Impact Assessment of Renewable Energy Integration: A Case Study on Sephu Solar PV Plant Integration

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Abstract
This paper examines the impact of integrating renewable energy resources into the Bhutan power grid, focusing specific on integration of 18 MW Sephu Solar Photovoltaic (PV) plant. The study evaluates grid stability and performance under different penetration levels of solar power. Dynamic simulation were carried using Power System Simulator for Engineering (PSSE) software to analyze two critical scenarios: the sudden disconnection of the PV plant and the occurrence of a three-phase fault at the point of coupling (POC). Further the study examines the effects of these scenarios on key system parameters such as bus voltage, system frequency, and the power output of conventional generator. The results show that the sudden disconnection of the PV plant causes voltage and frequency drops, with the severity increasing as the penetration level of solar power increases. Similarly, a three-phase fault at the PV connected bus results in substantial voltage fluctuations, including a temporary drop to zero, followed by oscillations that stabilize over time. These effects become severe with higher solar power penetration levels, underscoring the importance of addressing potential stability concerns. The study highlights the necessity of implementing proper under-voltage and under-frequency load-shedding relay settings at key substation to prevent unintended disconnection of the PV plant. Additionally, upgrading transformers at the 66/33 kV Gewathang substation is essential to accommodate reverse power flow resulting from the solar PV integration at Sephu.
Key Words: *Impact assessment, Renewable energy integration, Solar, PSSE*

1. INTRODUCTION

The integration of renewable energy resources (RES) such as wind and solar into the existing electric grid poses challenges due to their intermittent nature. The high-level penetration of RES like solar PV plant leads to reduction in the conventional generator capacity and a system inertia, which can affect the transient stability of the power system. A bulk PV penetration can significantly change the voltage profile and short circuit level of the power system. The intermittent nature of solar power due to varying irradiation, temperature and tripping of power electronic converters can affect the operation of power system.

Rapid fluctuation of the fossil fuel price, coupled with growing environmental concerns, have accelerated the transition to clean, safe, low emission, environmental friendly renewable energy resources (Alquthami et al., 2010) but it poses serious threats to the reliability of the grid due to high intermittency of these sources (Hazra et al., 2016). As the penetration of solar PV plants increases, it becomes essential to thoroughly evaluate and understand their impact on grid stability and operation. The intermittent nature of solar output can create significant challenges, particularly during sudden drops in solar irradiance from 100% to 25% within a short time frame. Such rapid fluctuations are especially problematic in scenarios with high levels of solar penetration (Alquthami et al., 2010).

The structure of power system is transitioning from conventional unidirectional power flow model to a modern framework dominated by converter-based distributed energy resources (DERs), as illustrated in Fig. *1* and Fig. *2*. The modern power system incorporates the integration of DERs at both the generation and distribution levels, resulting in bi-directional power flow.

Traditionally, distribution systems were not designed to function like transmission systems, as generation sources were not directly connected to them. However, with the increasing adoption of DERs, significant amounts of power are now being injected into the distribution system. This can lead to power being transferred from distribution systems with high shares of DERs to the upstream transmission system, creating bi-directional power flows. This paradigm shift necessitates redesigning distributed control and protection systems to effectively manage the complexities of bi-directional power flows in distribution networks.

The case study presents the impact analysis of 18 MW Sephu solar PV plant integration into the grid. The analysis focuses on two scenarios. The first scenario evaluates the tripping of solar PV plant under different penetration levels to assess the impact on grid stability. The second scenario examines a three-phase fault at the PV connected bus, a critical fault condition that could induce severe voltage fluctuations and affect the grid's operational security.

