Impact Analysis of Electric Vehicles on Distribution System

Ajay Kumar Jha, Rabin Shrestha

Abstract - With the vision of reducing the dependency on petroleum products for transportation and maximize the consumption of electricity generated, the GoN and NEA has set up plans to encourage the use of Electric Vehicles (EVs). EVs not only reduces the consumption of petroleum products for transportation but also helps in pollution free transportation. In order to compete with petroleum-based transportation, NEA has plans to set up EV charging station as many as possible. The increased number of charging station will increase the penetration level of EVs in the Distribution System.In this study of Impact Analysis of Electric Vehicles (EVs) on Distribution System, the effect of different penetration level of EV battery charging on Distribution System is analyzed. This thesis presents a methodology for modelling and analyzing load flow and harmonic analysis in a distribution system due to EVs. This study focuses on voltage deviation, line loss and total harmonic distortion caused due to different penetration level of EVs in the system. For the study purpose ETAP software is used and impacts on Patan feeder are studied on different cases of load periods and with and without EV penetration as well. Voltage Deviation and Line Loss are found to be increased at peak demand period with the increased EV penetration while THD is found to be increased at off peak period with the increased EV penetration. This is because at off peak period, with the increased EV penetration, the EV load is very high.

Keywords: **Electric Vehicles; Distribution System; Penetration Level; Load Flow; Line Loss; Harmonics; Power Quality**

1 BACKGROUND

The Government of Nepal (GoN) has to set a long-term vision to replace the use of Liquefied Petroleum Gas (LPG) and substantially reduce the consumption of petroleum products. The power utility company i.e., Nepal Electricity Authority (NEA) has plan to set up high-capacity batteries to consume the surplus power during off-peak hours and supply the power to manage the load of peak hours. Betting on the surplus in Nepal Power System after the completion of the 456 Mega Watt Upper Tamakoshi Hydroelectric Project (UTHEP), NEA is taking the initiative to promote electric vehicles for competent management of the surplus power. The power utility Company NEA has planning to install charging stations in different places of major cities to encourage people to shift to Electric Vehicles (EVs).

With the increase in generation of electricity, NEA has made plans to maximize the consumption of electricity by encouraging the charging of EVs during off peak and medium peak period through the reduction of tariffs in such periods. Charging during peak load period will definitely have impacts on Distribution System impacting Voltage Profile and Line Loss but increased EV penetration during off peak period will also have negative impacts on Distribution System. It will introduce harmonics in the system and eventually reduce the Power Quality of the system.

Power quality is one of the emerging issues to be addressed by a power system engineer. It is desirable that the system voltage and frequency limit not be violated beyond its prescribed limit. Similarly, the harmonics content of the system should be fundamental as can be possible by any means. The total harmonic distortion should be within the acceptable limit. According to the IEEE standard 519-1992 THD should be maintained within 5%.("IEEE Recommended Practices and Requirements for Harmonic Control in Electric Power Systems, 1992). If the THD is not maintained, then this might cause the power quality problems.

2. LITERATURE REVIEW

1.1 EV Charging Methods

There are basically 3 types of EV charging methods and they are briefly described below:

1.1.1 Battery Swap System (BSS)

This is based on paying monthly rent for the battery to the BSS owners. This method adopts slow charging technologies which helps to extend the battery life. (Ahmad *et al.*, 2018) It is much easier to integrate locally generated Renewable Energy Sources (REs) like Solar and Wind with the BSS system. This system allows the drivers to stay inside the vehicle and the discharged battery can be replaced quickly. Moreover, the battery kept at the BSS can be used in the V2G initiative. (Gschwendtner, Sinsel and Stephan, 2021)

1.1.2 Wireless Power Transfer (WPT)

This method is based on Electromagnetic Induction (EMI) and consists of two coils; primary coil and secondary coil. Primary coil is placed on the road's surface and secondary coil is placed inside the vehicle. This technique is gaining popularity recently due to its ability to enable the EV to recharge conveniently and safely. It has also advantage of charging while the vehicles in motion. (Sanguesa *et al.*, 2021)

Conductive Charging (CC)

This technology requires electric connection between the vehicle and charging inlet and has high efficiency in charging due to its direct connection.

