

Probabilistic Impact Assessment of Electric Vehicle Charging on Malaysia Low-Voltage Distribution Networks

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Abstract

The increasing number of Electric Vehicles (EV) charging on electricity distribution network could have a significant impact on the planning and operation of a power system network. This paper presents a case study investigating the impact of EV charging on a typical Malaysia residential Low-Voltage (LV) network by using OpenDSS as well as Monte-Carlo simulation approach. The residential LV network sample is provided by the local power utility (namely TNB). Some rearrangement of consumer load connection to feeders was made to comply with the utility requirement. In addition, the LV network has been modelled in detail to take into account the neutral wire and the self and mutual impedance of the cable. The impact of the EV charging on both newly developed residential areas and mature residential areas were evaluated in terms of voltage profile, voltage unbalance, feeders and transformer thermal limit as well as network losses. Results from the presented studies indicate that the LV network in Malaysia can safely accommodate up to 20% and 30% of EV penetration level for a mature residential area and newly developed residential area, respectively. Voltage unbalance and feeder's thermal loading overload are the main issues due to EV penetration. Furthermore, it is important to mention that the impact of EV is very locational and network dependent.

Keywords: Artificial Feeding, Bakhazr County, Qanat, Migration Motivation

1. Introduction

Increases in fuel prices and concern over environmental issues have led to popularity of Electrical Vehicle (EV) which has low carbon emission during operation. In Malaysia, the transportation sector contributes the second highest in carbon emission¹. Malaysia ratified the Kyoto Protocol in 2002 and pledged to reduce 40% of CO₂ intensity by 2020 referred to 2005 level^{1,2} and the introduction of the EV was one of the measures to achieve such commitment. Several policies such as National Automotive Policy³ and incentive remit taxes for importing the EV to Malaysia⁴ are being introduced by the Malaysian government in order to promote EV take up. With the current technology, EV users are likely to charge their cars at home with a single phase socket outlet for Level 2 charging⁵. However, this phenomena will introduce a new high electric demand to the electricity network, particularly

on the distribution level⁶ which will led to impact the current distribution network in several ways, such as voltage limit violation⁷ and thermal overloading⁶. Therefore it is crucially important for utility company to understand the potential impact of EV penetration on the electricity distribution network. A comprehensive model with consideration of US's context is proposed by Shafie et al.⁸ to investigate the impact of PHEV toward LV network in term of peak load increase, network losses and voltage deviation. Research shows that peak load and loss increment are the main issues that will be faced with the increment of EV penetration. Worst case scenario approach is being performed by Richardson et al.⁷ where impact of various EV penetration level toward LV network in term of voltage level and components' thermal loading are presented.

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The research shows that for a 20-40% penetration of EVs, the test network reached the limits of safe operation. Monte Carlo approach and deterministic approach are being used and result being compared by Leou et al.⁹ where impact of EV in term of voltage drop and feeder thermal loading are being assessed. The research conclude that deterministic approach is useful for worst and average case scenario studies, however Monte Carlo approach is suitable where there are various uncertainties need to take into account. Most of the studies are based on the European and US context where the studies were carried out based on the distribution networks configuration and parameters which could be very different from Malaysia. Therefore, it is necessary to perform the studies based on Malaysian distribution network and Malaysian context in order to understand the potential technical impacts of EV charging into the Malaysian distribution network. Therefore, this paper presents a case study investigating the technical impacts of EV charging on LV distribution network. More importantly, Monte Carlo approach is adopted in this research in order to take in to account the uncertainties that the utility company that might face with respect to EV charging location, starting time and charging energy required.