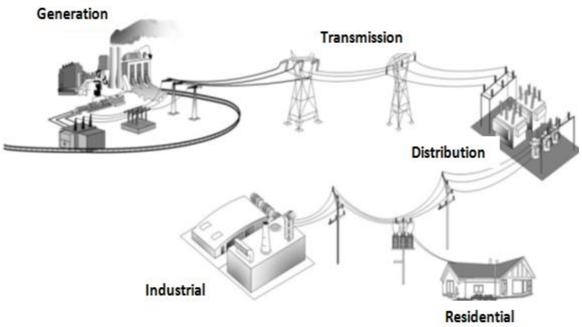

Fig. 1: *Conventional power system structure (Wangdee, 2017)*

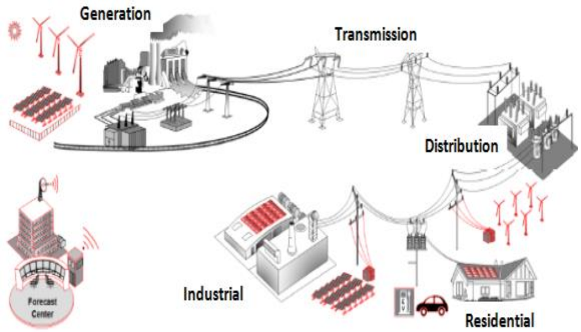

Fig. 2: *Modern power system structure (Wangdee, 2017)*

2. DRIVING FORCES FOR DERS INTEGRATION

Various driving forces have significantly increased the interest and focus on integrating distributed energy resources (DERs) into the power system. These forces stem from environmental concern and climate change mitigation, technological advancements, economic considerations, and evolving energy policies.

2.1. Environmental Concerns and Climate Change Mitigation

The growing urgency to reduce greenhouse gas (GHG) emissions has driven the transition from fossil fuels to cleaner, renewable energy resources like solar, and wind, which are typically distributed in nature. The reduction of environmental pollution and global warming acts as a key factor in preferring renewable energy over fossil fuels (Lis & Sobierajski, 2011). The utilization of DERs is anticipated to facilitate the generation of environmentally friendly, clean energy with significantly reduced environmental impact.

DERs play a crucial role in achieving sustainability targets and adhering to international agreements such as the Paris Accord. The Paris Agreement, often referred to as the Paris Accord, is a landmark international treaty adopted with its primary objective to combat climate change by limiting global warming and reducing GHG emissions worldwide. Based on climate pledge, India will increase its non-fossil fuel energy capacity to 500 GW by 2030. It will meet 50 per cent of its energy requirement from renewable sources by 2030, and target to achieve net zero by 2070 (Goswami, 2022).

2.2. Technological Advancements

Another driving force for the DERs integration is the technological advancements. The innovations in power electronics, smart grid technologies, and energy storage systems have made DERs more efficient, reliable, and easier to integrate into the grid.

(Wheatley, 2024) has carried out comprehensive reviewed on the significant developments in renewable energy sectors, particularly the technology advancement. The technological advancements in solar, wind, and bioenergy have reduced cost, improved efficiency, and accelerated global adoption. The Perovskite Solar Cells achieved efficiencies above 22% offering lower costs and higher performance than traditional silicon cells (Wheatley, 2024). The wind energy technologies have advanced significantly through improved turbine designs such as aerodynamic blades and lightweight materials. The innovations like floating turbines enables efficient and large-scale offshore wind farms integration (Wheatley, 2024).

2.3. Economic Incentive

The economic and financial incentives have of function of promoting and guiding investments in the energy sectors. Falling prices of renewable energy technologies like solar panels and wind turbines have significantly increase the affordability and economic feasibility of DERs. Furthermore, policy support through subsidies, tax incentives, and feed-in tariffs has played a crucial role in promoting their adoption. The state of art of economic and financial incentives on energy related intervention currently in force in Italy, Germany, and Czech Republic are presented by (Mutani et al., 2020), classifying broadly into type of intervention, recipient of the incentive, and methods of remuneration. In the United States, the Investment Tax Credit (ITC) has been instrumental in reducing the cost burden of renewable energy investments (Wheatley, 2024). Integrating DERs also presents opportunities for cost savings by minimizing transmission losses and deferring expensive infrastructure upgrades.

2.4. Policy and Regulatory Support

The growth of renewable energy technologies on a global scale necessitates supportive policy frameworks and regulation in order to facilitate a smooth integration. Effective policies are critical for driving adoption rates (Wheatley, 2024). Many governments and regulatory bodies have introduced policies and standards to promote DERs adoption, including net metering, renewable energy mandates, and clean energy targets. The utility reform and de-carbonization goals have encouraged utilities to incorporate DERs into their planning and operations.

In Germany, the Renewable Energy Sources Act has significantly contributed to the country's ongoing expansion in renewable energy capacity. Spain adopted feed-in-tariff to accelerate solar and wind energy development, sparking a surge in renewable energy installations (Wheatley, 2024). The United Kingdom implemented similar measures which propelled significant advancement in solar and wind energy projects (Wheatley, 2024).

3. CHANGING SYSTEM STRUCTURE

The integration of DERs like solar PV plants, wind farm, and battery storage system (BSS) in the distribution system as illustrated in Fig. *3* is changing the power flow direction. This will result in technical issues such as thermal capacity, grid losses, voltage profile, fault-level contributions, power quality, protection, system stability, grid planning, and grid operational issues (Wangdee, 2017) (Lis & Sobierajski, 2011).

