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Impact of Electric Vehicle Charging on Low Voltage Network Stability

Kunzang Chophel, Tshewang Lhendup*, Roshan Chhetri, Pravakar Pradhan

Centre for Renewable and Sustainable Energy Development, Electrical Engineering Department,
College of Science and Technology, Royal University of Bhutan, Rinchending, Bhutan
*Corresponding author: tshewanglhendup.cst@rub.edu.bt

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Abstract The global shift of vehicular transportation from conventional cars to electric vehicles present yet another challenge for the power utilities in meeting the growing demand for Electric Vehicles (EV). Large penetration of electric vehicles can have numerous impacts on the electric grid if left unaddressed. This paper presents the assessment of the impact of EV charging on the electricity distribution network at different penetration levels. A model of an existing electricity distribution network of Thimphu, the capital city of Bhutan was developed in DIgSILENT power factory simulation software. The impact of EV charging on the existing electricity distribution network was analysed based on three hypothetical assumptions, current status-quo, low uptake level, and high uptake level. The impacts were evaluated on two key parameters, the voltage stability, and the transformer loading. The load flow simulation indicated that a low voltage violation was triggered even at a low penetration level of 0.28% and the maximum penetration level is attained at 37.68% where the whole system is likely to breakdown due to severe voltage collapse on the distribution system. Based on the simulation results, a mitigation technique for voltage correction has been discussed.

Keywords: *electric vehicle, shunt capacitor, quick charger, home charger*

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1. Introduction

The EV was first launched in Bhutan by the Royal Government of Bhutan (RGoB) in 2014 to reduce high fossil fuel import and greenhouse gas (GHG) emissions from transport sector [1]. In the next 30 to 40 years, electric vehicles can become the most indispensable means of transport around the globe since the depletion of oil resources is becoming a pressing issue [2]. The motivation for electric vehicles seems to be more promising for the world [3]. Bhutan's cheap and clean electricity from hydropower can be the best substitute among other fuel sources for transportation.

Nevertheless, power utilities around the globe are experiencing system constraints due to the growing demand for EVs. This paper investigates the capacity of the 'as-is-where-is' distribution system's performance due to the additional load of EVs. The study was conducted on the existing domestic load and integrated EV load for three scenarios.

In recent years, Bhutan witnessed a rapid increase in the number of conventional cars in the transport sector, thus increasing tones of fossil fuel imports followed by traffic congestion. The depletion of fuel resources and the escalation of global fuel prices are some of the factors that have transformed fossil fuel cars to electric vehicles. Although Bhutan has cheap hydropower generation to fuel up electric cars the power demand for electric vehicles can have numerous consequences on the performance of the distribution system.

The dynamic nature of EV charging can impose a high stability problem on the power system network. The high demand for EV charging will have power stress on the utilities around the globe. For instance, in North America, the power companies had to build extra generating plants to support the additional load of EVs [4]. Voltage stability due to high penetration of EVs is one of the standing challenges faced by new EV adoption [5]. Several studies conducted in the past reported that voltage instability is more significant due to EV charging. Studies have also shown that voltage imbalance is caused by single-phase loads of EVs on the distribution network. Further, the high inrush current drawn by EV charging causes voltage dips for residential customers which often coincide with peak hours of household loads [6]. The studies conducted on the low voltage European Union network indicated that voltage violations at the feeder end were more common with the controlled charging [7].

Haq, Strunz, Cecati & Abbas [8] investigated the voltage imbalance caused by poor charging methods. The study has looked into two charging methods, uncontrolled charging and tariff-based charging. The outcome indicated that uncontrolled charging leads to unbalance voltages that exceed a limit below 2%. Tariff based charging method was enforced to encourage EV owners to charge during valley hours at low tariff mainly to shift the peak hour congestion period. Voltage drops and distribution power losses are the main factors caused by the penetration of a large number of EVs followed by traffic congestion on the road network [9]. The charging characteristics of plug-in hybrid EVs (PHEV) have been investigated to ascertain influence on load profiles due to EV deployment. The studies have indicated that 24-29% of the daily energy consumption has shown an upward trend by charging at public places than charging at home [10]. The impact assessment on the Canadian distribution system concluded that the impact on the system is much more significant with the fast charging system than the slow charger [11]. Impact studies carried on the Chinese distribution system has observed that voltage stability and phase unbalance at a different penetration level of EVs are caused by uncoordinated charging. A similar study has adopted a smart charging technique for maximizing the charging periods and deliver uninterrupted power flow on the system [12]. From these studies, it is evident that with increasing EV penetration, the stability issues of the distribution network are imminent. Therefore, there is a need to investigate up to what level of EV penetration the current distribution system can withstand without upgrading the existing infrastructure along with the normal domestic load growth.

