cause voltage and power fluctuations that lead to voltage sags, swells, flickering, and harmonics, impacting grid stability. High wind energy penetration exacerbates these stability issues [3, 6]. Solar PV systems face voltage regulation challenges as traditional grids are designed for one-way power flow. High PV penetration can lead to instability, with issues like flicker, harmonic distortion, unwanted oscillations, and frequency declines [5]. Advances in power electronics and distributed energy storage systems, such as battery storage, are essential in managing these challenges. These technologies help stabilize the grid and provide a buffer against the variable nature of renewable energy sources [4, 9]. Smart grid technologies, anti- islanding, and solar-grid forecasting improve control and reliability. Micro grids and distributed energy resources offer flexible solutions for energy management. Robust interconnection protocols and advanced inverters are crucial for ensuring reliable operation with increasing renewable energy penetration [10]. Overall, integrating renewable energy into the grid reduces fossil fuel dependence and meets rising energy demands, but requires advanced technologies and strategies to maintain grid stability and reliability [11]. The variable output of renewable energy sources (RES), such as wind and solar, can alter the operation of utility units when integrated into the utility grid. This integration transforms the passive distribution system into an active one, affecting the balance between active and reactive power, which can contribute to voltage instability. To interconnect distributed generation (DG) systems to the utility grids, the basic and most important parameters that need to be controlled are the phase sequence, frequency, and amplitude of phase voltages. When solar energy is injected into the utility grid, a large current is injected causing voltage sag in the network. It is to be noticed that the entire power system inertia is proportional to the initial rate of change in frequency (due to any disturbance) and dependent upon the overall inertial response of all synchronous generators in the system. However, by displacing conventional synchronous generators with solar and wind power plants, the total system inertia will be reduced. This reduction in system inertia renders the system incapable of managing frequency and voltage instability.

3 Methodology

This project involves designing the Sephu solar PV system using PVsyst software and analyzing its power generation, economic investments, and other factors, with data from renewable energy experts in Bhutans Ministry of Energy and Natural Resources. Additionally, the Sephu solar PV system is simulated in PSSE software to validate real and reactive power generation results. The project also includes designing the western grid of Bhutan in PSSE software using 2023 data from the Bhutan Power System Operator. Power flow and contingency analyses are conducted on the western grid before and after integrating the Sephu PV system to assess challenges. To mitigate any grid fluctuations post-integration, a STATCOM device is implemented.

3.1 Sephu Solar PV System

In figure 1 specifications of the PV array for the Sephu Solar PV system, detailing all the essential characteristics of both the PV modules and the inverter can be seen. Figure 1 illustrates these specifications based on initial parameters, indicating that a total of 40,766 PV modules, each with a capacity of 365 Wp, were used. Under optimal conditions, this configuration yields a maximum power output of 13.58MW. Regarding the inverter, a 30kW model with 490 units was selected, resulting in a total AC power output of 14,700kW as determined by the PVsyst software. The Sephu PV system was also simulated using PSSE software. Due to the softwares limitation in modeling individual PV arrays for each system, the entire PV array was represented by a single bus. This bus was modeled as a synchronous generator to indicate the overall generation of Sephu Solar PV plant.