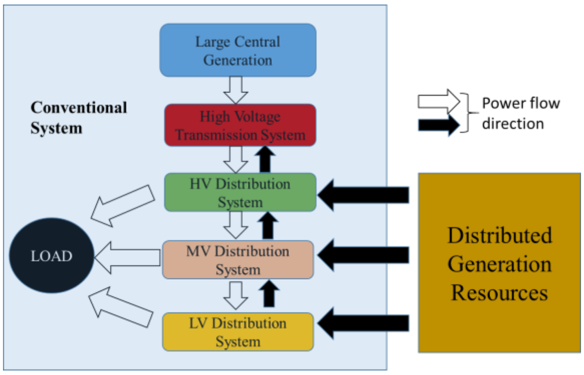

Fig. 3: *Modern grid structure with DERs (Wangdee, 2017)*

The technical impacts due to integration of DERs are discussed detailed below.

3.1. Thermal capacity

The integration of DERs into distribution networks alters power flow patterns. As DER penetration levels increases, the current flowing through distribution lines rises, potentially exceeding the thermal capacity of network components. This brings the network components closer to their thermal limits. If the thermal limits of network components are at risk of being exceeded due to DERs connection, the affected circuits must be upgraded to those with higher thermal ratings to ensure safe and reliable operation (Lis & Sobierajski, 2011) (Wangdee, 2017).

3.2. Voltage Profile

In a system without DERs, distribution lines typically operate as radial networks, delivering power to consumers. These systems often experience significant voltage drops, primarily due to long feeder distances and conductors with relatively low current-carrying capacity.

However, integrating DERs into the distribution network can help mitigate voltage drops and, in some cases, even increase voltage levels at specific points (Bhatt & Affijulla, 2017). DERs could also contribute to voltage flicker through sudden variations in the output due to change in solar irradiation and the variable wind speed on turbines.

3.3. Fault-level contribution

The integration of DERs into the distribution network significantly impacts fault level, which is the magnitude of current flowing during a fault, and result the overall fault level to exceed the designed fault level of the distribution equipment. The DERs located closer to fault points can inject significant fault current, intensifying fault level locally. The increased fault level can be mitigated, either by upgrading the distribution equipment or by reconfiguring distribution network.

3.4. Power quality

The integration of DERs into the power system can have both beneficial and adverse effects on power quality, influenced by factors such as the type of DERs, their location, and prevailing system conditions. Two critical aspects of power quality affected by DER integration are transient voltage variations and harmonic distortion in network voltage (Wangdee, 2017).

On the positive side, DERs like solar PV systems equipped with voltage control capabilities can help maintain voltage levels within acceptable limits by providing or absorbing reactive power. Conversely, sudden fluctuations in DER output, particularly from intermittent sources such as solar and wind, may result in voltage instability. Additionally, a high penetration of DERs in the distribution network can cause overvoltage, especially during periods of low demand and high generation.

3.5. Protection issues

When DERs are integrated into the distribution system, the current may flow in the reverse direction, contrary to the original design. This change can lead to protection mal-operations or failures, increasing the risk of widespread supply disruptions. The existing protection system in the distribution network may not operate correctly due to bi-directional power flows and reduced fault current contributions from DERs.

3.6. System stability issues

The integration of DERs into the power system network introduces several system stability challenges. These issues arise due to the distinct characteristics of DERs, such as their intermittent nature, distributed deployment, and dependence on power electronic interfaces. The rapid changes of DER output can lead to voltage instability.

Inverter-based DERs, in particular, do not contribute to system inertia, reducing the grid's ability to resist frequency changes during disturbances. The variability in DER output can cause rapid frequency changes, especially in weak or islanded grid. Unlike synchronous generators, many DERs are not designed to provide frequency support, limiting their effectiveness in maintaining frequency stability.

4. NETWORK DESCRIPTION

The whole Bhutan power system network modeled in PSSE software (Samten et al., 2024) was utilized for this study, with the Indian grid simplifies as aggregated load and generation. The model includes the dynamic representations of generators, governors, exciter, and power system stabilizer (PSS) for Tala Hydropower Plant (THP), Mangdechhu Hydropower Plant (MHP), and Chhukha Hydropower Plant (CHP). THP having high generation capacity has been considered as the swing bus for this particular study.

The dynamic simulation is carried out utilizing the Siemens PSSE (Power System Simulator for Engineering). Fig. ***4*** illustrated the integration of the 18 MW Sephu solar PV plant into the existing grid. The power from PV plant will be transmitted through 33 kV distribution lines to Phobjikha and Yurmo substations, than to the transmission voltage level.