2. Methodology

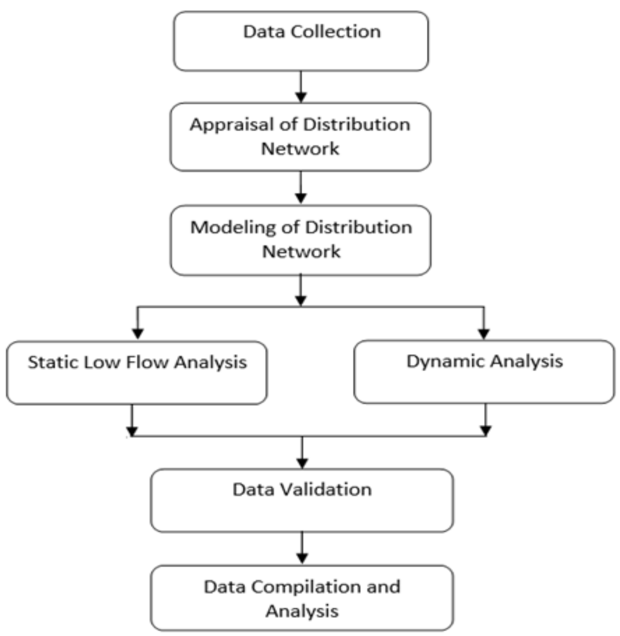

Figure 1. Methodology adopted in this study

Three hypothetical approaches were adopted to assess the impact level of EV penetration on the distribution system. They are short term assessment (Current status-quo); medium-term (Low Uptake) and long term (High Uptake) scenarios. Low and high uptake is based on projection by SAARC Energy Centre's study on "*Action Plan on Electric Utilities Supply of Companies of SAARC Countries to Introduce EV Charging Infrastructure*" [13] but were up scaled to 2050. A model of existing electricity distribution network of Thimphu with EV was developed in the DIgSILENT power factory simulation software using the data obtained from Bhutan Power Corporation (BPC). The model was then simulated to appraise the existing distribution system and validate the simulation results with the measured values. Single line diagram of DIgSILENT model is shown in Appendix. The methodology adopted in this paper is shown in Figure 1.

2.1. Domestic Load Forecast

For any growing town, domestic load growth is inevitable. The domestic load growth was projected based on the average growth of Thimphu from 2004 to 2018 [14] as shown in Table 1 [13]. The above load data shows a compounded annual growth rate (CAGR) of 6.81% over these periods. This was used as an annual load increment in the simulation.

Table 1. Average Peak Load of Thimphu

Year	Average Peak Load (MW)	Year	Average Peak Load (MW)
2004	10.29	2012	18.72
2005	10.46	2013	19.38
2006	10.77	2014	20.76
2007	12.25	2015	21.68
2008	13.64	2016	22.47
2009	14.71	2017	23.74
2010	16.17	2018	25.87
2011	17.32		

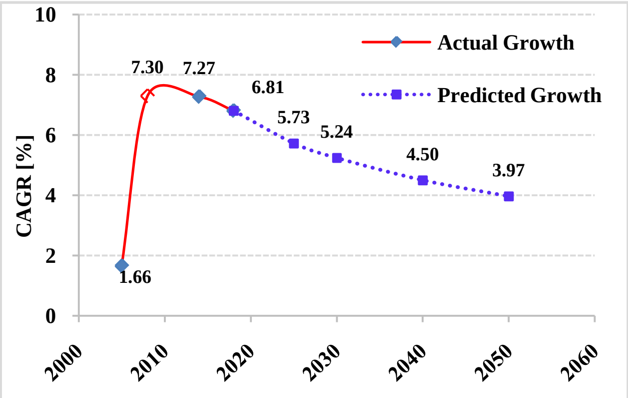

Figure 2. CAGR of Domestic Load of Thimphu (plotted based on [13])

The domestic load growth is expected to drop from 6.81% to 5.73% by 2025. It is further expected to drop to 3.97% by 2050 as illustrated in Figure 2.

