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STATIC VOLTAGE STABILITY ASSESSMENT WITH REACTIVE POWER COMPENSATION IN POWER SYSTEM

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Abstract

Today, the demand for electricity is increasing rapidly. However, the generation and transmission capability is not growing as fast as it should to meet the demand, leading the power system to operate under severe conditions. This situation raises the problem of instability in the system. Therefore, voltage stability analysis is very essential and a burning concern to properly operate the system. This study performs steady-state voltage stability analysis and analyzes the impact assessment of reactive power compensation on the voltage stability of the Integrated Nepal Power System section, Madhesh Pradesh. Since this region contains most of the industrial load, it seems to be a suitable region for the study of the voltage stability analysis. The analysis was done using PV and QV curves along with the sensitivity analysis and also by using DIgSILENT Powerfactory software. The result showed that implementing reactive power compensation through a 5 MVAr capacitor bank in 132 kV distribution network improved the active power voltage stability margin by a maximum of 8.86%, as observed through loadflow analysis in DigSILENT powerfactory. Additionally, the financial evaluation indicated a payback period of 1.5 years, confirming the economic feasibility of capacitor bank installation.

Keywords: Static voltage stability, Voltage stability margin, PV and QV curves, Reactive power compensation, Capacitor bank

1. Introduction

Today's increasing energy demands have led to significant growth in power systems, resulting in extensive coverage and complex interconnections. This evolution introduces greater complications for maintaining power system stability while enhancing power transfer capability. Voltage stability is one of the critical aspect of the power system as it ensures a reliable and continuous supply of electricity. It is the ability of the system to retain the normal operating voltage after being subjected to disturbances like faults, lightning surges, switching of loads and so on. Based on the time period of the disturbances, voltage stability is broadly classified into two groups: Static and Dynamic stability.

Static Voltage Stability refers to the ability of the system to maintain normal operating voltage levels when subjected to small and gradual changes in load variation. The main causes of static voltage instability are generation limits, transmission infrastructure limits, high reactive power demand, etc. Among these, the most prominent is the deficiency of reactive power in the system. When a system has more reactive power requirement, the voltage of the system starts to drop, and if not solved in time, it may cause cascading outages and even blackout of the entire system (Kundur, 1993).

To ensure efficient and reliable operation of the power system, it is critical to effectively manage both voltage and reactive power. This management is essential to maintain voltage levels at all buses within acceptable limits (Van Cutsem and Vournas, 2007).

The straight forward way to improve the system's voltage stability would be increasing the generation and make system more interconnected, which is highly expensive and requires more time. So another method would be providing reactive power externally using compensation devices, to

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improve the functioning of the transmission system, which consequently help the system's stability (miller, 1982).

Likewise, the reactive power compensation device must be placed strategically so that maximum benefit can be obtained, as they cannot be placed anywhere we want, considering they are expensive devices. As voltage instability is one of the major problem in the power system, lots of studies are being done for its improvement. During studies of voltage stability, different methods have been discovered and used. In Mogaka et al., 2021, it demonstrates that voltage instability in power systems is primarily driven by inadequate reactive power support, and that identifying weak buses and critical lines through static analysis methods is key to improving voltage stability. The authors uses a comprehensive methodology combining QV modal analysis, V-Q sensitivity analysis, and PV/QV curve assessments for its study.

The authors of Reddy, 2011 have carried out static voltage stability assessment using PV and QV curves and modal analysis to identify the critical point in the system. This study shows that reactive power compensation plays a significant role in improving voltage profiles and enhancing system stability, especially at critical buses.

Shao Yao and associates studied the effect of reactive power reserve on the voltage stability of the system in Yao et al., 2014. Increasing reactive power reserves, by minimizing the initial output of generator, enhances static and transient voltage stability in a power system. Strategically managing these reserves through proper placement and sizing of compensation devices significantly strengthens system stability.

By installing a shunt capacitor bank in the load substation and injecting the appropriate reactive power into the system, it is shown that the static voltage stability is improved by maintaining voltage levels and preventing voltage collapse under increasing load conditions (Furukakoi et al., 2016).

Generally, the stability of the system is analyzed on the basis of the stability margin of the PV and QV curves of that system. But sensitivity of the voltage for the change in active and/or reactive power is crucial to the power system, as it indicates how far the operating point is from the critical point. In Rahman et al. (2020), the effectiveness of different voltage stability indices, including dV/dP and dV/dQ, is evaluated, and it was found that these indices are more effective in transmission system than in the distribution. These indices help locate critical points where reactive power compensation (like capacitor placement) can be most effective.