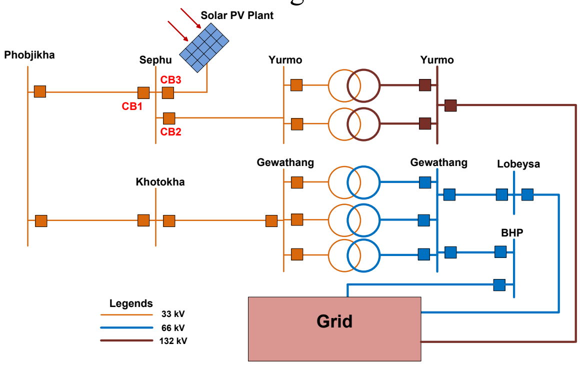

Fig. 4: *Network with Sephu Solar PV Plant*

5. DYNAMIC MODELLING OF SOLAR PV

The dynamic model of PV converter and electrical control model to represent the model of Sephu solar PV plant are presented in this section.

5.1. PV Converter Model

The PVGU1 model i.e., user written generator model to represent photo-voltaic (PV) system available in PSSE model library has been used to represent the solar power converter. The syntax to develop the PVGU1 PV converter model is shown as:

IBUS 'USRMDL' ID 'PVGU1' 101 1 0 9 3 3 CON (J) to CON (J+8) /

The parameters used and the description of the converter model (PVGU1) is given in Table 1.

***Table 1**: Parameters of PV converter model PVGU1*

Sl. no	Con Value	Con Description
1	0.0200	TIQCmd, Converter time constant for IQcmd, sec
2	0.0200	TIpCmd, Converter time constant for IPcmd, sec
3	0.4000	VLVPL1-Low Voltage power logic (LVPL), volt
4	0.9000	VLVPL2-LVPL voltage 2 (pu)
5	1.1100	GLVPL-LVPL gain
6	1.2000	High voltage reactive current (HVRC) logic, voltage (pu)
7	2.0000	HVRC logic, current (pu)
8	2.0000	Rip_LVPL, Rate of reactive change
9	0.0200	T_LVPL, Voltage sensor for LVPL, second

5.2. Electrical Control Model

The electrical control model for PV converter considered in this study is PVEU1 (user written electrical control model for photo-voltaic (PV) systems) available in PSSE software. The syntax to develop the PVEU1 electrical control model is shown below:

IBUS 'USRMDL' ID 'PVEU1' 102 0 4 24 10 4 ICON (M) to ICON (M+3) CON (J) to CON (J+23)/

The parameters and the description of the electrical control model (PVEU1) considered is in Table **2**.

***Table 2:** Parameters of electrical control model PVEU1.*

Sl. no	Con Value	Con Description
1	0.1500	Tfv-V-regulator filter
2	18.0000	Kpv-V-regulator proportional gain
3	5.0000	Kiv-V-regulator integrator gain
4	0.0500	Kpp-T-regulator proportional gain
5	0.1000	Kip-T-regulator integrator gain
6	0.0000	Kf-Rate feedback gain
7	0.0800	Tf-Rate feedback time constant
8	0.4700	QMX-V-regulator max limit
9	-0.4700	QMN-V-regulator min limit
10	1.1000	IPMAX-Max active current limit
11	0.0000	TRV-V-sensor
12	0.5000	dPMX-Max limit in power PI controller (pu)
13	-0.5000	dPMN-Min limit in power PI controller (pu)
14	0.0500	T_POWER-Power filter time constant
15	0.1000	KQi-MVAR/Volt gain
16	0.9000	VMINCL
17	1.1000	VMAXCL
18	120.0000	KVi-Volt/MVAR gain
19	0.0500	Tv-Lag time constant in WindVar controller
20	0.0500	Tp-Pelec filter in fast PF controller
21	0.0000	ImaxTD-Converter current limit
22	0.0000	Iphl-Hard active current limit
23	0.0000	Iqhl-Hard reactive current limit
24	18.000	PMAX of PV plant

6. SIMULATION AND RESULTS ANALYSIS

6.1. Steady-State Analysis

Before the integration of the Sephu Solar PV plant, the power flow is unidirectional, flowing from the transmission system to the distribution system to meet load demand. This scenario is depicted in Fig. ***5***, where the transformers at Yurmo and Gewathang substations function as distribution transformers, stepping down voltage from 132 kV and 66 kV to 33 kV, respectively.