PV Array Characteristics

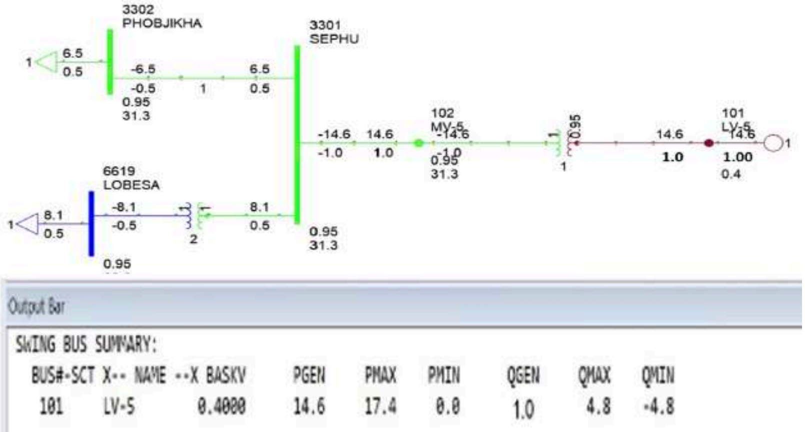
PV module		**Inverter**	
Manufacturer	Generic	Manufacturer	Generic
Model	JAM60-S20-365-MR	Model	SUN2000-30KTL-M3-400V
(Original PVsyst database)		(Original PVsyst database)	
Unit Nom. Power	365 Wp	Unit Nom. Power	30.0 kWac
Number of PV modules	40766 units	Number of inverters	490 units
Nominal (STC)	14.88 MWp	Total power	14700 kWac
Modules	2398 string x 17 In series	Operating voltage	200-1000 V
At operating cond. (50°C)		Max. power (=>55°C)	33.0 kWac
Pmpp	13.58 MWp	Pnom ratio (DC:AC)	1.01
U mpp	528 V	Power sharing within this inverter	
I mpp	25738 A		
Total PV power		**Total inverter power**	
Nominal (STC)	14880 kWp	Total power	14700 kWac
Total	40766 modules	Max. power	16170 kWac
Module area	76165 m^2	Number of inverters	490 units
		Pnom ratio	1.01

Figure 1: Sephu PV Array characteristics

The figure 1 indicates the Sephu Solar PV system with three buses: Sephu (bus 3301), Phobjikha load (bus 3302), and Lobesa load (bus 6619). A single synchronous generator represents the entire PV array. According to the load flow analysis in Figure 2, the system generates 14.6 MW of active power and supplies 1 MVar of reactive power. This power is transmitted to the Sephu bus, where it is stepped up to 33 kV before distribution to the Phobjikha and Lobesa load buses, ensuring efficient power delivery across the network.

3.2 Western Grid Simulation in PSSE Software

The Western grid simulation is conducted using PSSE software. It comprehensively replicates the components of systems, performs load flow analysis to assess stable operating conditions, and scrutinizes dynamic performance and stability.



```
SWING BUS SUMMARY:
 BUS#-SCT X-- NAME --X BASKV     PGEN   PMAX   PMIN    QGEN    QMAX   QMIN
  101      LV-5        0.4000     14.6   17.4    0.0     1.0     4.8   -4.8
```

Figure 2: Load flow analysis result

Simulation of Bhutans Western grid in PSSE software was done with 35 buses and 8 transformers, despite constraints in the student version limiting their use. One transformer per voltage step-up was strategically employed to balance representation of generation stations. This approach ensured a comprehensive simulation of the grid within the softwares constraints.

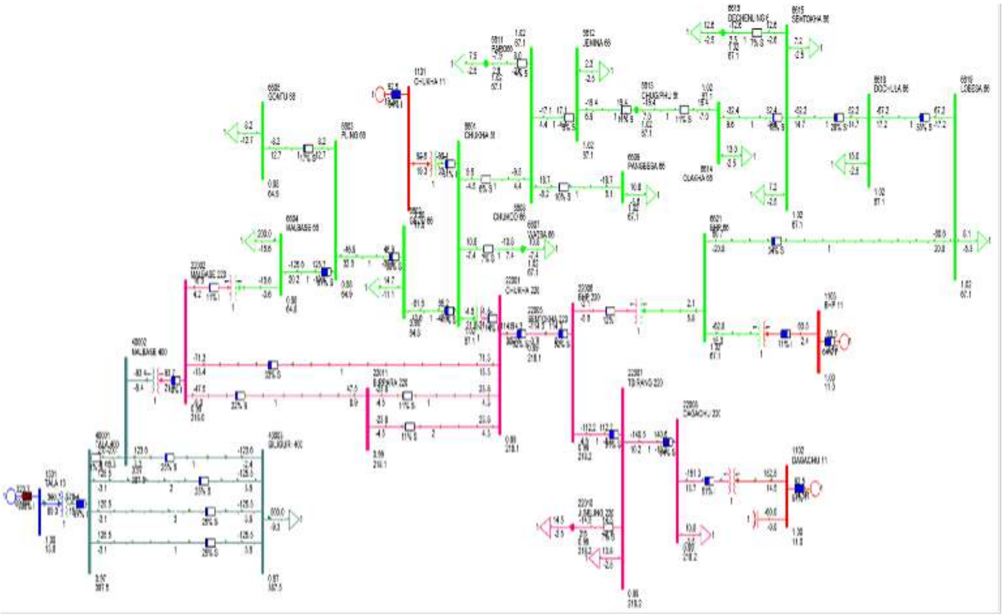
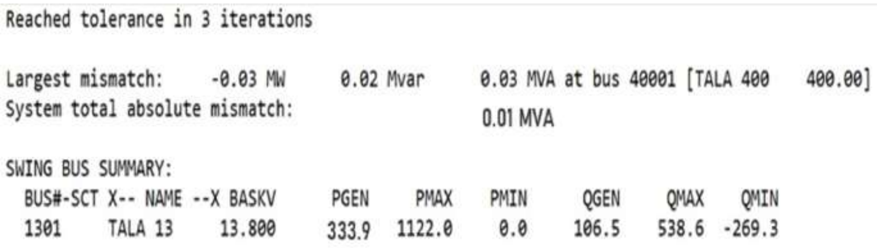