This paper aims to assess the effect of reactive power compensation on the Madhesh Pradesh section and analyze the financial feasibility of the investment in the compensation device. For this study, DIgSILENT PowerFactory software has been used and stability of the system is analyzed using PV and QV curves and the sensitivity of the buses.

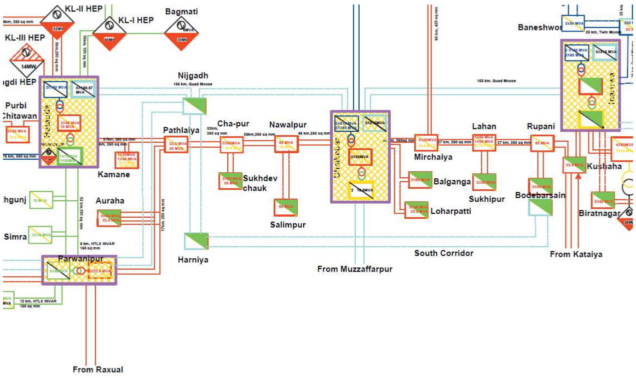

Figure 1. Modeled section of Integrated Nepal Power System Nepal Electricity Authority, 2023

Section II contains the description of the system, followed by the methodology of the paper. Section III contains the results and analysis, and the study is concluded in Section IV.

2. System Description and Methodology

2.1. System Model

For the study, the Madhesh Pradesh section of Integrated Nepal Power System is taken as it includes most of the industrial loads in Nepal, thus highly vulnerable to instability. Figure 1 shows the modeled section where a generator of capacity 160 MW is connected to the Hetauda substation, representing all the power flowing to the section from the western part. Upper Tamakoshi hydropower of capacity 240 MW is connected to Dhalkebar substation, and a generator of capacity 80 MW, representing all the hydropower in the Koshi corridor, is connected to Inaruwa substation. Dhalkebar 400 kV line is taken as the external grid as power from India is imported from that line. The generators were modeled using the built-in model in DIgSILENT PowerFactory, where all the generators are set up in voltage control mode.

A total of 10 substations which support 132 kV or higher voltage are modeled. The load on each substation is modeled by analyzing the capacity of the transformer on the substation and taking a load factor of 0.5, assuming not all loads are running on average during steady state.

The Transmission line parameters were calculated using the information of the conductors in the annual report of Nepal Electricity Authority. Most of the Transmission line conductors in this section were BEAR conductors except for the Dhalkebar-Inaruwa 400 kV line, which was QUAD MOOSE conductor.

Table 1. Substation Load Data

Substation	Load (MVA)	Load (MW)
Parwanipur	50	40
Pathlaiya	25	20
Cha-pur	30	24
Nawalpur	24	19.2
Dhalkeber	60	48
Mirchiaya	15	12
Lahan	25	20
Rupani	23	18.4
Hetauda	40	32
Inaruwa	70	56
Tingla	8	6.4

Table 2. Power sources for the model (Nepal Electricity Authority, 2023)

Generation	Capacity(MW)
Hetauda substation	160
Upper tamakoshi	456
Koshi corridor	80

All the generators are modeled to operate in voltage control mode with their automatic voltage regulators enabled. The standard IEEE AVR model available in DIgSILENT PowerFactory was used to model it. The AVR maintains the generator terminal voltage at the set reference value by adjusting the excitation voltage within pre-defined limits. The inclusion of AVR modeling is indispensable in the static voltage stability assessment because reactive power limits and excitation control influence the characteristics of the PV and QV of the system directly.

Table 1, Table 2 and Table 3 shows the information about the load, generation units with their capacities and transformer rating of the system.(Nepal Electricity Authority, 2023).

2.2. Capacitor Placement

For the placement of the compensation device (capacitor bank), the active and reactive power margin of the different buses were first analyzed. The bus having the least active power margin is prone to instability, whereas the bus having the least reactive power margin requires the most reactive power support, where the capacitor bank was placed, also.

The size of the capacitor bank is determined from the QV curve of the selected bus in which capacity of the capacitor bank is the reactive power required to maintain the bus voltage at 1 p.u. After capacitor placement, the margins are analyzed again to observe the effect of compensation.