Different types of charging facilities used under this technology are as follows:

- Level 1 charger
- Level 2 charger
- Level 3 charger

Level 2 and Level 3 are employed for a public charging station

Table 1 Charging Power Level (Yilmaz and Krein, 2013)

Power Level	**Converter**	**Usage**	**Expected Power**
Types	**Location**		**Level**
Level 1	On Board	Home and	1.44 kW (15A)
120V AC	Single Phase	Office	1.92 kW (20A)
		Residential	3 kW (16 A)
Level 2	On Board	Outlet	6 kW (32A)
208V AC	Single Phase	Commercial	15.5 kW (80A)
240V AC		Outlet	
Level 3		Commercial	50 kW
480V AC	Off Board	Fast Charging	100 kW
600V DC	Three Phase	Station (FCS)	250 kW

Due to the increasing number of EVs, Society of Automobile Engineers (SAE) has proposed AC and DC charging standards for the US and EU considering the voltage and current levels as shown in Table 2.

Table 2 SAE Standards Current and Voltage Level for AC and DC Charging

Standards	**Phase**	**Level**	**Voltage(V)**	**Current(A)**	**Source**
SAEJ1772	Single	1	120	16	AC
	Single	2	240	32-80	AC
	DC	1	200-450	80	DC
	DC	2	200-450	200	DC

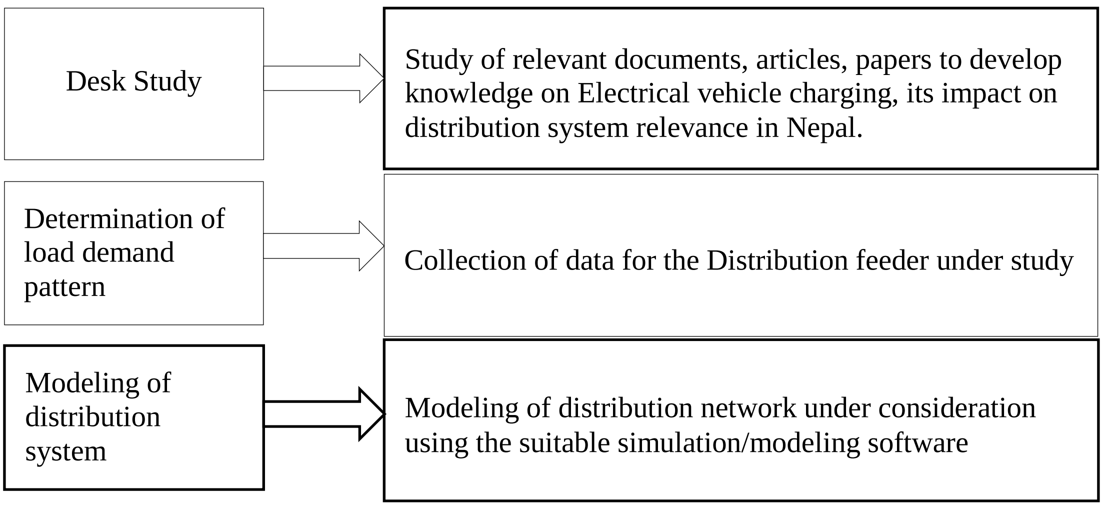
An electric grid consists of generation, transmission, and distribution systems. The generation system composed of power plants that generate electricity from a variety of sources such as coal, gas, solar, wind etc.

The transmission system consists of transmission lines that transfers electricity between generation and distribution systems, and it also includes transformers to step up the electricity to the higher voltage. The distribution system mainly consists of substations, and transformers to step down the electricity to a level used by end-use customers; usually 230/400 V for residential customers, and larger voltage levels for some commercial and industrial customers. The impact of EV charging on the electric grid as a whole is mainly influenced by two aspects; (1) the level of EV penetration, and (2) the point in time and the duration of EV charging. (Bunga, Eltom and Sisworahardjo, 2014)

3. METHODOLOGY

The outline of this work begins from the literature review, in which the electric vehicle charger and its impact on voltage profile of the distribution network, when integrated to the existing network is studied. The distribution system is modelled in ETAP and simulation, Load Flow and Harmonic Analysis is performed.

The study was carried out by following the frame work as shown in **Error! Reference source not found.**.