Figure 3: Western Grid Simulation in PSSE Software

Following a load flow simulation, a contingency analysis was conducted. The contingencies examined included the tripping of the line between Chukha 66kV and Chumdo 66kV, the line between Semtokha 66kV and Dochula 66kV, and the line between Malbase 66kV and Pling 66kV. Among these, the contingency analysis revealed that the tripping of the line between Malbase 66kV and Pling 66kV resulted in several critical issues.

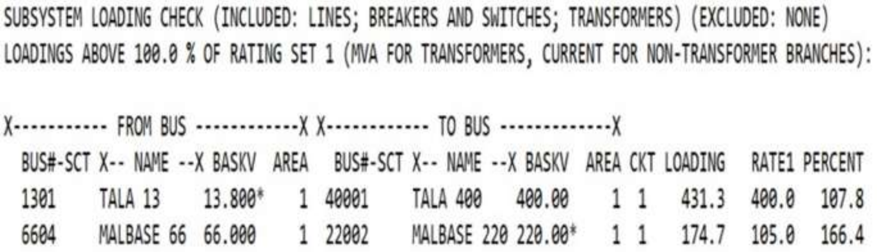


```
Reached tolerance in 3 iterations

Largest mismatch:     -0.03 MW      0.02 Mvar      0.03 MVA at bus 40001 [TALA 400    400.00]
System total absolute mismatch:                    0.01 MVA

SWING BUS SUMMARY:
  BUS#-SCT X-- NAME --X BASKV     PGEN    PMAX    PMIN    QGEN    QMAX    QMIN
  1301      TALA 13     13.800    333.9  1122.0    0.0    106.5   538.6  -269.3
```

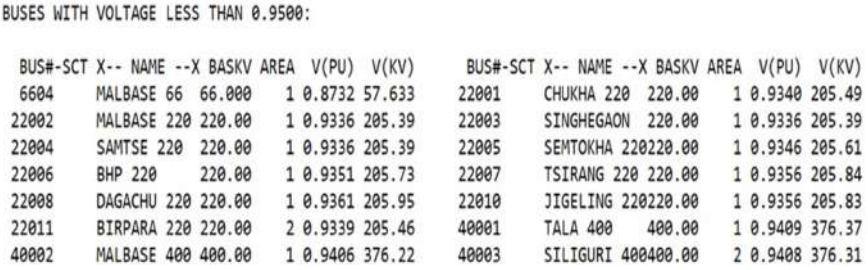
Figure 4: Load flow analysis result



```
SUBSYSTEM LOADING CHECK (INCLUDED: LINES; BREAKERS AND SWITCHES; TRANSFORMERS) (EXCLUDED: NONE)
LOADINGS ABOVE 100.0 % OF RATING SET 1 (MVA FOR TRANSFORMERS, CURRENT FOR NON-TRANSFORMER BRANCHES):

X----------- FROM BUS ------------X X------------ TO BUS -------------X
  BUS#-SCT X-- NAME --X BASKV  AREA   BUS#-SCT X-- NAME --X BASKV  AREA CKT LOADING   RATE1 PERCENT
  1301     TALA 13      13.800*   1  40001     TALA 400     400.00    1  1    431.3   400.0   107.8
  6604     MALBASE 66  66.000     1  22002     MALBASE 220 220.00*    1  1    174.7   105.0   166.4
```