2.3. Financial Analysis

The financial analysis of the investment in capacitor bank is based on the financial benefit it can provide after installation. After determining the size, its equivalent costs in real world are analyzed and compared with the benefits it will bring to the system. Other benefits are also searched and analyzed.

Table 3. Transformer Ratings

Transformer	Rating(MVA)
400/220 kV	945
220/132 kV	950

The power loss cost is calculated using the Equation (1) as (Silwal and Shakya, 2020):

Annual Energy Loss Cost:

$$LLF * Total\ Power\ Loss * p.u.\ Energy\ Cost * 8760 \quad (1)$$

Load factor of Nepal is taken as 55% (Energy Development Council Nepal, 2016). Using this loss cost, the financial feasibility is analyzed.

3. Results and Discussion

3.1. Voltage Stability Analysis

The weaker busses are first identified based on voltage profiles. Parwanipur, Pathlaiya, Chapur, Nawalpur, Lahan and Rupani were identified as the weaker busses as the voltage limit of +/- 5% was exceeded. Active power margin is observed on each of the weaker busses in order to find the weakest bus. The active power margin is the margin between the operating point and the critical point on the PV curve.

In addition to this, sensitivity analysis is carried out to identify the critical bus. From the analysis of dV/dQ and dV/dP, Rupani was identified as the weakest bus as shown in Table 5 indicating it can become instable with the least amount of change in active and reactive power as compared to other buses.

From the QV curve analysis, the same Rupani bus was found to be reactive power deficient. From the QV curve of the bus, size of the capacitor bank was found to be 43.5 MVAr. Then capacitor bank was installed at the Rupani bus and the further analysis was carried out.

Figure 3 shows the improvement of the stability margin after the installation of capacitor bank of the desired size and location in the system. Figure 5 and Figure 6 shows similar effect in other buses.

On reevaluating the margins of active and reactive power after capacitor placement, it was found that significant increment in margins only occurred near the compensated bus (Mirchaiya and Lahan) and the substation far away from Rupani bus did not show any increment in stability margin. This indicated the need of another compensation point.