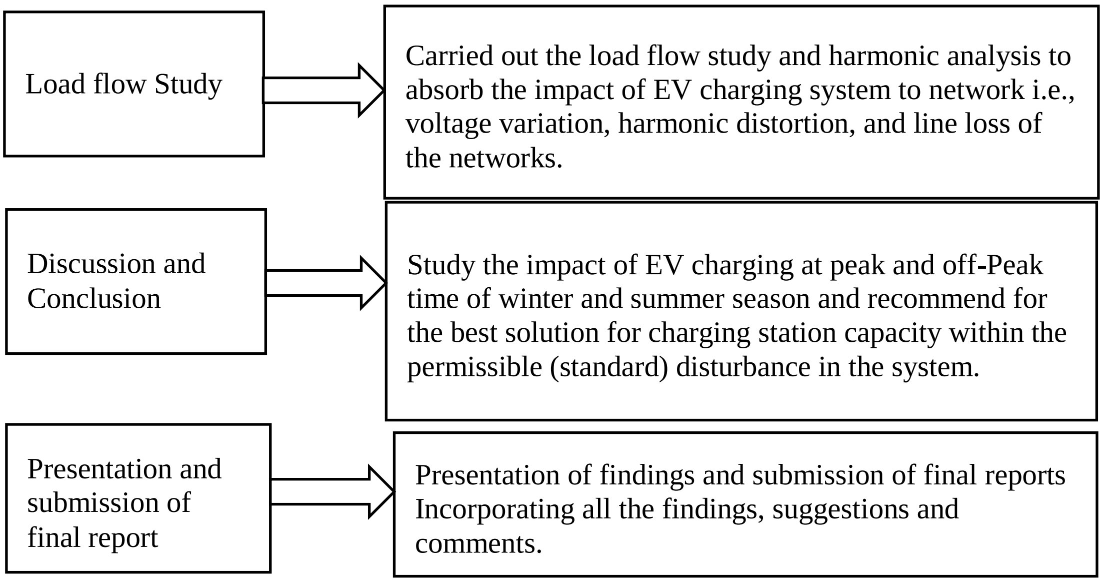


Figure 3-1: Research Framework

Selection of Distribution Feeder

The modelled Distribution System is a radial system, receiving power from a three-phase source at 11 kV. The selected feeder is Patan Feeder under Pulchowk DCS as it comprises of two charging stations located at Sajha Charging Station and Labim Mall Charging Station. There are altogether 18 transformers connected to this feeder. . Transformers of rating 200 kVA and 1000 kVA are installed at Sajha and Labim Mall Charging Station respectively. Patan Feeder of Pulchowk DCS, as represented by GIS map as shown in Figure 2 was selected for the study

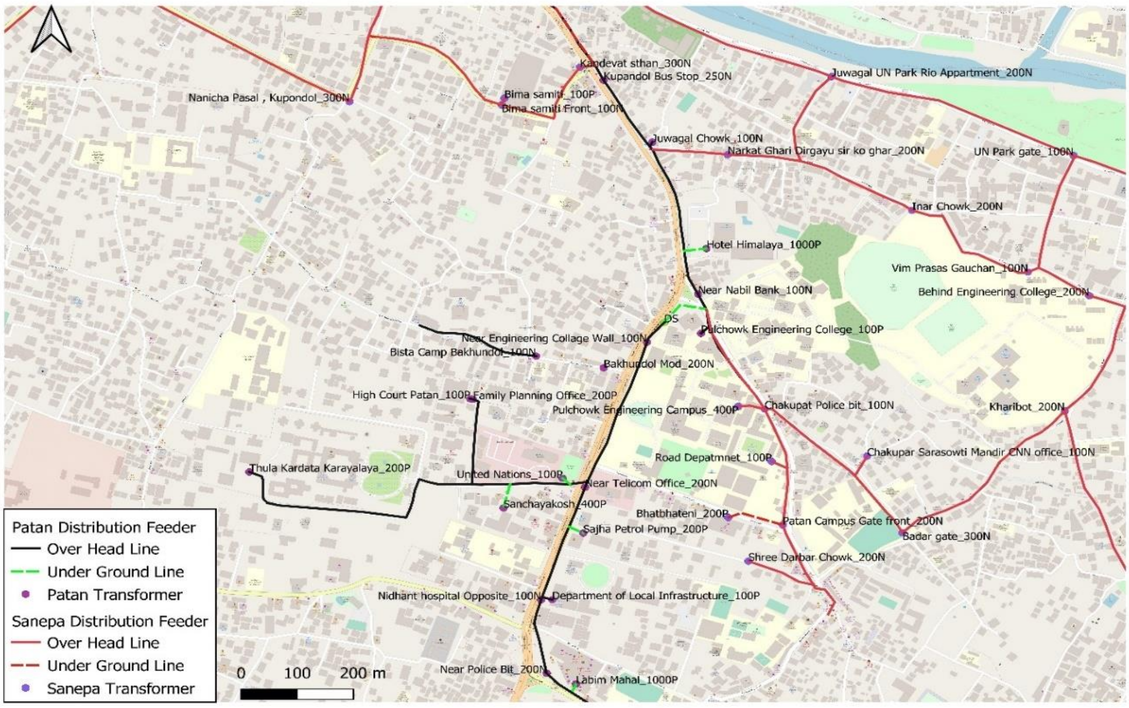


Figure 2 GIS map of Patan Feeder, Pulchowk DCS (source: Pulchowk DCS)

Electrical Transient Analyzer Program (ETAP)

Electrical Transient Analyzer Program (ETAP), software is the main tool used for the simulation of test system in our case. ETAP is the most comprehensive analysis platform for the design, simulation, operation, control, optimization, and automation of generation, transmission, distribution, and industrial power systems.