2.2. EV Forecast

The number of EVs was forecasted based on three uptake scenarios, the current status-quo, the low uptake level, and the high uptake level. The current status-quo includes the EV strength as of 2019 whereas, for low and high uptakes, a compounded annual growth rate of 10% and 20% [13] respectively have been derived from the vehicular growth trend from 2013 to 2018 as per the historical data [15]. These scenarios include a light vehicle fleet only comprising government, private, and taxi fleets but in the future, the city buses may be also considered. Table 2. shows the estimated growth of electric vehicles by 2050 for different scenarios assuming only light vehicles.

Table 2. Estimated number of Electric Vehicles (2019-2050)

Scenarios	Year	Total EV	Penetration level
Current Status-quo	2019	100	
Low Uptake	2025	587	0.28%
	2030	946	
	2040	2,454	
	2050	6,364	
High Uptake	2025	833	37.68%
	2030	2,074	
	2040	12,842	
	2050	79,512	

According to the National Statistics Bureau of Bhutan, the annual population growth rate is expected to fall from the current level of 1% to 0.3% by 2047. With the population growth so saturating, it is expected that the total vehicle fleet will eventually saturate by 2050. Accordingly, considering the penetration level as the ratio of EVs to the total projected light vehicle fleets of 211,000 by 2050, a penetration level of 0.28% is reached by 2025 for low uptake level and maximum penetration of 37.68% will be attained at 2050 for high uptake level.

2.3. EV Load Forecast

The power demand by the EV is the power drawn through the various Quick Chargers (QC) and Home Chargers (HC) that will be installed at various locations. The power consumption drawn by each QC and HC is 50 kW and 7.4 kW respectively. The probabilistic power demand by EVs in 2019 is around 1.74 MW. For low uptake level, the power required will be around 63 MW and 787 MW for high uptake level by 2050. Table 3 illustrates the total power demand by EVs in the respective years.

Table 3. Estimated Power Demand of EVs for different Uptake Level

Scenario	Year	Total EV	Total QC	Total HC	Load (MW)		Total Load (MW)
					QC	HC	
Status-quo	2019	100	20	100	1.0	0.7	1.7
Low Uptake	2025	587	30	587	1.5	4.3	5.8
	2030	946	50	946	2.5	7.0	9.5
	2040	2454	122	2454	6.1	18.2	24.3
	2050	6364	320	6364	16.0	47.1	63.1
High Uptake	2025	830	40	830	2.0	6.1	8.1
	2030	2070	100	2070	5.0	15.3	20.3
	2040	12842	642	12842	32.1	95.0	127.1
	2050	79500	3980	79500	199.0	588.3	787.3

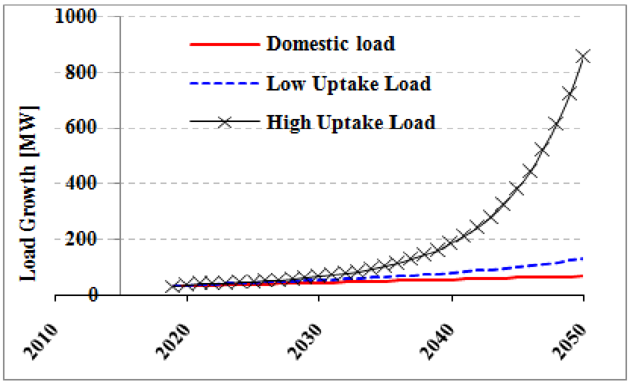

Figure 3. Load forecast for domestic and EVs (2019-2050)

The total load forecast for both EV and the domestic load growth is represented by Figure 3. The cumulative power demand for a low uptake level is around 131 MW and 855 MW for high uptake level by 2050.

2.3. Modeling of Distribution Network with EVs

A base model of Thimphu Distribution Network (TDN) was developed in DIgSILENT power factory simulation software. The core Thimphu town is fed through 11 kV feeders emanating from 33/11 kV substations. The TDN has 118 busbars, 147 nodes, and 250 lines. A total of 304 loads which represent both domestic and the EV loads on the low voltage lines is lumped at the distribution transformer (DT) level. A total of 20 QCs and 100 HCs as shown in Table 4 were used for the base model simulation study. For further simulations of the network, forecasted EV loads for the same year were added.

