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Addressing Under-Voltage Issues through Shunt Capacitor Installation

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Abstract:

Over the last five years, Bhutan had experienced a significant national load growth of around 56%. This rapid increase in electrical load requirements has resulted in undesirable issues in some areas of the transmission network. This paper analyzes the persistent under-voltage issues observed at the high voltage side of the 66/33 kV Paro substation. A voltage stability analysis of the network was performed using Siemens' Power System Simulator for Engineering (PSSE) software to propose remedial actions to the power transmission and distribution company, Bhutan Power Corporation Ltd. (BPC). Considering future load demand and network reconfiguration, the simulation results showed that the use of a 75 MVAR shunt capacitor at the Jamjee 66 kV bus would improve the voltage at the Paro substation and other neighboring substations, thus maintaining the voltage within the acceptable limit of ± 5% of the nominal voltage.

Keywords **—Power System, PSSE, Shunt Capacitors, Under-voltage, Voltage regulation.**

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I. INTRODUCTION

Bhutan possesses a considerable quantity of hydropower resources, which is equivalent to 30 gigawatts of power generation potential and an annual production capacity of 120 Terra-watt hours [1]. The country's first 336 megawatts hydropower plant, known as the Chhukha Hydropower Plant (CHP), was established in 1986-88 that brought about the much-needed revenue to support socio-economic development in the country by exporting power to India. Since then, significant advancements have been made in hydropower development in Bhutan. Currently, the total installed capacity of hydropower in the country is 2326 megawatts, accounting for 8.44% of its total potential.

To effectively plan, manage, and adapt to market changes and global shifts, Bhutan's power sector has a specific structure, as illustrated in Fig. 1. The Ministry of Energy and Natural Resources (MoENR) serves as the primary administrative body for the Royal Government of Bhutan (RGoB) in this sector. Under MoENR, the Department of Energy (DoE) is responsible for power system planning, policy-making, and coordination with other stakeholders.The Electricity Regulatory Authority (ERA) oversees these power companies and electricity tariffs as an independent regulator.

The Bhutan Power System Operator (BPSO) functions as the Transmission System Operator (SO) and holds the responsibility for operating the national grid. Its primary duties include ensuring the safe and secure operation of the power system, providing a reliable power supply, and optimizing power trade both within and outside of the country.This office has WAMS technology implemented in the system to supplement the existing SCADA/EMS systems. It has been shown to improve BPSO's performance concerning overall system operation and control [2].

Bhutan Power Corporation Ltd. (BPC), which oversees the transmission and distribution networks, and Druk Green Power Corporation Ltd. (DGPC), which owns and runs the nation's hydropower plants, are the two power companies in the country.

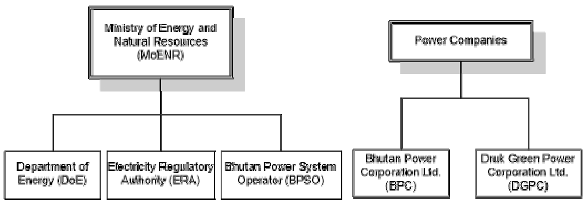


Fig. 1Structure of the Power Sector in Bhutan

Over recent years there has been a significant increase in the demand for electricity in Bhutan and it indicates the country's development and economic growth. This rapid rise is due to several factors, such as urbanization and industrialization. With the growing urbanization, the electricity demand has increased significantly, as more people are using electrical appliances, such as air conditioners, refrigerators, and televisions. Moreover, with the growth of industries, there has been a significant increase in the demand for electricity for manufacturing and processing operations. The growth in coincidental Bhutan peak load from 2007 to 2022 is shown in Fig. 2.

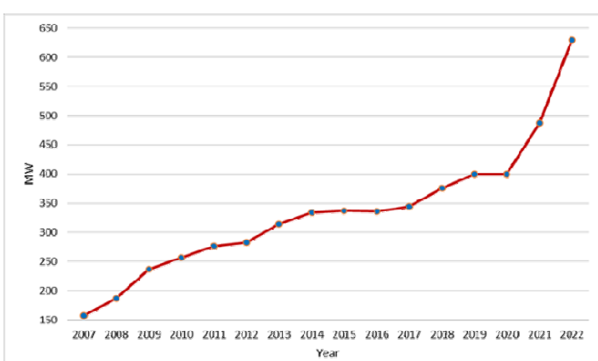


Fig. 2Coincidental Peak Loads of Bhutan from 2007 to 2022

This increase in coincidental load over the last few years has resulted in putting greater stress on the electrical grid and a reduction in the quality of power and voltage, thereby causing damage to sensitive equipment connected to the network.