Inside the ETAP simulation, there are different simulators like Load Flow Analysis, Transient Stability Analysis, Optimal Power Flow, Optimal Capacitor Placement, and Reliability Analysis & Short Circuit Analysis and also Harmonic Load Flow Analysis.

Among the above, the Load Flow Analysis is used for primary purpose on the constructed Test System, which is run to find the bus Voltage Profile, Line Losses, Reactive and Active Power Flow through the lines and also THD.

Distribution System Load Data Analysis

As the enough load data were not provided by the power distributor, some assumptions have been made as per the charging time slots characterized by NEA. As per NEA, the charging time slots and rate are as follows:

Table 3 Charging slots as per power demand under the study

Charging Slots	Time	Rate (Rs)
Off Peak Hours	11 PM – 5 AM	3.70
Medium Peak Hours	5 AM – 5 PM	5.50
Peak Hours	5 PM – 11 PM	7.00

Keeping this table in mind, and due to lack of enough load data, the load data for Off Peak Hours, Medium Peak Hours and Peak Hours are divided by 25%, 50% and 75% loading of Distribution Transformers as per their kVA ratings. The power factor is assumed to be 0.85.

4. RESULTS AND DISCUSSION

4.1 Voltage Profile without EV Penetration

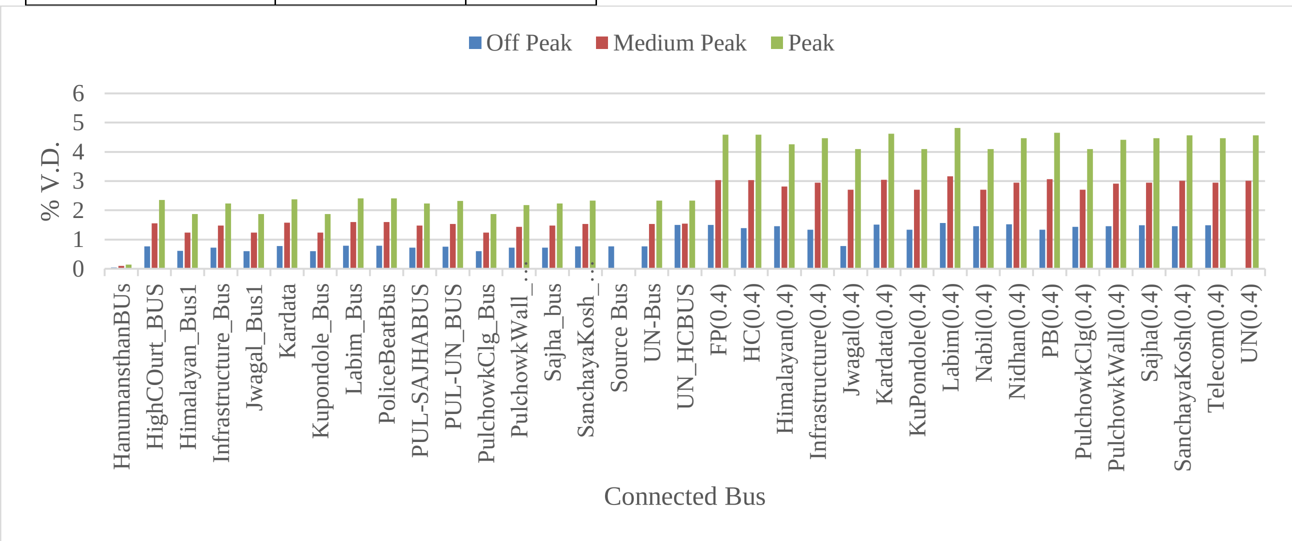


Figure 3 % Voltage Deviation at different bus at different power demand without EV penetration

4.2 Line Loss without EV Penetration

Table 4 Line Loss at different power demand without EV Penetration

Power Demand	**Line Loss**	
	P(kW)	**Q(kVAR)**
Off Peak Demand	10.9	13.6
Medium Peak Demand	44.4	55.4
Peak Demand	102	127