However, as shown in Fig. ***6***, the integration of the 18 MW Sephu Solar PV plants alters the power flow direction. This shift raises concerns regarding the network's protection system and the operational suitability of the 66/33 kV transformers at Gewathang substation. With reverse power flow occurring contrary to the original design, the existing transformers needs to be upgraded with the one capable of functioning as an interconnecting transformer (ICT) to accommodate bidirectional power flows effectively.

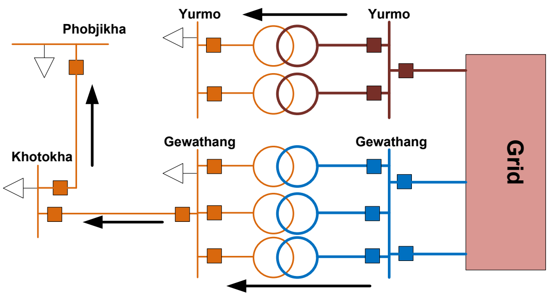

Fig. 5: Power flow without Sephu Solar PV Plant

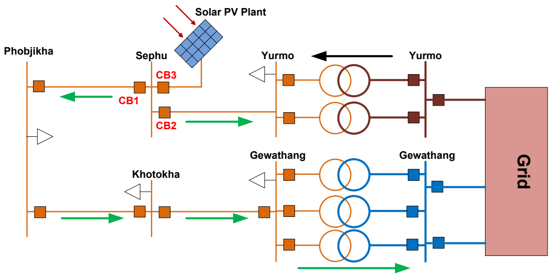

Fig. 6: Power flow with Sephu Solar PV Plant

6.2. Contingency Analysis

The contingency analysis is one of the important aspect of power system to ensure efficient power system operation and to maintain reliability. It helps in identifying potential failure and preparing the system to handle unexpected outages, thereby maintaining the stability and reliability of the power supply (Samten et al., 2025). The contingency analysis are carried out for two scenario.

a. Scenario 1: CB1 OPEN

When CB1 opens while solar plant remains operational, the entire power output from the solar plant is redirected towards the Yurmo substation. This creates a significant challenges, as the 33 kV transmission line has a maximum power transfer capacity of approximately 18 MVA, considering 324 A conductor ampacity at 40°C ambient temperature. Under this contingency, the power flow in the line approaches or exceeds 90% of its thermal capacity, pushing the line close to its operational limits.

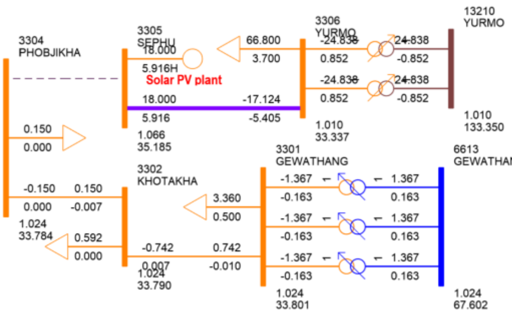

Fig. 7: Power flow scenario during contingency Scenario 1

b. Scenario 2: CB2 OPEN

As illustrated in Fig. *8*, the contingency scenario 2 resulted power flow in 33 kV Sephu till Gewathang lines operating close to its thermal limit. Operating a transmission line near to its thermal capacity can result in thermal stress, accelerated equipment aging, conductor sagging, and increased line losses. Addressing these challenges proactively is essential to improve the system's reliability, safety, and efficiency.

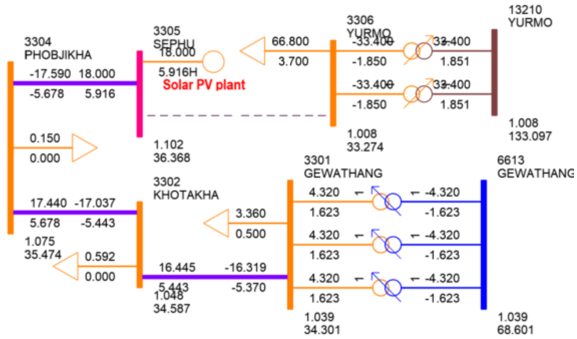

Fig. 8: Power flow scenario during contingency Scenario 2

6.3. Tripping of Solar PV Plant

The sudden tripping of a solar PV plant have significant consequences on the stability and performance of the power system. It affects the voltage profile, system frequency, and the dynamic behavior of conventional generators. As the solar penetration levels increases, the magnitude of these impact becomes more pronounced due to the larger share of power contributed by solar PV plant. To assess and understand these impacts, dynamic simulations were carried out using the PSSE software. These simulations allow for a detailed analysis of the transient and dynamic responses of the power system, providing insights into how voltage, frequency, and generator behavior are influenced by solar PV plant tripping.