2. LV Network Modeling

Taman Impian Putra, a newly developed residential area located in Port Dickson, Malaysia, was chosen as the reference network¹⁰. This LV network information was provided by Tenaga Nasional Berhad (TNB), the electric utility company in Malaysia. The given data are the cable types, cable rating, number of main feeders, and transformer rating. The LV network is a three-phase four wire radial system with a number of LV feeders emanating from the LV busbar of the 11 kV/400V distribution transformer and the network diagram is shown in Figure 1. Since the detailed network topology data is not readily available; a site visit was made to estimate the network path and its associated length. Some load and feeders rearrangement were carried out in order to comply with TNB's requirement of 50% feeders and transformer maximum loading at the initial design stage. Consumers are assumed to be evenly distributed along the feeders. The sizes and types of cable used in this LV network are shown in Table 1.

This residential area consists of a mixture of 3 different types of houses, namely terrace houses, semi-detached

houses and bungalows with an assumed average after diversity maximum demand of 1.5kW, 5kW and 8kW respectively¹¹. All consumers are modeled as constant power load with power factor of 0.95. Apart from the newly developed residential area, a matured network was also considered in this study. The matured network case assumes that Taman Impian Putra has annual demand growth of 2% or 3% over the 10 years, which experience 25% of load growth from its original level¹¹. The feeders loading condition for the newly developed and matured residential area are shown in Table 2.

Table 1. Cable type and size that used in this LV network

Branch section		Type of Cable
From	To	
500kVA Transformer	Bus 2	4 X 500 mm ² PVC/ PVC AL.
750kVA Transformer	Bus 2	7 X 500 mm ² PVC/ PVC AL.
Bus 2	Piecing connection A,B,C,D, E, F, G	185 mm ² 4C AL. XLPE
Piecing Connection A,B,C,D, E, F, G	Node	Aerial Bundle Cable (ABC) 3 x 185 mm ² + 120mm ² AL.
Node	House	16 mm ² PVC/PVC Cu.

The Open Distribution Simulation Software (OpenDSS) developed by the Electric Power Research Institute¹² was used as simulation tool to model the network.

Besides, the self-impedance and mutual-impedance of the cable are being considered in this work in order to model the given LV network more accurately and was modeled by the methods as described in the literature¹⁰. In addition, the neutral wire was also considered in the LV network modeling.

3. Consumer Demand Modeling

A typical aggregated Malaysian domestic load shape as shown in Figure 2 was used in this study¹³. The 24-hour load shape was assigned to each of the houses located across the network. It can be noted that the residential consumer demand starts to increase in the evening at about 5pm when people start coming home after work and reaches the maximum at 7pm, and this high demand continues until midnight. This is due to the warm weather in Malaysia where it is common for the consumers to switch on their air-conditioners during the evening to night time, which contributes to the above average demand during the evening to midnight period.

On the other hand, the demand is at the lowest during the working hour period (9am to 4pm) where the residents are out for school or work¹³. This is very different from the house demand in other countries such as the UK, where the demand is lowest during mid night¹⁴. Figure 3 shows the domestic unrestricted profile for the UK. It can be seen that the electric demand among the domestic unrestricted users start to increase when people start coming back home around 5pm and reach the maximum at around 6pm. However, the demand decreased and reached the minimum at 4.30am the next day.

This is because not much electrical appliances are operating during the night while people are sleeping. The demand starts increasing when people wake up at around 6am and remain low after people go to school and work. In addition, it can be observed that the domestic unrestricted demand profiles in the UK provide a significant opportunity to shift the consumers' EV charging to the low demand periods over the night. As shown in Figure 2, the Malaysian domestic load profile has less opportunity in this regards given the high demand over the night.

Table 2. Feeders loading condition

Feeder	Number of consumer	Total feeder loading (%) for newly developed network (185mm ²)	Total feeder loading (%) for matured network (185mm ²)
Feeder A	37 Single storey House; 15 Terrace House	43.7	54.6
Feeder B	64 Single storey House	41.7	52.2
Feeder C	33 Terrace House	43.0	53.8
Feeder D	36 Terrace House	47.0	58.7
Feeder E	8 Semi-D; 12 Bungalow	59.0	73.9
Feeder F	10 Semi-D; 7 Bungalow	46.0	57.6
Feeder G	10 Semi-D; 7 Bungalow	46.0	57.6