4.3 EV Penetration at Sajha and Labim Mall Charging Station at different power demand

Table 5 EV Penetration when both Sajha and Labim operating at the same time

Sajha & Labim Mall	**kVA Rating**	**Off Peak**		**Medium Peak**		**Peak**	
		P(kW)	**Q(kVAR)**	**P(kW)**	**Q(kVAR)**	**P(kW)**	**Q(kVAR)**
10%	1200	76.5	47.7	51	31.8	25.5	15.9
20%	1200	153	95.4	102	63.6	51	31.8
30%	1200	229.5	143.1	153	95.4	76.5	47.7
40%	1200	306	190.8	204	127.2	102	63.6
50%	1200	382.5	238.5	255	159	127.5	79.5
60%	1200	459	286.2	306	190.8	153	95.4
70%	1200	535.5	333.9	357	222.6	178.5	111.3
80%	1200	612	381.6	408	254.4	204	127.2
90%	1200	688.5	429.3	459	286.2	229.5	143.1
100%	1200	765	477	510	318	255	159

This table shows active and reactive power consumed by Sajha and Labim Mall Charging Stations operating simultaneously at different penetration level of EVs and at different power demand.

Voltage Profile at different cases of EV Penetration **Twenty Percent EV Penetration**

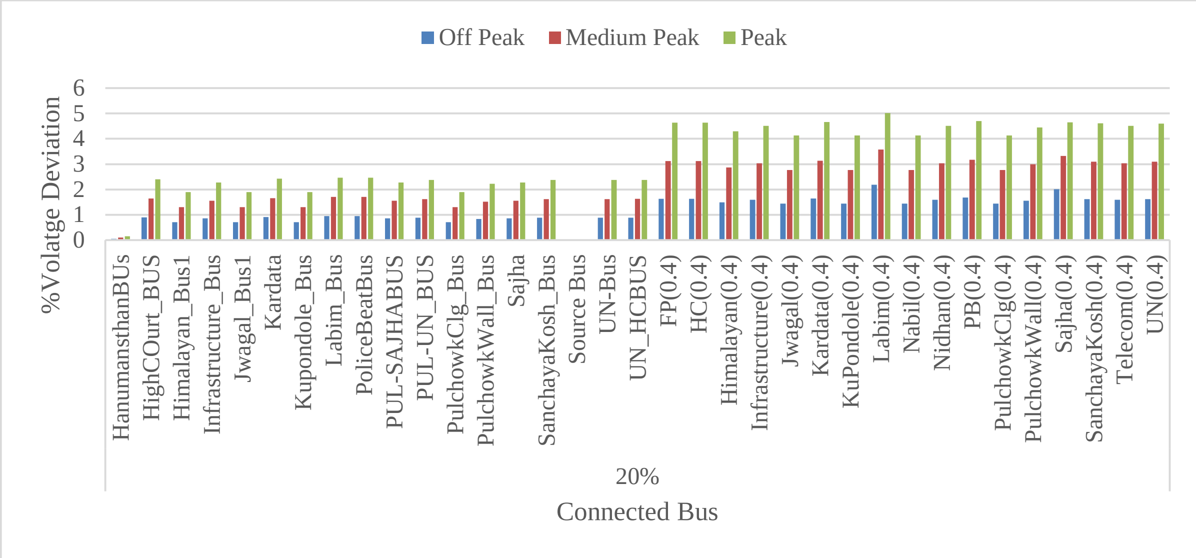


Figure 4 %Voltage Deviation at different Bus at different power demand at 20% EV Penetration when Sajha and Labim Mall Charging station operating simultaneously