Repeating the above process for busses unaffected by the

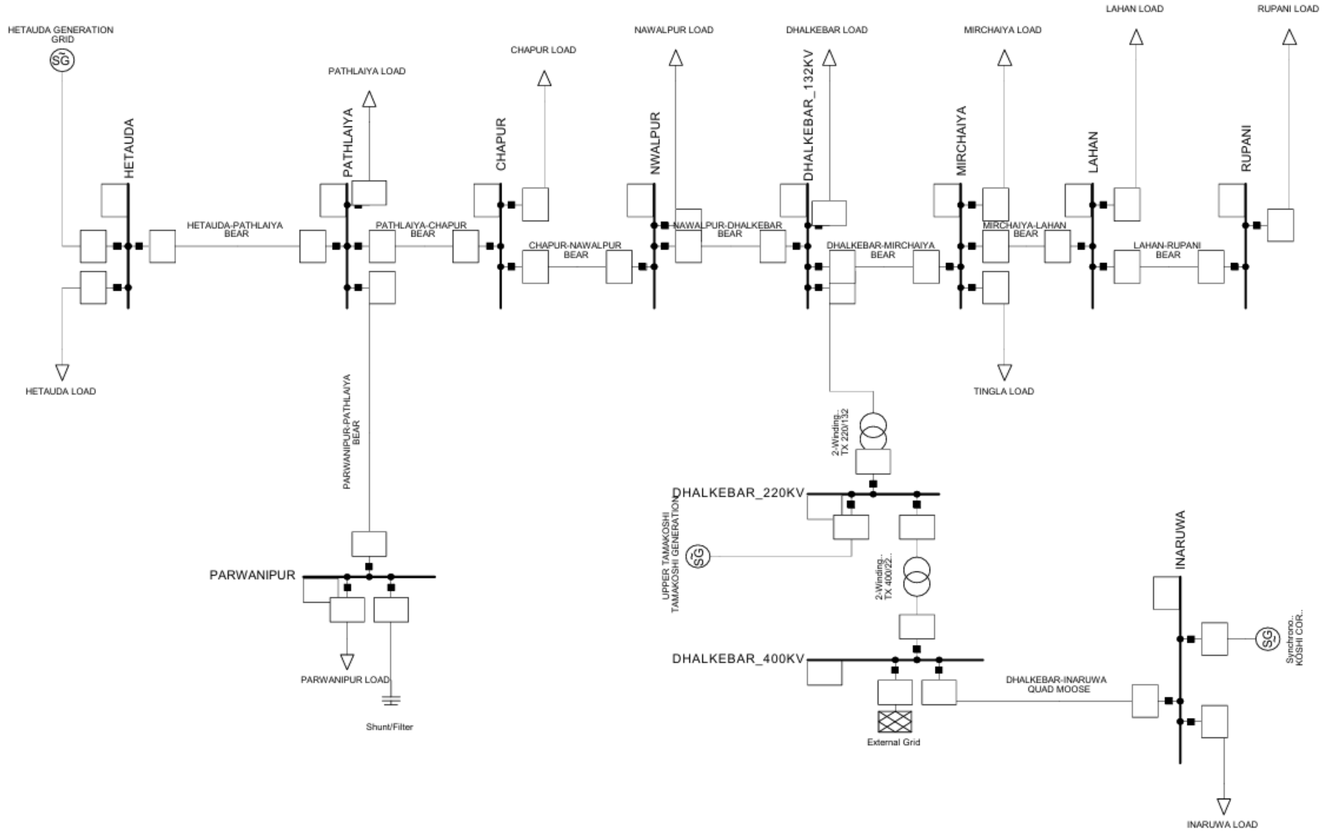

Figure 2. DIgSILENT Model of Integrated Nepal Power System

Table 4. Stability Margin Comparison before and after capacitor placement

Bus	Margin Increment (%)
Rupani	8.8
Lahan	6.7
Mirchaiya	4.3
Nawalpur	0.2
Chapur	0.2
Pathlaiya	0.12
Parwanipur	0.12

compensation, another possible compensation point was identified to be Parwanipur and required reactive power was found to be 78.8 MVAr. On placing capacitor on the bus, the stability margin of the busses near the compensated bus increased. This indicated that the effect of compensation decreases with increase in distance. Table 4 shows the stability margin comparision before and after the placement of capacitor bank in the system.

3.1.1 Active Power Margin Calculation

The active margin is defined as the difference between the level of loading associated with the critical point of

Table 5. Sensitivity of different busses at base case

Bus	dV/dP	dV/dQ
Parwanipur	-0.0014	0.00146
Pathlaiya	-0.0006	0.0006
Cha-pur	-0.0008	0.001
Nawalpur	-0.0008	0.0008
Mirchiaya	-0.0004	0.001
Lahan	-0.0008	0.0018
Rupani	-0.0014	0.003