At t=5s, the power system operates under normal conditions and suddenly solar PV plant is disconnected to observe the impact of its tripping. As a result of the disconnection, the PV plant's output drops to zero.

a. Impact on Bus Voltage

The sudden tripping of solar PV plant can lead to voltage dips or instability, especially in weak grid areas or at nodes with high solar penetration. In this case, the attention is primarily focused on the voltage behavior at nearby substation buses during different solar power output.

The bus voltage of 33 kV Sephu, Yurmo, and Phobjikha during the tripping solar PV plant with different penetration levels are illustrated in Fig. ***9***, Fig. ***10***, and Fig. ***11*** respectively. It can be clearly seen that tripping of PV plant leads to oscillation in the voltage. The magnitude of the voltage perturbation is influenced by the penetration level. The higher the penetration, the higher is the magnitude of oscillation. However, from the simulation for the tripping of PV plant, the voltage at the selected buses was found within the normal operating bandwidth of 0.95 and 1.05 time of the nominal values (Electricity Regulatory Authority, 2024).

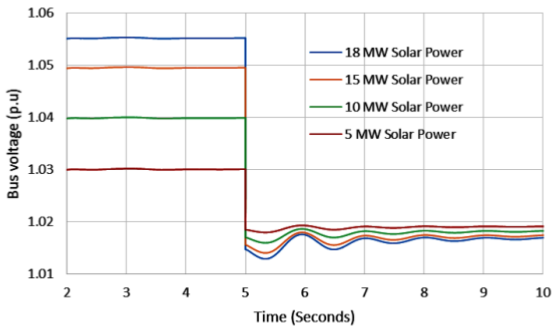

Fig. 9: *Sephu bus voltage during solar plant tripping*

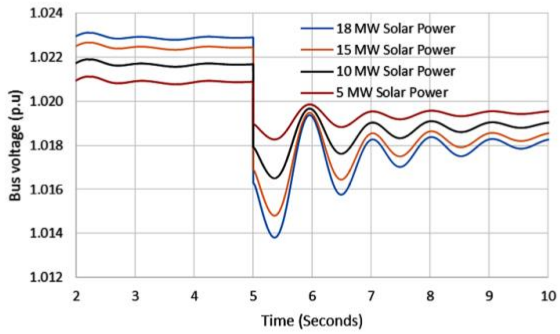

Fig. 10*: Yurmo bus voltage during solar plant tripping*

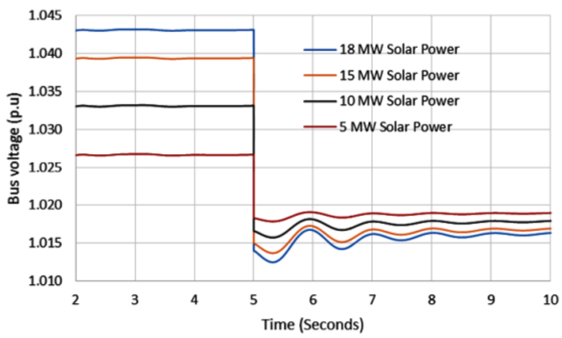

Fig. 11: *Phobjikha bus voltage during solar plant tripping*

b. Impact on System Frequency

The Solar PV systems, being inverter-based, typically do not contribute to system inertia. When inverter-based DERs are disconnected, the responsibility for maintaining frequency stability shifts to conventional generators, which can result in rapid frequency fluctuations. Fig. ***12*** illustrates the system frequency response during the tripping of the Sephu Solar PV plant at varying penetration levels. The frequency dip is minimal when the solar plant is injecting lower power. However, as the penetration level increases, the frequency dip becomes more pronounced upon the sudden disconnection of the solar PV plant from the grid.

During the tripping of the 100% penetration level, the bus frequency at point of coupling (POC) drops to almost 49.899 Hz, falling below the acceptable frequency limit of 49.9 Hz to 50.05 Hz (Electricity Regulatory Authority, 2024). To maintain system stability, the under frequency load shedding relay (UFLS) of that bus must take appropriate action.