Table 4. Distribution of QCs and HCs on 11kV feeders

Sl.No	Feeder/Location	QC	HC
1	Babesa	2	11
2	Chubachu	4	14
3	Dechencholing (D/Choling)	4	10
4	DPH	3	13
5	Lungtenphu (L/Phu)	2	12
6	Motithang	3	14
7	RICB	1	13
8	TMH	1	13
	Total	20	100

Each of the QC stations is supplied from a dedicated transformer 11/0.415kV of 63 kVA, three-phase system and the supply to the HC are from the distribution mains of the residential supply system.

3. Results and Discussion

The voltage magnitude and phase angle at each bus, and active and reactive power flow in each element were calculated using DIgSILENT power factory simulation software. It uses the Newton-Raphson iterative method to approximate the correct solution of the power network. This method has more advantages over the other tools as it requires less iteration and is widely used irrespective of the network size [16].

The simulation results show that voltage profiles and the transformer loading are the two factors that impede the performance of the distribution system as the penetration level on the distribution system increases. In the status quo, when the penetration level was just 100 EVs, no voltage violations were observed, however when the penetration level increased to 0.28%, both overload and under voltage violations were observed which are discussed in the following sections.

3.1. Voltage Profiles for Domestic Load with Existing EVs (Current Status Quo)

The voltage profile on all buses was observed above the standard limit of 0.95 p.u. Figure 4 illustrates the voltage profiles for the current status-quo. All bus voltages were observed within 0.98 p.u and 1.0 p.u. range.

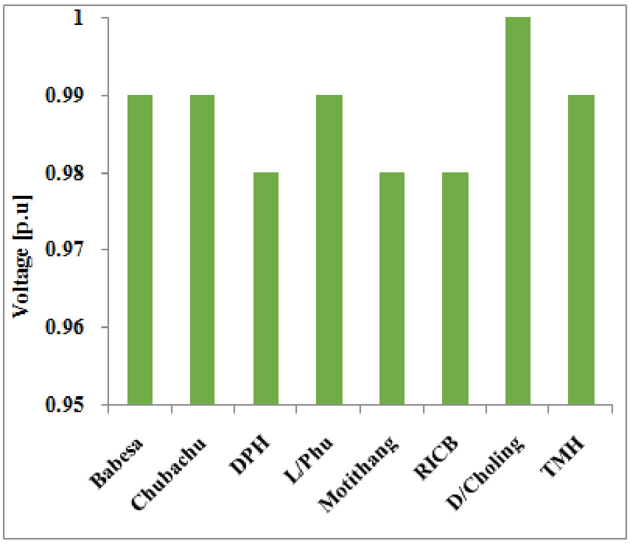

Figure 4. Voltage profile on 11 kV feeders for current status-quo

3.2. Voltage Profiles for Low EV Uptake Level

When the EV penetration level reached 0.28%, the voltage profiles for most of the substation buses fell below the standard limit (0.95 p.u). For instance, the customer at the far end of the RICB feeder suffers from under-voltage. As the penetration increases, the voltage dip on the feeder also increases. When the EV penetration reaches 3.02%, the majority of system elements fail because of severe voltage drops. Major reinforcement of lines and substations will be required to maintain the standard voltage. Figure 5 illustrates the voltage profile for each substation at a different penetration level of EVs.

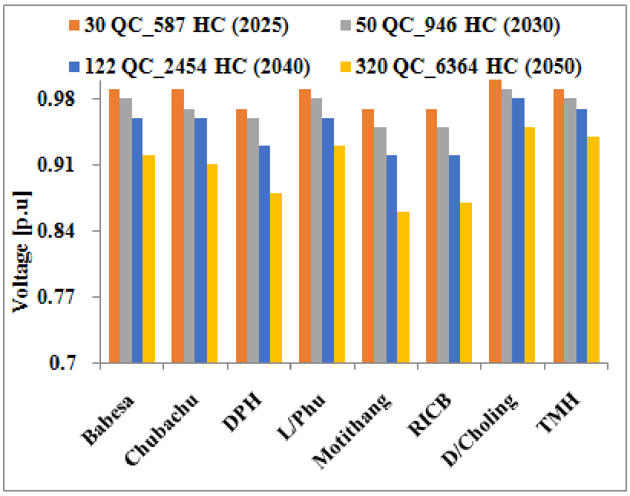

Figure 5. Voltage profile on 11 kV feeders for low uptake level

3.3. Voltage Profiles for High EV Uptake Level

Similarly, for high uptake level, when the EV penetration level reached 0.39%, a low voltage was observed for some customers at the feeder end. The worst case was when the EV penetration level reached 37.68%, the whole system disintegrates due to severe voltage violation on all the substations having as low as 0.1p.u. Figure 6 illustrates the voltage profiles on the various substations buses.