Figure 5: Result of out of limit voltage after



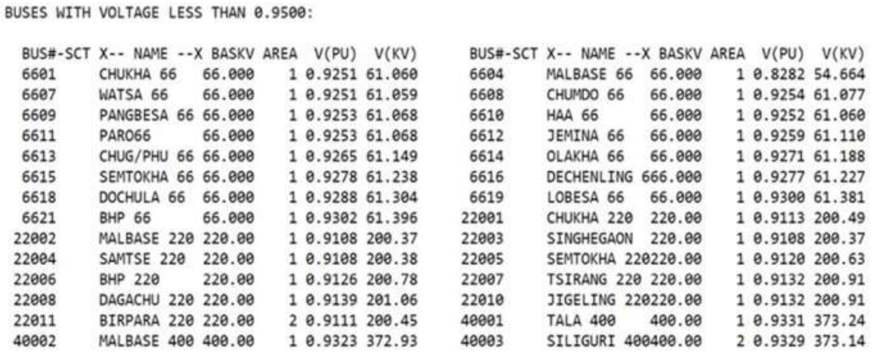
```
BUSES WITH VOLTAGE LESS THAN 0.9500:

  BUS#-SCT X-- NAME --X BASKV AREA  V(PU)  V(KV)      BUS#-SCT X-- NAME --X BASKV AREA  V(PU)  V(KV)
   6604     MALBASE 66  66.000    1 0.8732 57.633     22001     CHUKHA 220  220.00    1 0.9340 205.49
  22002     MALBASE 220 220.00    1 0.9336 205.39     22003     SINGHEGAON  220.00    1 0.9336 205.39
  22004     SAMTSE 220  220.00    1 0.9336 205.39     22005     SEMTOKHA 220220.00    1 0.9346 205.61
  22006     BHP 220     220.00    1 0.9351 205.73     22007     TSIRANG 220 220.00    1 0.9356 205.84
  22008     DAGACHU 220 220.00    1 0.9361 205.95     22010     JIGELING 220220.00    1 0.9356 205.83
  22011     BIRPARA 220 220.00    2 0.9339 205.46     40001     TALA 400    400.00    1 0.9409 376.37
  40002     MALBASE 400 400.00    1 0.9406 376.22     40003     SILIGURI 400400.00    2 0.9408 376.31
```