Therefore, this paper discusses the under-voltage issues that are being experienced at 66/33 kV Paro substationsin different scenarios. At the same time, there is installation of 2x50 MVAR capacitor banks at the Semtokha substation, integration of 220/66/33 kV Jamjee substation to the network, and reconfiguration of the 66 kV networks. To understand the system dynamics due to this reconfiguration, the simulation study is carried out and their corresponding results are presented. It was observed that the installing the75 MVAR shunt capacitor at the Jamjee 66 kV bus could effectively improve the stability and reliability of the power system.

The rest of the paper is structured as follows: SectionIIdescribes the under-voltage issues observed in different scenarios and in Section IIIpresents the simulation and modelling analysis done. Section IV provides the study carried out on mitigating the under-voltage issues and finally in SectionV, the conclusion and way forward recommendations are summarized.

II. UNDER-VOLTAGE ISSUE DESCRIPTION

The peak-load trend of the Paro substation over the last decade is presented in Fig. 3. This domestic load growth has resulted into under-voltage issues in Paro substation and some nearby substations such asPangbisa, and Haa.

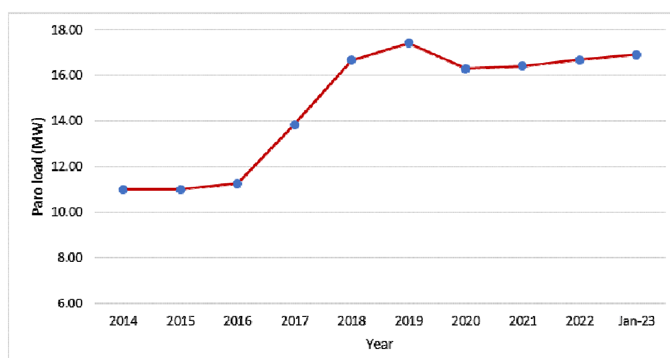


Fig. 3Peak load of Paro from 2014 to 2022

Fig. 4. shows the real-time voltage profiles of Paro substation during different scenarios, such winter, summer, and contingency scenario respectively. It can be seen from Fig. 4 (a) that the voltage at the Paro substation was within ±5% of the nominal voltage [3] during morning hours until 2020. However, thereafter the voltages began to deteriorate due to the increased load demand.As the load during summer at Paro is relatively less compared to winter, the voltage profile is found to be within the normal limit. The minimum, maximum, and average voltage of Paro substation during winter and summer is presented in Table 1 and Table 2, respectively.

TABLE I
THE MINIMUM, MAXIMUM, AND AVERAGE VOLTAGE OF PARO DURING WINTER

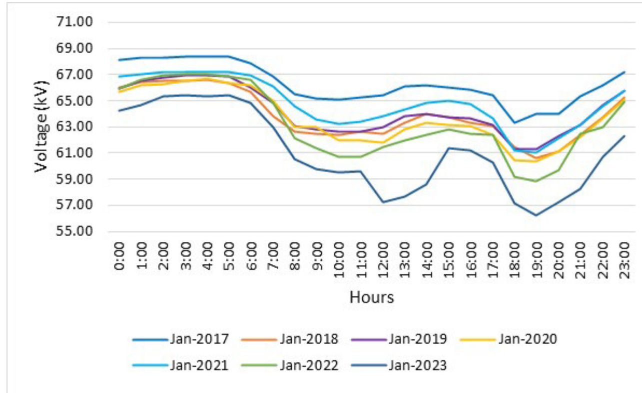
Voltage (kV)	2017	2018	2019	2020	2021	2022
Minimum	60.00	60.00	60.78	60.08	57.37	58.64
Maximum	68.93	67.62	67.84	67.46	67.65	67.78
Average	66.32	64.59	64.75	64.15	64.66	63.70