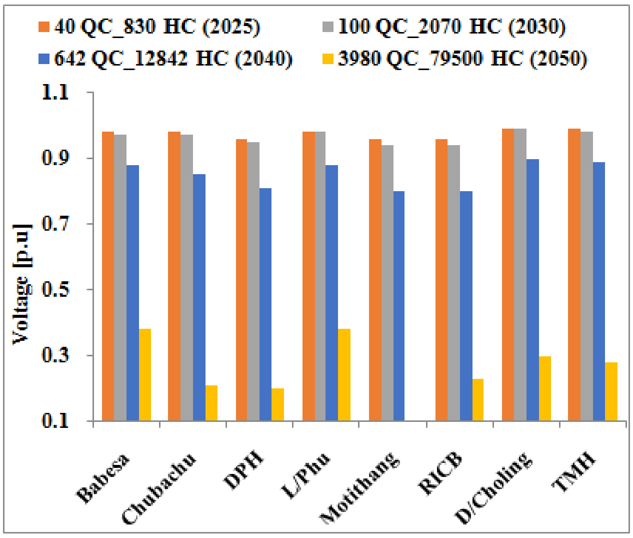

Figure 6. Voltage profile on 11 kV feeders for high uptake level

3.4. Transformer Loading for Current Status-quo

EV penetration at the current status-quo did not see any significant problem. However, the loading conditions for two substations (Motithang and Olakha) were almost 79.98%. The rest of the substations were loaded between 45% to 70%. The 66/33 kV Dechencholing substation was the most lightly loaded with 36.49%. Figure 7 shows the percentage loading of transformers at various penetrations of EVs.

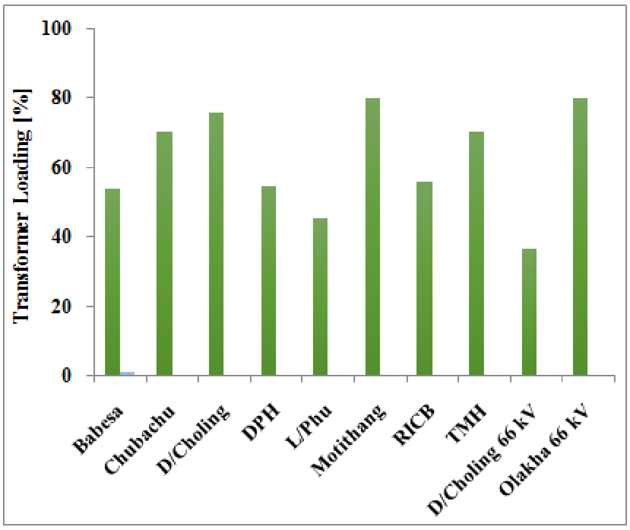

Figure 7. Transformer loading on 11 kV feeders for current status-quo

3.5. Transformer loading for Low Uptake Level

The majority of transformers are loaded beyond 100% of their rated capacities. As normally prescribed by the power utilities, if the loading of transformers exceeds 80% to 90%, it indicates that a contingency plan is urgently needed [9]. The loading on present infrastructure increases by almost 5 times more without any technological improvement on the distribution network. Figure 8 illustrates the percentage loading impact at different penetration of EVs on various substations.

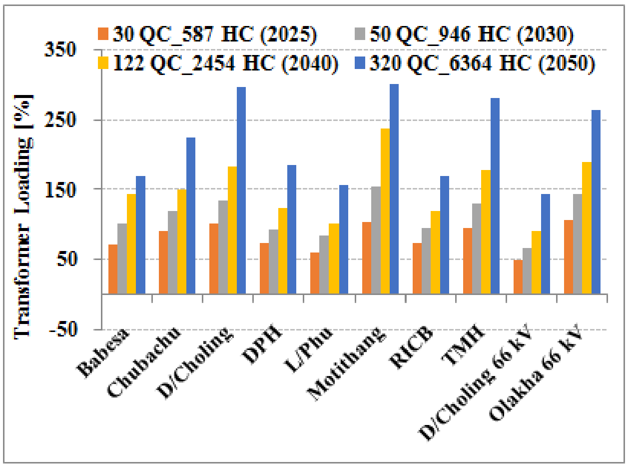

Figure 8. Transformer loading on 11 kV feeders for low uptake

3.6. Transformer loading for High Uptake Level

In the high uptake level, all secondary power transformers are found loaded above 100% except 66/33 kV Dechencholing substation which is at 75.88% when the penetration level reached 0.98%. Beyond this point, loading on transformers will be three times higher by 2030, eight times higher by 2040, and almost eleven times higher by 2050. Figure 9 illustrates the percentage loading impact on various substations.