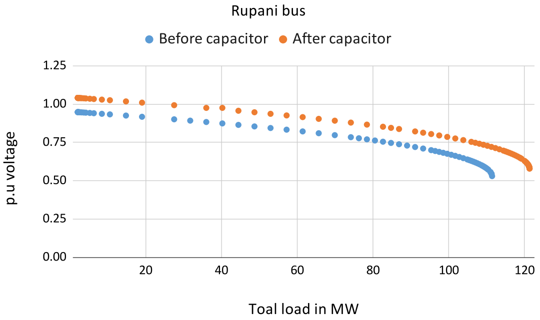

Figure 3. Improved stability margin of Rupani bus

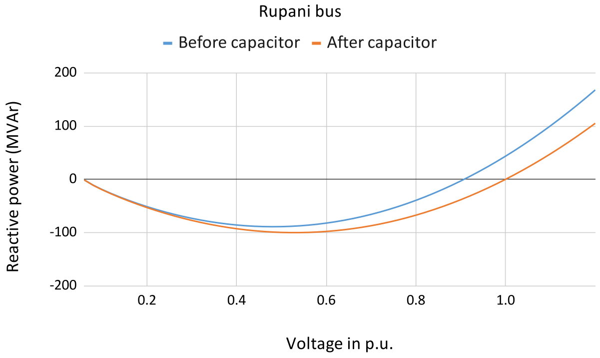

Figure 4. Improved reactive power margin of Rupani bus

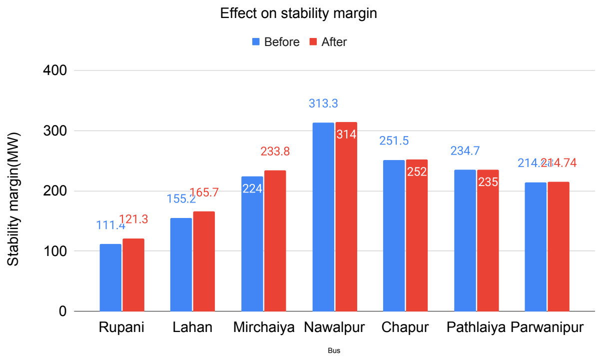

Figure 5. Stability margin from PV curves after installing capacitor bank

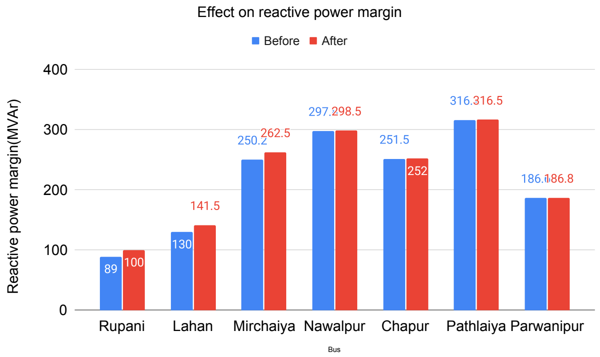

Figure 6. Reactive power margin from QV curves after installing capacitor bank

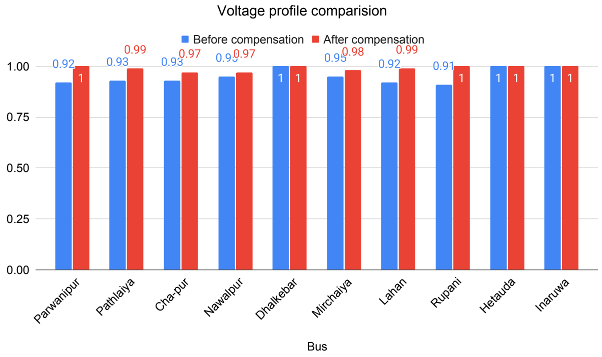

Figure 7. Voltage Profile Comparision before and after compensation

the PV Curve and the operating point described in the standard scenario. Besides, it has to be noticed that in the pre-capacitor installed situation, there was little active margin on the Rupani bus due to low voltage and because of deficiences in reactive power. After the installation of the capacitor bank, it has to be realized that there was an improvement of voltage in the bus, moving it from the critical point of the PV Curve, together with the improvement of the load level in the nose point of the curve, shifting to higher loading, producing an improvement of the active margin of 8.86%. Similar results would appear at the neighbouring buses, but reduced effects are found at mpre remote buses. Figure 7 shows the voltage profile comparision of all the buses before and after compensation.

3.2. Financial Analysis

The Financial analysis is done on the placement of capacitor on Rupani bus only. Capacitor cost for single unit of 5 MVAr, 33 kV was found to be $ 3000 (Made-in-China, 2025). And required capacity being 43.5 MVAR, the combination of the capacitor unit was found to be: 4 units in series and 9 strings (1 string = 4 units in series) in parallel. So a total of 36 units were needed whose cost sums up to $ 108000.

Implementing capacitor bank minimizes the loss in the system. It was found that the loss of the entire modeled system decreased from 8.83 MW to 8.25 MW. Energy cost per unit in Nepal is Rs 9.5 per unit i.e $ 0.068 per unit (Nepal Electricity Authority, 2025). Calculating the annual loss cost of before and after capacitor bank installation showed reduction in cost by $ 86373. If this reduction in loss cost is taken as benefit, then the payback period will be 1.5 years. This indicates that the investment in capacitor bank is viable.

4. Conclusion

In this study, the voltage stability assessment of Madhesh Pradesh section of Integrated Nepal Power System is carried out using PV and QV curves along with sensitivity analysis. Capacitor bank placement of 5 MVAr 132 kv was carried out and the findings showed that improvement in voltage stability was seen only on nearby busses with maximum of 8.6% and indicated necessity of multiple compensation for larger system. Furthermore, the financial analysis of the capacitor bank installation indicated a payback period of 1.5

years which signifies that the investment on capacitor bank is viable and can prove beneficial for the system. However, it should be noticed that as electrical distance increases, the decrease of the compensating effect follows the law of reactive compensation in power system. It is due to reactive compensation mainly compensates local voltage, because there are larger reactances between any two of the nodes and reactive power transfer ability over long distance between them is very low. It can be confirmed that the best improvement of the shunt compensating effect appears in the voltage stability concerning the distribution of nodes.

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