TABLE II
THE MINIMUM, MAXIMUM, AND AVERAGE VOLTAGE OF PARO DURING SUMMER

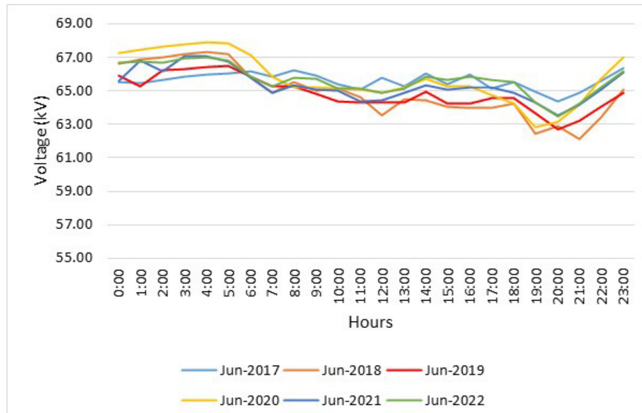
Voltage (kV)	2017	2018	2019	2020	2021	2022
Minimum	63.19	60.48	62.28	61.68	62.59	63.26
Maximum	67.69	67.31	67.86	68.57	67.32	68.32
Average	65.82	64.82	65.19	65.88	65.30	65.64

The voltage profile during a contingency was considered when the Olakha-Changedaphu 66 kV line was taken offline to conduct a fault locator test. At the instant of opening the line, the voltages in 66 kV Changedaphu, Jemina, Chumdo, Haa, and Paro dipped as shown in Fig. 4 (c).

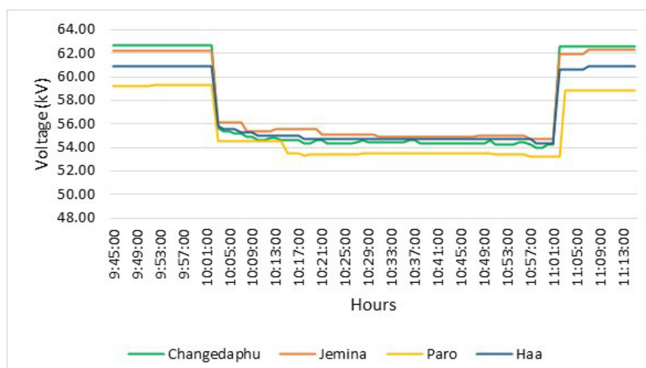
Fig. 5 illustrates the load characteristics of Paro for both winter and summer seasons. The data shows that the voltage profile during summer is more stable due to a lower load demand as compared to winter. From the figure, it can be seen that the maximum load during winter was near to 16 MW, whereas during the summer, it remained around 8 MW.



(a) Voltage profile of Paro 66 kV bus during winter

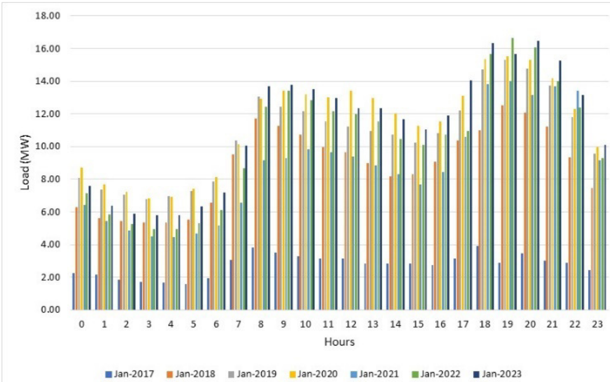


(b) Voltage profile of Paro 66 kV bus during summer

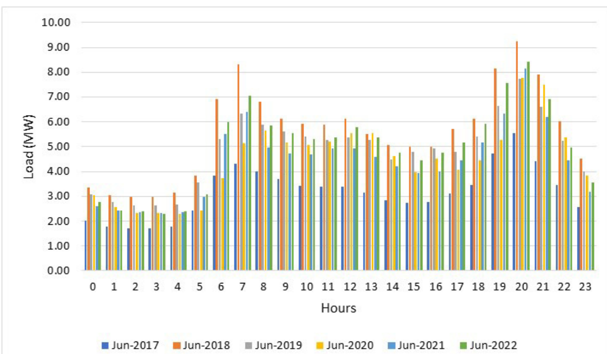


(c) Voltage profile of Paro 66 kV bus during contingency

Fig. 4Voltage profile of Paro substation during different scenario



(a) Loadprofile of Parosubstation during winter



(b) Loadprofile of Parosubstation during summer

Fig. 5 Load profile of Paro substation during winter and summer

To tackle the voltage issues observed above, the BPC is in the process of installing 2x25 MVAR capacitor bank at 66 kV bus of 220/66 kV Semtokha substation. At the same time, there will be integration of 220/66/33 kV substation and reconfiguration of 66 kV networks thereby having possibility to change the dynamics of the power system behaviour.