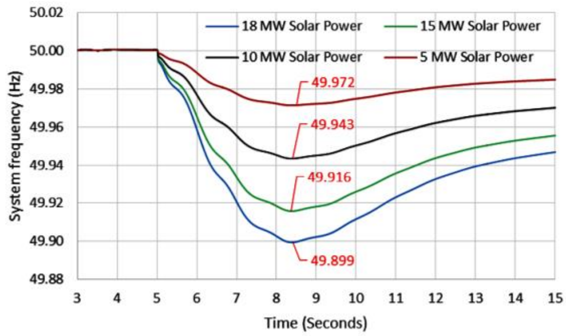

Fig. 12: *System frequency during solar plant tripping*

c. Impact on Conventional Generator Output

The tripping of a solar PV plant requires conventional generators to rapidly adjust their output to compensate for the sudden loss of active power. This dynamic adjustment places additional stress on the generators, potentially leading to increased wear, tear, and reduced efficiency. The dynamic responses of the Mangdechhu (MHP) generator and Tala (Swing generator) during the tripping of the Sephu Solar PV plant at varying penetration levels are shown in Fig. ***13*** and Fig. ***14***, respectively. The results indicate that the power output undergoes oscillatory before stabilizing at a new equilibrium. In this process, the conventional generators partially compensate for the lost solar PV generation, resulting in an overall increase in their total power output. During the normal operating conditions (upto t = 5 s), the power output from the swing generator decreases as the level of PV penetration increases. This is because the swing generator is responsible for maintaining the load-generation balance.

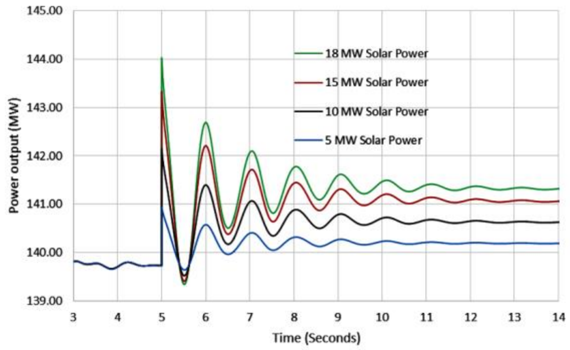

Fig. 13: *Power output behavior of MHP generator during solar plant tripping*

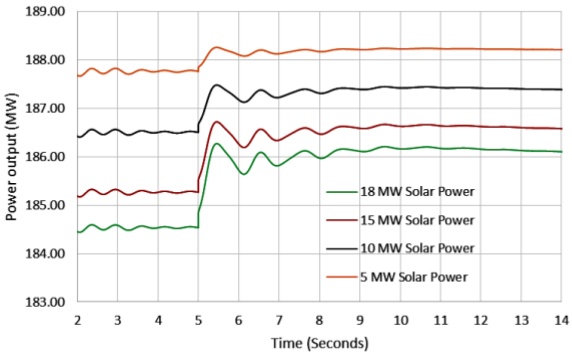

Fig. 14: *Power output behavior of Swing generator during solar plant tripping*

6.4. Three-phase Fault at PV Connected Bus

A three-phase fault is initiated at Sephu 33 kV bus (PV connected bus). The system is running in normal condition until t = 5 s and the fault is cleared within 200 ms. The impact of three-phase fault in the bus voltage, system frequency, and the power output by Solar PV plant and the conventional machine are analyzed for maximum power generation from Sephu PV plant.

a. Impact on Bus Voltage

The three-phase fault, considered one of the most severe fault types in a power system, is applied at the PV connected bus, Sephu 33 kV to assess its impact. The analysis focuses on the voltage response of nearby substation buses, such as the Yurmo and Phobjikha 33 kV buses. As shown in Fig. ***15***, the bus voltage magnitude at the POC drops to zero during the fault and remains at that level until the fault is cleared. Following fault clearance, the bus voltage exhibits oscillations before eventually settling back to its pre-fault level. The post-fault oscillation may further increased with the higher penetration levels, potentially compromising voltage stability. Without effective measures to mitigate these conditions, the system may face challenges in maintaining stability.

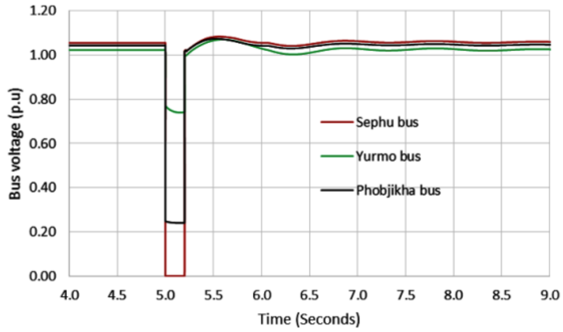

Fig. 15: *Voltage profile during three-phase fault at PV connected bus*

b. Impact on System Frequency

The impact of three-phase fault in PV connected bus is depicted in Fig. ***16***. From the simulation, frequency oscillation at the POC is observed during the fault. The frequency drops to 49.834 Hz and settle at 50.02 Hz after extended duration of around 6 s. The frequency drops below the limit may trigger the operation of UFLS relay.