Figure 6: Result of line with overloading after tripping

3.3 Western Grid Simulation After the Integration of Sephu PV

After conducting thorough simulations on the Western Grid using PSSE, the next step was to seamlessly integrate the solar PV into the existing infrastructure of the western grid. With the incorporation of 14.6 MW of solar PV, specifically the Sephu Solar PV, into the western grid, a noticeable impact was observed. The power generation from the slack bus, notably the Tala 13 kV bus, experienced a reduction. Prior to the integration, the slack bus was generating a robust 333.9 MW. However, after integrating the solar PV, this generation capacity decreased to 319.8 MW with voltage sag near the slack bus. Additionally, four buses (i.e., Gedu 66, Malbase 66, Gomtu 66 and Pling 66) experienced voltage drops below the nominal range after integration of the Sephu PV system. To address this voltage sag, a STATCOM was deployed at three locations: the Sephu bus, the Tala Slack bus, and the Malbase bus. This implementation led to improved voltage levels at these buses, as demonstrated in the contingency analysis presented below. The initial integration of solar PV into the western grid, prior to contingency analysis, showed several critical issues when the Malbase 66 kV to Pling 66 kV line tripped. The contingency analysis revealed significant overloading on the Tala 13 kV line at 107.8% and the Malbase 66 kV line at 166.4%, along with 28 buses failing to reach their nominal voltage levels. These conditions indicate potential operational inefficiencies and risks to grid stability and equipment integrity.



```
BUSES WITH VOLTAGE LESS THAN 0.9500:

  BUS#-SCT X-- NAME --X BASKV AREA  V(PU)  V(KV)      BUS#-SCT X-- NAME --X BASKV AREA  V(PU)  V(KV)
   6601    CHUKHA 66   66.000    1 0.9251 61.060       6604    MALBASE 66  66.000    1 0.8282 54.664
   6607    WATSA 66    66.000    1 0.9251 61.059       6608    CHUMDO 66   66.000    1 0.9254 61.077
   6609    PANGBESA 66 66.000    1 0.9253 61.068       6610    HAA 66      66.000    1 0.9252 61.060
   6611    PARO66      66.000    1 0.9253 61.068       6612    JEMINA 66   66.000    1 0.9259 61.110
   6613    CHUG/PHU 66 66.000    1 0.9265 61.149       6614    OLAKHA 66   66.000    1 0.9271 61.188
   6615    SEMTOKHA 66 66.000    1 0.9278 61.238       6616    DECHENLING 666.000    1 0.9277 61.227
   6618    DOCHULA 66  66.000    1 0.9288 61.304       6619    LOBESA 66   66.000    1 0.9300 61.381
   6621    BHP 66      66.000    1 0.9302 61.396      22001    CHUKHA 220  220.00    1 0.9113 200.49
  22002    MALBASE 220 220.00    1 0.9108 200.37      22003    SINGHEGAON  220.00    1 0.9108 200.37
  22004    SAMTSE 220  220.00    1 0.9108 200.38      22005    SEMTOKHA 220220.00    1 0.9120 200.63
  22006    BHP 220     220.00    1 0.9126 200.78      22007    TSIRANG 220 220.00    1 0.9132 200.91
  22008    DAGACHU 220 220.00    1 0.9139 201.06      22010    JIGELING 220220.00    1 0.9132 200.91
  22011    BIRPARA 220 220.00    2 0.9111 200.45      40001    TALA 400    400.00    1 0.9331 373.24
  40002    MALBASE 400 400.00    1 0.9323 372.93      40003    SILIGURI 400400.00    2 0.9329 373.14
```

Figure 7: Result of buses with voltage out of range after tripping

3.4 Implementation of Station in Western Grid

As electricity demand and capacity increase, power quality issues like reactive power and harmonic distortion threaten grid stability. STATCOM, a leading FACTS component, excels in managing reactive power with rapid response times as fast as 10ms and superior dynamic performance compared to SVC. It maintains full capacitive output at low voltages, enhancing transient stability, and requires only half the installation space of SVC. Additionally, STATCOM can handle currents up to 3 per unit (pu) for 2 seconds, ensuring power quality and stability by injecting reactive current during faults and correcting voltage fluctuations. After installing the STATCOM, tested various positions to address voltage and overloading issues. Initially placed at the Sephu bus, it showed voltage sag at eight buses and overloading at two. Moving it to Tala 13.8kV resolved some issues, but Malbase 66kV still experienced voltage sag during emergencies. Finally, installing the STATCOM at Malbase 66kV eliminated all voltage and overloading problems, confirming it as the optimal location for ensuring grid stability and performance.

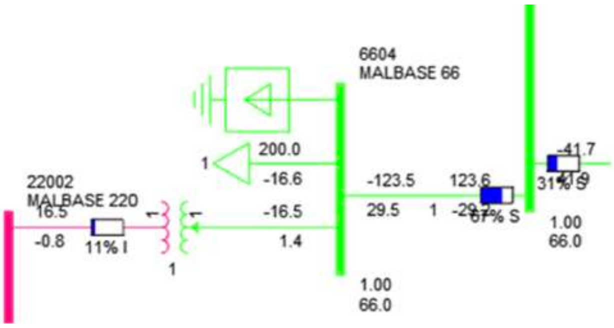
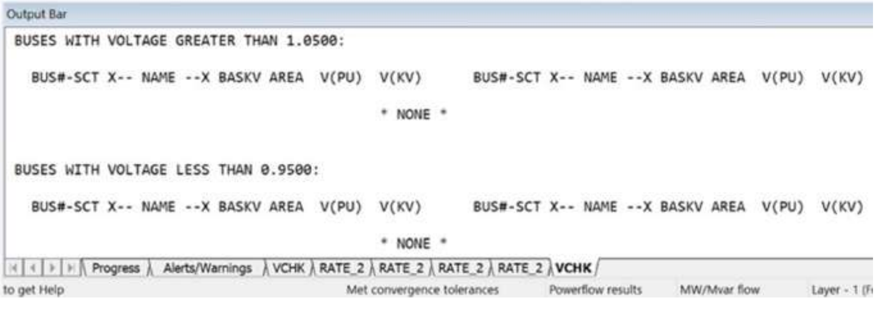