III. SIMULATION MODELLING AND ANALYSIS

This sectiondescribes the voltage stability analysis carried out using the PSSE software under the new system configuration scenario.

A. Overview of transmission system under study

Fig. 6depicts the transmission network under study, which is a part of the larger Bhutan transmission system. For the voltage improvement in the transmission system, 2x25 MVAR shunt capacitors areconsidered available at Semtokha 66 kV bus along with the integration of the 220/66/33 kV Jamjee substation and reconfiguration of 66 kV lines.

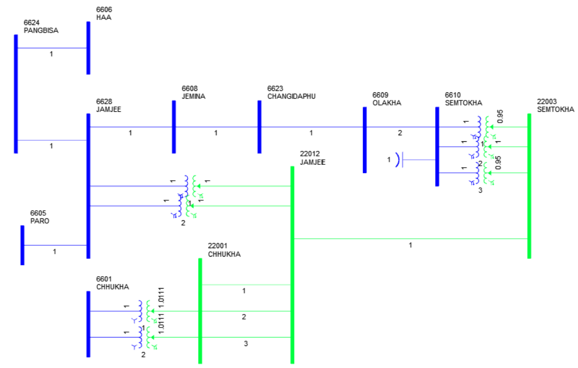


Fig. 6Transmission network under study

B. Results and Findings

The voltage stability analysis was conducted for current load demand of the substations, considering the new network configuration and the availability of 2x25 MVAR shunt capacitor at Semtokha 66 kV bus. The simulation results, presented inTable 3, indicate that only the bus connected with shunt capacitor and the Olakha substation, which is closest to the shunt capacitor, have voltages within the permissible limit. Paro will still experience low voltage with 59.73 kV, followed by Haa and Pangbisa, both at 59.80 kV and 60.17 kV, respectively.

TABLE 3

VOLTAGE PROFILE WITH SHUNT CAPACITORAND NEW NETWORK CONFIGURATION

Substations	Simulation result (kV)
Jamjee	207.39
Semtokha	208.41
Jamjee	61.39
Semtokha	64.32
Olakha	63.96
Changedaphu	62.12
Jemina	61.62
Paro	59.73
Pangbisa	60.17
Haa	59.80

The above results clearly show that there are still under-voltages persisting in the system despite the presence of shunt capacitor. Therefore, the following section intends to rectify using the simulation with the help of one of the voltage improvement methods.

IV. UNDER-VOLTAGE MITIGATION STRATEGIES

The simulation modelling and network described in Section III is extended to mitigate the persisting under-voltage issues. Among the various voltage improvement mechanisms such as excitation control at generating stations, shunt reactors, and FACTS devices, the shunt capacitors play a major role in maintaining system voltage within prescribed limits and hence enhancing the voltage profile. Therefore, in this paper,the shunt capacitor bank is chosen based on the advantages over others such as long life spans, require minimal maintenance, and easy installation [4],[5]. This would prove cost effective and flexible solution for improving the voltage in the system.

A. Base case model validation in PSSE

To ensure the accuracy of the voltage stability study, the base case power system model in PSSE was validated by comparing the actual bus voltages of the 66 kV substations voltage with the simulation results. The comparison is presented in Table 4 and the deviation between the actual and simulated bus voltage of the 66 kV network was found to be less than 5%. This is considered acceptable, and it indicates that the power system model is suitable for performing any kind of power system studies, in this case, the analysis of the impact of shunt capacitors on voltage regulation.

TABLE 4

REAL-TIME BUS VOLTAGE COMPARISON WITH SIMULATION VOLTAGE

Substations	SCADA (kV)	Simulation result (kV)	Deviation (%)
Changedaphu	60.25	58.05	3.65
Chumdo	56.00	55.35	1.15
D/Ling	64.30	63.43	1.35
Dochhula	63.46	63.90	-0.69
Haa	54.00	54.56	-1.04
Jemina	57.00	56.64	0.64
Olakha	64.01	61.53	3.87
Paro	52.81	54.20	-2.40

B. Selection of candidate bus

According to [6], the selection of the candidate bus for reactive power compensation is computed by the equation (1) below:

$$V_{norm}(i) = \frac{V(i)}{0.95} \quad (1)$$

Where $V_{norm}(i)$ is the normalized voltages and $V(i)$ the base case voltage magnitudes.