4.4.2 Fifty Percent EV Penetration

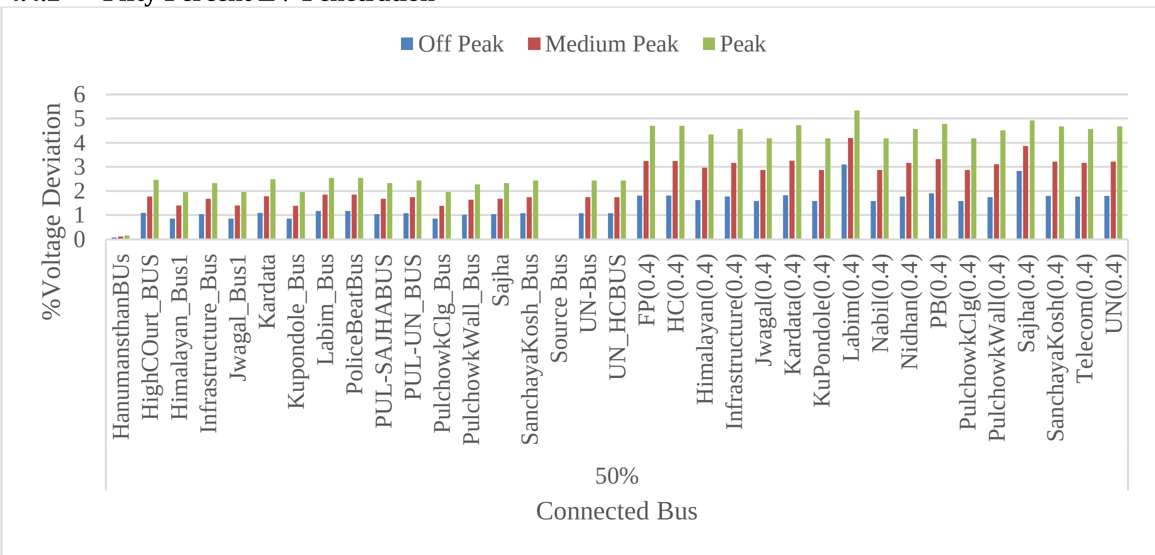


Figure 5 %Voltage Deviation at different bus at different power demand at 50% EV Penetration when Sajha and Labim Mall Charging station operating simulatneously

Eighty Percent EV Penetration

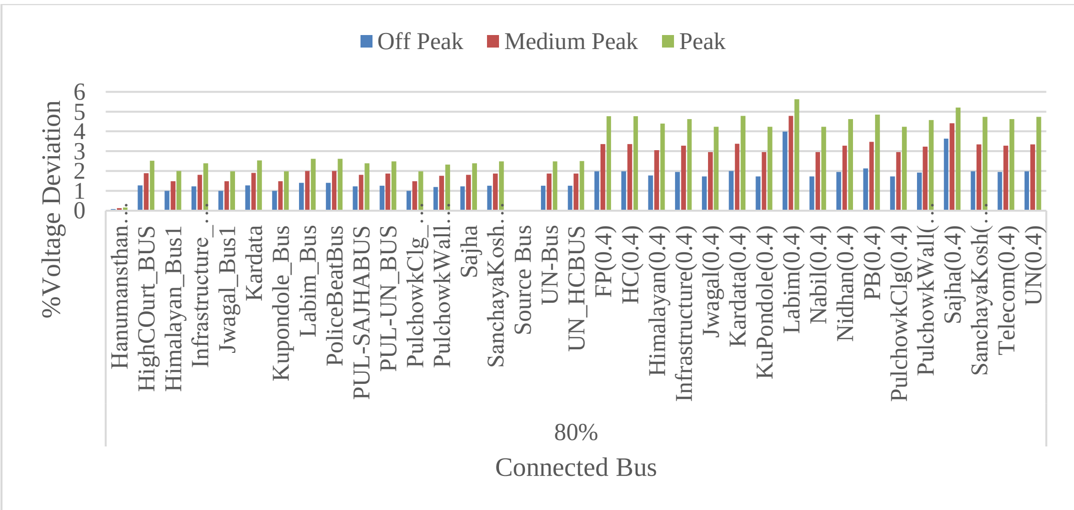


Figure 6 %Voltage Deviation at different bus at different power demand at 80% EV Penetration when Sajha and Labim Mall Charging station operating simulatneously

From above results, it is clear that the percentage voltage deviation goes on increasing with the increased EV Penetration. Voltage Deviation is higher on Peak Demand.

4.5 Line Loss with EV Penetration

Table 6 Line Loss at different power demand at different EV Penetration Level when Sajha and Labim Mall Charging Station operating simultaneously

EV Penetration Level (%)	Power Demand					
	Off Peak		Medium Peak		Peak	
	P(kW)	Q(kVAR)	P(kW)	Q(kVAR)	P(kW)	Q(kVAR)
10	12.8	16.3	46.8	58.8	104	130
20	14.9	19.6	49.3	62.4	105	132
30	17.2	23.6	51.9	66.2	107	135
40	19.7	28.2	54.6	70.4	109	137
50	22.3	33.3	57.3	74.8	111	140
60	25.2	39.1	60.2	79.4	113	143
70	28.3	45.4	63.1	84.3	115	146
80	31.6	52.3	66.1	89.5	117	149
90	35	59.7	69.2	94.9	119	152
100	38.6	67.7	72.4	101	121	155

From above results, it is clear that Line Loss goes on increasing with the increase in EV Penetration Level. Line loss is greater at Peak Demand period.