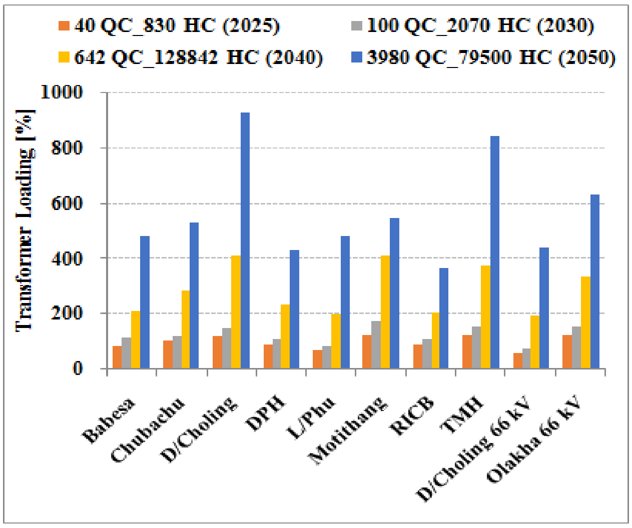

Figure 9. Transformer loading on 11 kV feeders for high uptake

4. Compensation Technique and Improvement Measures

There are various compensation techniques available using devices such as shunt reactors, Static var compensator (SVC), Synchronous condensers, Booster transformers, and LTC transformers [17]. Among others, shunt capacitors can boost voltages at the localised area and is more flexible for deployment in the distribution system. It is cheaper, easy to operate and control, and can be installed at any point in the network [17]. However, for large compensations required, shunt capacitors are not effective and therefore, other methods such as synchronous condensers may be appropriate for use. Table 5 shows the capacitors required for compensating the voltage deficiency on different feeders.

Table 5. Voltage Compensation Requirement for each Substation/Feeders for Low Uptake Level (2050)

Substation	Shunt Compensator		Voltage [p.u]		Install Location
	No	Mvar	Before	After	
Babesa	3	2.9	0.92	0.99	Substation
Chubachu	3	2.9	0.91	0.98	Substation
DPH	6	5.8	0.88	0.98	Substation
Lungtenphu	5	4.8	0.93	1.00	Lungtenphu feeder
Motithang	5	4.8	0.86	0.97	Survey feeder
RICB	10	9.6	0.87	0.99	Substation
Dechencholing	3	2.9	0.95	1.00	Substation
TMH	1	1.0	0.94	0.96	Substation

Although the simulation results show that shunt compensation is effective, this method requires large capacitor banks and will be too costly. For bulk compensation, synchronous condensers are preferred as it can generate reactive power even when input voltages are very low. Also, it can withstand short circuit faults and overload up to 20% [17].

Nonetheless, utilities generally prefer other improvement measures such as the construction of double circuit lines and underground cabling. Construction of additional ring networks and installation of power transformers at various locations, and upgrading the distribution lines from 11 kV to 33 kV voltage levels.

Voltage profiles for both the uptake levels after the compensation are shown in Figure 10. The line graphs depict the voltage profiles before the compensation while the histogram represents the voltage profiles after the compensation [13]. The bus voltages were improved above 0.96 p.u after the compensation.