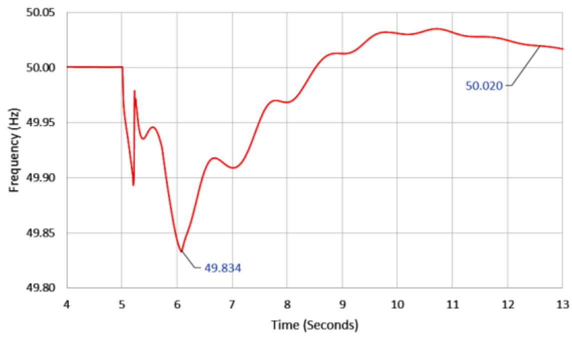

Fig. 16: *Frequency response during three-phase fault at PV connected bus*

c. Impact on Power Output

Fig. ***17*** illustrates the power output of the solar PV plant and the swing generator during a three-phase fault at the PV connected bus and the response of MHP generator is depicted in Fig. ***18***. As shown, the solar PV plant's power output drops to zero during the fault and returns to its pre-fault level once the fault is cleared. In contrast, the power delivered by the swing generator experiences significance oscillations before stabilizing after some time.

The oscillatory behavior in the output of conventional generators in the post-fault condition is attributed to the dynamics of the rotating machines, whereas the solar PV plant, being inverter-base and does not have rotating machines, exhibits a smooth response without oscillations (Bhatt & Affijulla, 2017).

Consequently, the solar PV plant's output stabilizes more quickly than that of the conventional generator following the fault. The power output oscillation from the conventional generators increases with increase in the PV penetration levels (Bhatt & Affijulla, 2017).

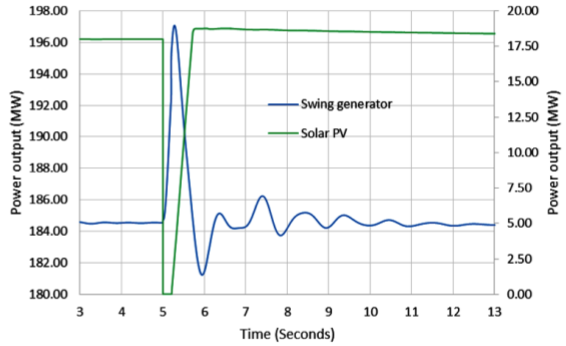

Fig. 17: *Output power responses from PV and Swing generator during three-phase fault at PV connected bus*

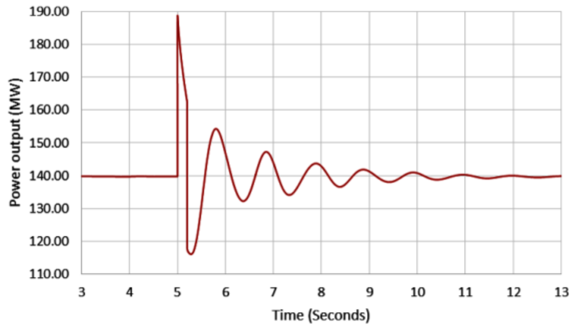

Fig. 18: *MHP generator response during three-phase fault at PV connected bus*

7. CONCLUSION

This study evaluates the impact of integrating 18 MW Sephu Solar PV plant into the grid, focusing on varying levels of solar power penetration. Dynamic simulations were conducted using Power System Simulators for Engineering (PSSE) software to analyze grid stability under two scenarios: the sudden disconnection of the PV plant and a three-phase fault at the PV connected bus, each tested across different penetration levels.

The simulation results reveal no significant threats to overall grid stability. However, the integration of the Sephu Solar PV plant causes minor voltage drop, and frequency dips to 49.899 Hz which violates the normal frequency limit specifies by Grid Code of Bhutan. To mitigate potential issues, it is crucial to ensure appropriate under voltage and under frequency load shedding relay settings at critical locations such as point of coupling (POC), Phobjikha, and Yurmo substations at the 33 kV level. Proper relay configurations are necessary to prevent unintended disconnection of the solar PV plant, as the observed voltage and frequency variations could affect its operational reliability.

Additionally, the transformers at the 66/33 kV Gewathang substation must be upgraded to function as interconnecting transformer. This upgrade is essential to accommodate the reverse power flow direction resulting from the integration of the Sephu Solar PV plant.

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