4.6 Total Harmonic Distortion

Table 7 Total harmonic Distortion at different demand at different EV Penetration Level when Sajha and Labim Mall Charging Station operating simultaneously

EV Penetration Level (%)	Power Demand					
	Off Peak		Medium Peak		Peak	
	Sajha	Labim	Sajha	Labim	Sajha	Labim
10	1.69	1.77	0.92	0.986	0.392	0.429
20	3.16	3.34	1.78	1.91	0.775	0.847
30	4.46	4.76	2.58	2.79	1.15	1.25
40	5.62	6.04	3.33	3.62	1.51	1.65
50	6.68	7.72	4.05	4.41	1.86	2.04
60	7.64	8.31	4.72	5.15	2.2	2.42
70	8.53	9.32	5.36	5.87	2.54	2.79
80	9.35	10.26	5.96	6.55	2.86	3.15
90	10.11	11.13	6.54	7.2	3.18	3.51
100	10.83	11.96	7.09	7.82	3.49	3.85

From above results, it is clear that Total Harmonic Distortion goes on increasing with the increase in EV Penetration Level. Total Harmonic Distortion is greater at Off Peak Demand period.

5. CONCLUSIONS

Following conclusions are drawn out based on the results obtained and specific objectives of the study:

- Voltage Deviation and Line Loss goes on increasing with the increase in power demand even without EV Penetration. Maximum Voltage Deviation is 4.82% at Labim Bus at peak demand period. Line Loss is maximum at peak demand period and is 102 kW.
- The impacts of EVs in Distribution has been realized by increasing the Penetration Level of EV in the system. For same percentage EV Penetration but for different demand period, kW and kVAR Penetration of EV is different. For example: at Off peak period, Medium Peak and Peak period, 10% EV Penetration is equal to 12.75 kW, 8.5 kW and 4.25 kW respectively at Sajha Charging Station, while corresponding values are 63.75 kW, 42.5kW and 21.25 kW respectively for Labim Mall Charging Station and when both stations are operating simultaneously, corresponding values are 76.5 kW, 51 kW and 25.5 kW respectively.
- With the increase in EV Penetration level at different periods, Voltage Deviation and Line loss increases. Maximum Voltage Deviation is 5.83% at Labim Bus at 100% EV Penetration (255 kW EV load) during peak period and Line loss is equal to 121 kW, which is also highest at the same period and same penetration level

when both Sajha and Labim Mall Charging station are operating simultaneously.

- THD also goes on increasing with the increase in EV Penetration Level, but the major difference is that THD is greater at Off Peak demand than that in Peak demand because power consumed by EV load is greater in Off Peak Period at the same penetration level as explained above.
- When Sajha Charging Station is operating alone, then THD limit (5%) is crossed at 50% EV Penetration (i.e., 63.75 kW EV Load) during Off Peak Period while THD limit is crossed at 90% EV Penetration (i.e., 76.5 kW EV Load) during Medium Peak Period.
- When Labim Mall Charging Station is operating alone, then THD limit (5%) is crossed at 40% EV Penetration (i.e., 255 kW EV Load) during Off Peak Period while THD limit is crossed at 70% EV Penetration (i.e. 297.5 kW EV Load) during Medium Peak Period.
- When Sajha and Labim Mall Charging Station are operating simultaneously, then THD limit (5%) is crossed at 40% EV Penetration (i.e., 306 kW EV Load) during Off Peak Period while THD limit is crossed at 60% EV Penetration (i.e., 306 kW EV Load) during Medium Peak Period.

6. SUGGESTIONS AND RECOMMENDATIONS

EVs are estimated to become a means of electrifying road transportation through technological advances and need for eco-friendly solutions. With the adoption of EVs, a challenge to the existing infrastructure of the electrical grid in terms of generation, transmission and mainly distribution will arise; as higher EV penetration may introduce new peaks into the system, which may cause overloading in electrical distribution components and cause power quality problems. Also with the higher EV penetration, there will be increase in the use of converters; which causes rise in THD and finally reducing power quality.

This study examines the impacts of EV battery charging on a 11 kV Distribution System at various penetration level of EVs. The existing Distribution System; Patan Feeder of Pulchowk DCS is modelled and simulated using ETAP software. This study is focused on voltage deviations, line loss and total harmonic distortion. With the increase in EV penetration level, it has been found that voltage deviations, line loss and total harmonic distortion are increased causing negative impacts in power quality of the Distribution System. Even THD limit violation has also been observed at higher penetration level of EVs.

Since these challenges will be inevitable with the increased adoption of EVs, smart or coordinated charging, optimization of grid, use of harmonic filters will be indispensable to meet the new energy requirements without straining the infrastructure.

As already mentioned in limitations, this thesis doesn't consider the contribution of other renewable resources like wind and solar power in the system. Further study can be done to study the impacts of EV combined with the contribution of solar and wind power. Bidirectional EV charging is not also considered due to its unavailability in Nepal so future studies can be done regarding bidirectional charging also. Last but not the least, the design of Harmonics Filter to tackle harmonics introduced by EV Penetration in the system, can be of good research material.