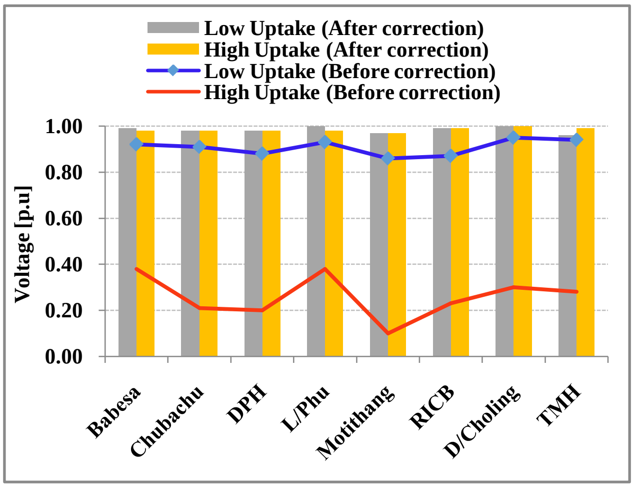

Figure 10. Voltage profiles after adding capacitor banks for high uptake level

5. Conclusions

The purpose of this study was to ascertain up to what level of EV penetration the current distribution system can withstand without undergoing any improvement on the existing infrastructure along with the normal domestic load growth. The assessment was performed separately for existing domestic load and domestic load with EV over the periods from 2019 till 2050 as per the forecast. The analysis indicated that when the EV penetration level reaches 0.28% both low voltage stability and transformer loading violations were observed on some of the distribution networks. The EV penetration on the current status-quo did not foresee any problem, however, as the penetration increases over the periods, both low voltage and overload violations have been observed for both the uptake levels. The worst part was when the EV penetration reaches 37.68% where the whole network will collapse due to poor voltage regulation. The simulation results indicated that voltage instability was the dominant factor for poor stability. Overloading of lines and equipment was the other limiting factor for EV penetration. Both EV and domestic load growth has contributed to the overall instability of TDN. Mitigation methods for both uptake levels were studied and the shunt compensation method was found effective for low voltage corrections.

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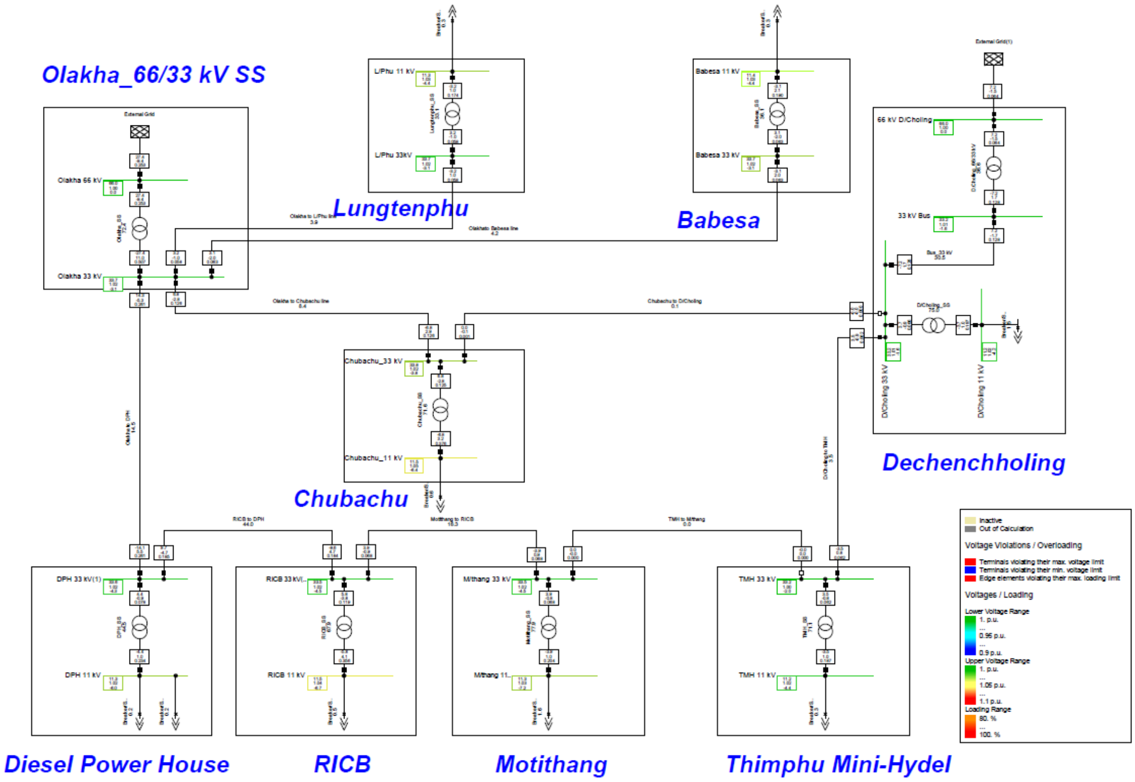
Appendix-1


Olakha_66/33 kV SS
Lungtenphu
Babesa
Dechenchholing
Chubachu
Diesel Power House
RICB
Motithang
Thimphu Mini-Hydel