Figure 8: STATCOM at Malbase 66kV



```
BUSES WITH VOLTAGE GREATER THAN 1.0500:

  BUS#-SCT X-- NAME --X BASKV AREA  V(PU)  V(KV)      BUS#-SCT X-- NAME --X BASKV AREA  V(PU)  V(KV)
                                              * NONE *

BUSES WITH VOLTAGE LESS THAN 0.9500:

  BUS#-SCT X-- NAME --X BASKV AREA  V(PU)  V(KV)      BUS#-SCT X-- NAME --X BASKV AREA  V(PU)  V(KV)
                                              * NONE *
```

Figure 9: Voltage limit checking

4 Result and Discussion

The western grid's power flow analysis using PSSE software showed a generation of 333.9 MW. Contingency analysis simulating a line trip between Malbase 66 and Pling 66 resulted in voltage drops below 0.95 pu at 14 buses and an overload at Malbase 66kV. Integrating 14 MW from the Sephu PV system reduced the slack bus Tala 13.8 kV generation to 319.8 MW but increased voltage instability, affecting 28 buses and overloading two. To mitigate this, STATCOM was tested at various locations: Sephu bus reduced issues but left some voltages low; Tala 13.8kV bus improved conditions but still had one low voltage; finally, placing STATCOM at Malbase 66kV resolved all voltage and overloading issues, confirming it as the optimal location.

5 Recommendations

To strengthen this project result, future research should prioritize conducting thorough dynamic analyses to assess system behavior during transient events like load changes, generation fluctuations, and faults. These studies are essential for ensuring resilient grid integration of renewable energy. Researchers should also investigate how STATCOMs impact power system harmonics to maintain high power quality despite their operational effects. With Bhutan, planning 16 solar PV plants totaling 1226 MW by 2029, theres a significant opportunity for further study. Expanding grid simulations to include both eastern and western sides will offer a comprehensive view, potentially revealing insights for optimizing overall grid stability and performance.

6 Conclusion

In conclusion, the incorporating of the Sephu solar PV system into Bhutans Western Grid presents both opportunities and challenges. The project aimed to evaluate, distributed generation af- fects grid stability and propose solutions to mitigate potential issues. Using PVsyst and PSSE software, it was found that the Sephu solar plant would significantly boost energy generation, re- ducing dependence on conventional sources. However, the intermittent nature of solar power poses challenges, particularly in managing voltage stability. Simulation highlighted voltage instability and overloading at specific bus locations post-integration. Implementing a STATCOM at the Malbase 66 kV bus effectively improved voltage stability, addressing potential disruptions from solar power fluctuations. These findings emphasize the need for meticulous planning and robust management strategies when integrating renewable energy to ensure grid reliability and stability.

Acknowledgement

We extend our heartfelt thanks to Mr. Chenga Dorji and Mr. Tshewang Rinzin from the Department of Electrical Engineering for their invaluable recommendations and efficient research support. Special gratitude to Mr. Karchung, Head of Department, for his assistance in our project's advancements. Their ongoing help was crucial to our success, providing guidance whenever needed. We are deeply appreciative of the Electrical Engineering tutors for their insightful feedback. Additionally, thanks to Mr. Samten from Bhutam Power System Operator (BPSO) for his support with the PSSE software and Mr. Minjur from Ministry of Energy and Natural Resources (MoENR) for supplying essential data on Sephu Solar PV, enabling our project's completion.

References

[1] Nirosha, Chelumala, and P. S. Kumar Patra. "Power quality issues of wind and solar energy systems integrated into the grid." Adv Sci Lett 26.5 (2020): 514-23.

[2] Gautami, Sarika, R. Tiwari, and B. Vishwavidyalaya. "A Survey on Smart Grid-Connected Photovoltaic Power Systems and Its Issues." IJOSTHE 4.3 (2017).