The buses with $V_{norm}(i)$ values below 1.01 are regarded as potential candidate buses for requiring reactive power compensation. From the voltage stability analysis considering the peak load and generation of February 2023, the buses that require the reactive power compensation are shown in Table 5.

TABLE 5

CANDIDATE BUSES THAT REQUIRE REACTIVE POWER COMPENSATION

Substation	Simulation voltage (kV)
Jamjee	207.39
Jamjee	61.39
Changedaphu	62.12
Jemina	61.62
Paro	59.73
Haa	59.80
Pangbisa	60.17

It can be seen that all the study buses are candidate buses that required reactive power compensation for under-voltage mitigations. However, based on the practical experiences and considering the source substation, the Jamjee66 kV bus was selected for the installation of a shunt capacitor as indicated in Fig. 7.

C. Shunt capacitor size selection considering the current load scenario

The selection of suitable shunt capacitor size for voltage improvement in the study network is purely based on sensitivity analysis. The sensitivity analysis was performed in PSSE with different power flow solutions with different shunt capacitor ratings of 25 MVAR, 50 MVAR, and 75 MVAR.

Both normal and contingencies are considered to find the suitable shunt capacitor size.The contingencies are as below:

- Contingency 1 (CON1): Outage of 66 kV Olakha – Changedaphu line.
- Contingency 2 (CON2): Outage of 1x220 kV CHP – Jamjee line.
- Contingency 3 (CON3): Outage of 2x220 kV CHP – Jamjee line

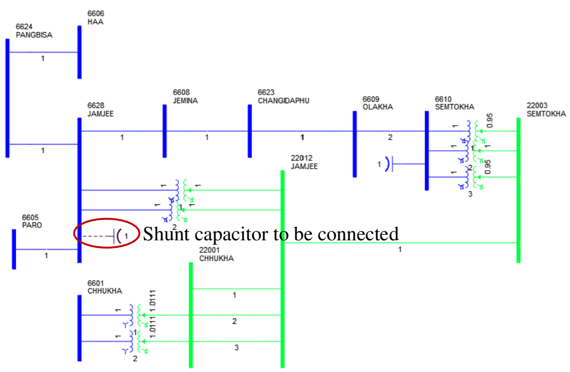


Fig. 7 Updated network under studywith shunt capacitor to be connected

The sensitivity analysis for suitable shunt capacitor size selection was carried out with the present load. The simulated voltage profile with 20 MVAR, 50 MVAR, and 75 MVAR shunt capacitors is presented in Table 6, Table 7, and Table 8, respectively. From the analysis, it was seen that the 25 MVAR shunt capacitor is not adequate for reactive power compensation. On the other hand, the 75 MVAR resulted during normal operation and contingencies 1 and 2. During contingency 3, the voltage of the bus that is connected with the shunt capacitor resulted in high voltage (more than 1.05 p.u). With the current load condition, the 50 MVAR shunt capacitor is found to be most suitable as the voltage profile during both normal and contingencies are within the normal operating range. However, the future load growth has to be considered and the selection of a shunt capacitor is important. Considering the future load demand and finding the adequate reactive power compensation for voltage improvement with reducing unnecessary expenditure. Therefore, the sensitivity analysis considering the future load growth is being carried out in the next section.

TABLE 6

SIMULATED VOLTAGE PROFILE WITH 25 MVAR SHUNT CAPACITOR

25 MVAR shunt capacitor				
Substations	**Normal (kV)**	**CON1 (kV)**	**CON2 (kV)**	**CON3 (kV)**
Jamjee	64.50	63.88	63.92	62.20
Changedaphu	64.11	62.64	63.55	61.88
Jemina	64.16	63.08	63.58	61.88
Paro	62.95	62.32	62.35	60.57
Pangbisa	63.35	62.72	62.76	61.00
Haa	63.00	62.37	62.40	60.64