REFERENCES

1. Giordano, G. (2018) 'Electric vehicles', Manufacturing Engineering, 161(3), pp. 50–58.
2. Ul-Haq, A. et al. (2015) 'Impact of Electric Vehicle Charging on Voltage Unbalance in an Urban Distribution Network', Intelligent Industrial Systems, 1(1), pp. 51–60.
3. Sher, H. A., Addoweesh, K. E. and Khan, Y. (2013) 'Harmonics Generation, Propagation and Purging Techniques in Non-Linear Loads', An Update on Power Quality.
4. Ramaswamy, P. C. et al. (2016) 'Impact of Electrical Vehicles on Distribution Network; Real World Case Studies', Cired Workshop Paper.
5. Aziz, M. et al. (2015) 'Utilization of Electric Vehicles and Their Used Batteries for Peak-Load Shifting', Energies Journal.
6. Abdullah, M. A. et al. (2016) 'Impact of EV Charger Load on Distribution Network Capacity: A Case Study in Toronto', Canadian Journal of Electrical and Computer Engineering.
7. Kazerooni, M. et al. (2012) 'Impact Analysis of EV Battery Charging on the Power System Distribution Transformers', International Electric Vehicles Conference, Greenville.
8. Gomez, J.C. and Morcos, M. M. (2003) 'Impact of EV battery chargers on the power quality of distribution systems', IEEE Trans. Power Delivery, vol.18, pp. 975-981.
9. Lu, Y. and Jiang, J. (2005) 'Harmonic-study of electric vehicle chargers', IEEE International Electrical Machines and Systems Conf., vol. 3, pp. 2404-2407.
10. Lu, Y., Zhang, X. and Pu, X. (2006) 'Harmonic Study of Electric Vehicle Chargers', Proceedings of the CSU-EPSA, vol. 18, pp. 51-54.
11. Chan, C. C. and Chau, K. T. (1997) 'An overview of power electronics in electric vehicles," IEEE Transactions on Industrial Electronics, Vol. 44, No. 1, pp. 3-13.
12. Chen, Z. (2003) 'Harm of Harmonic in Power Supply System and Suppressing Technique', Electric Switchgear. vol. 6, pp.1-5.
13. Pan, A. and Zhu, Y. (2016) 'Harmonic Research of Electric Vehicle Fast Chargers', IEEE PES Asia-Pacific Power and Energy Conference.
14. Trovao, P. J. et al. (2011) 'Electric Vehicle Chargers Characterization:Load Demand and Harmonic Distortion', Proceeding of the International Conference on Electrical Power Quality and Utilisation, EPQU.
15. Kutt, L. et al. (2014), 'Electric Vehicle Charger Load Current Harmonics variation due to supply voltage level differences-Case Example', 2014 International Symposium on Power Electronics, Electrical Drives, Automation and Motion, SPEEDAM.
16. Malano, A. A., Muller, S. and Meyer, J. 'Harmonic Interaction of Electric Vehicle Chargers in a Central Charging Infrastructure', Proceedings of International Conference on Harmonics and Quality of Power, ICHQP.
17. Bunga, S. K., Eltom, A. H. and Sisworahardjo, N. (2014) 'Impact of Plug-in Electric Vehicle battery charging on a distribution system', 2014 IEEE Industry Application Society Annual Meeting, IAS 2014.
18. Gschwendtner, C., Sinsel, S. R. and Stephan, A. (2021) 'Vehicle-to-X (V2X) implementation: An overview of predominate trial configurations and technical, social and regulatory challenges', Renewable and Sustainable Energy Reviews, 145, p
19. Ahmad, A. et al. (2018) 'A Review of the Electric Vehicle Charging Techniques, Standards, Progression and Evolution of EV Technologies in Germany', Smart Science, 6(1), pp. 36–53.
20. Yilmaz, M. and Krein, P. T. (2013) 'Review of battery charger topologies, charging power levels, and infrastructure for plug-in

electric and hybrid vehicles', IEEE Transactions on Power Electronics, 28(5), pp. 2151–2169
21. Papadopoulos, P. et al. (2012) 'Electric vehicles' impact on British distribution networks', IET Electrical Systems in Transportation, 2(3), pp. 91–102.
22. Sanguesa, J. A. et al. (2021) 'A Review on Electric Vehicles: Technologies and Challenges', Smart Cities, 4(1), pp. 372–404

Ajay Kumar Jha and Rabin Shrestha, Department of Mechanical and Aerospace Engineering, Pulchowk Campus, Institute of Engineering, Tribhuvan University, Nepal