[3] Tajudin, M. Nayeim Fazumy Mohd, M. N. M. Hussain, and M. M. Hussain. "Integrated model of solar PV interconnection using PSSE software."

[4] Meliani, Meryem, et al. "Grid-Connected PV System Simulation Study." International Conference on Digital Technologies and Applications. Cham: Springer Nature Switzerland, 2023.

[5] Bhatt, Gaurav, and S. Affljulla. "Analysis of large-scale PV penetration impact on IEEE 39-Bus power system." 2017 IEEE 58th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON). IEEE, 2017.

[6] Nwaigwe, K. N., P. Mutabilwa, and E. Dintwa. "An overview of solar power (PV systems) integration into electricity grids." Materials Science for Energy Technologies 2.3 (2019): 629-633.

[7] Ding, Fei, and K. A. Loparo. "Dynamic modeling and stability analysis of grid-connected and autonomous distributed generation system." 2015 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT). IEEE, 2015.

[8] Kumar, Jerry, et al. "Design and performance analysis of PV grid-tied system with energy storage system." International Journal of Electrical and Computer Engineering 11.2 (2021): 1077.

[9] Anees, A. Sharique. "Grid integration of renewable energy sources: Challenges, issues and possible solutions." 2012 IEEE 5th India International Conference on Power Electronics (IICPE). IEEE, 2012.

[10] Basso, S. Thomas. "High-penetration, grid-connected photovoltaic technology codes and standards." 2008 33rd IEEE Photovoltaic Specialists Conference. IEEE, 2008.

[11] Brown, Merwin, et al. "Integrating Renewable Generation with the Electricity Grid: Distribution System Issues." (2012).

[12] Abbasy, H. Nabil, and H. M. Ismail. "A unified approach for the optimal PMU location for power system state estimation." IEEE Transactions on Power Systems 24.2 (2009): 806-813.

[13] Hill, A. Cody, et al. "Battery energy storage for enabling integration of distributed solar power generation." IEEE Transactions on Smart Grid 3.2 (2012): 850-857.

[14] Lupangu, C., and R. C. Bansal. "A review of technical issues on the development of solar photovoltaic systems." Renewable and Sustainable Energy Reviews 73 (2017): 950-965.

[15] Volkmar. "High Penetration PV: Experiences in Germany and technical solutions." IEA PVPS Task 14 (2013).

[16] Deshmukh, Shruti, et al. "Design of Grid-Connected Solar PV System Integrated with Battery Energy Storage System." 2023 3rd Asian Conference on Innovation in Technology (ASIANCON). IEEE, 2023.

[17] Queiroz, D., J. A. Melo, et al. "Renewable Energy Generators Interconnection: The United States Experience and Challenges to Overhaul the Brazilian Regulatory Model." 2023 IEEE CHILEAN Conference on Electrical, Electronics Engineering, Information and Communication Technologies (CHILECON). IEEE, 2023.

[18] Department of Renewable Energy, Ministry of Economic Affairs, Royal Government of Bhutan for the Asian Development Bank. Bhutan: Renewable Energy for Climate Resilience Main Report. The Asian Development Bank (ADB). IEE, 2022.

[19] Ma, Y., A. Huang, and X. Zhou. A review of STATCOM on the electric power system, International Conference on Mechatronics and Automation, Aug. 2015, doi: 10.1109/icma.2015.7237475.

[20] Yu, N. Q., N. P. Li, N. W. Liu, and N. X. Xie. Overview of STATCOM Technologies, International Conference on Electric Utility Deregulation, Restructuring and Power Technologies, Dec. 2004, doi: 10.1109/drpt.2004.1338063.

[21] Aggarwal, Manju, S. K. Gupta, and G. Kasal. "D-statcom control in low voltage distribution system with distributed generation." 2010 3rd International Conference on Emerging Trends in Engineering and Technology. IEEE, 2010.

[22] NEPSI. NEPSI Tech Talk Session 39: Modeling AMSCs DVAR STATCOM in Siemens' PSSőE Power System Software," YouTube, May 24, 2023. [Online]. Available: `https://www.youtube.com/watch?v=mvxuhBzVSN0`.