TABLE 7

SIMULATED VOLTAGE PROFILE WITH 50 MVAR SHUNT CAPACITOR

50 MVAR shunt capacitor				
Substations	**Normal (kV)**	**CON1 (kV)**	**CON2 (kV)**	**CON3 (kV)**
Jamjee	67.91	68.47	67.40	65.93
Changedaphu	66.29	67.33	65.81	64.41
Jemina	66.93	67.73	66.43	64.99
Paro	66.46	67.04	65.94	64.43
Pangbisa	66.83	67.40	66.32	64.82
Haa	66.50	67.07	65.98	64.48

TABLE 8

SIMULATED VOLTAGE PROFILE WITH 75 MVAR SHUNT CAPACITOR

75 MVAR shunt capacitor				
Substations	**Normal (kV)**	**CON1 (kV)**	**CON2 (kV)**	**CON3 (kV)**
Jamjee	71.67	73.68	71.25	70.06
Changedaphu	68.68	72.63	68.29	67.18
Jemina	69.98	73.00	69.58	68.43
Paro	70.32	72.38	69.89	68.68
Pangbisa	70.65	72.70	70.23	69.02
Haa	70.35	72.40	69.92	68.71

D. Shunt capacitor size selection with 2025 load scenario

The shunt capacitor size selection considering the future load demand is analysed, and the simulated voltage with 50 MVAR, 75 MVAR, and 100 MVAR shunt capacitors are presented in Table 9, Table 10, andTable 11, respectively. It is of utmost crucial that the voltage profile in all substations is maintained within the limit during the contingencies. Taking the 2025 load scenario, it was found that a 50 MVAR shunt capacitor is not adequate for voltage improvement in the study system. The voltages remain below the normal operating range both during normal operation and during contingencies. On the other hand, the 100

MVAR shunt capacitor resulted in high voltage. Therefore, the suitable shunt capacitor size is 75 MVAR as the voltages are maintained within the limit even during all contingencies.

TABLE 9

SIMULATED VOLTAGE PROFILE WITH 50 MVAR SHUNT CAPACITOR

50 MVAR shunt capacitor				
Substations	**Normal (kV)**	**CON1 (kV)**	**CON2 (kV)**	**CON3 (kV)**
Jamjee	64.57	65.15	63.76	61.06
Changedaphu	61.89	62.98	61.09	58.41
Jemina	63.03	63.87	62.21	59.52
Paro	61.53	62.15	60.66	57.76
Pangbisa	64.11	64.69	63.28	60.56
Haa	63.76	64.35	62.93	60.19

TABLE 10

SIMULATED VOLTAGE PROFILE WITH 75 MVAR SHUNT CAPACITOR

75 MVAR shunt capacitor				
Substations	**Normal (kV)**	**CON1 (kV)**	**CON2 (kV)**	**CON3 (kV)**
Jamjee	68.20	69.30	67.48	65.24
Changedaphu	64.23	68.26	63.35	62.70
Jemina	65.99	69.08	65.29	63.07
Paro	65.37	67.54	64.62	62.54
Pangbisa	67.76	69.35	67.04	64.78
Haa	67.44	69.52	66.72	64.44

TABLE 11

SIMULATED VOLTAGE PROFILE WITH 100 MVAR SHUNT CAPACITOR

100 MVAR shunt capacitor				
Substations	**Normal (kV)**	**CON1 (kV)**	**CON2 (kV)**	**CON3 (kV)**
Jamjee	72.20	76.08	71.61	69.80
Changedaphu	66.82	74.26	66.25	64.53
Jemina	69.26	75.00	68.68	66.91
Paro	69.59	73.63	68.96	67.06
Pangbisa	71.80	75.70	71.20	69.37
Haa	71.50	75.42	70.90	69.06

V. CONCLUSION

The paper presented the under-voltage issues persisting at the Paro substation in Bhutan over the years due to an increase in the national load demand. To improve the voltage, Bhutan Power Corporation Ltd. is in the process of installing the shunt capacitor at the Semtokha substation. But with the integration of the Jamjee substation and reconfiguration of the 66 kV lines, the simulation studies show the under-voltage problem would remain. Therefore, the authors concluded through the sensitivity study that the installation of a 75 MVAR shunt capacitor at Jamjee 66 kV bus could improvethe voltage profile in the transmission network at all contingencies considered. The information and the results obtained would be valuable for Bhutan Power Corporation Ltd.

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