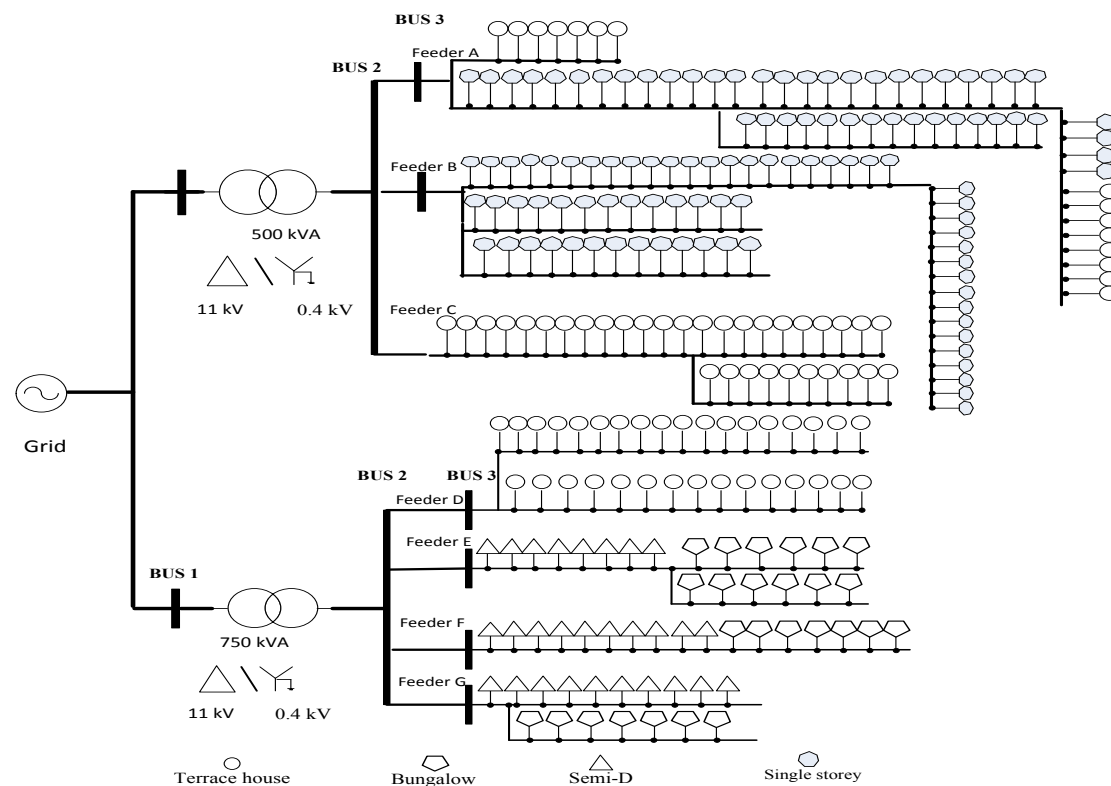


Figure 1. The one line diagram of LV distribution network of Taman PD Impian Putra.

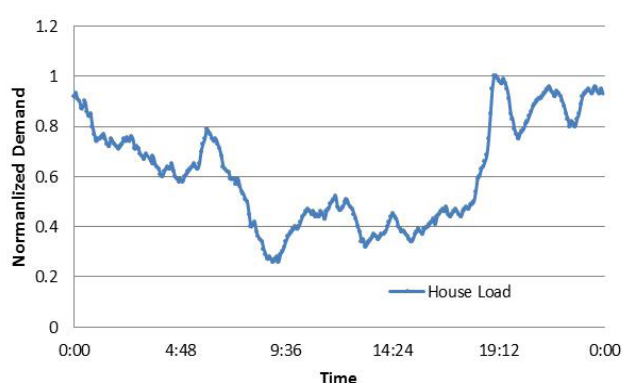


Figure 2. Malaysia's typical house load demand pattern¹³.

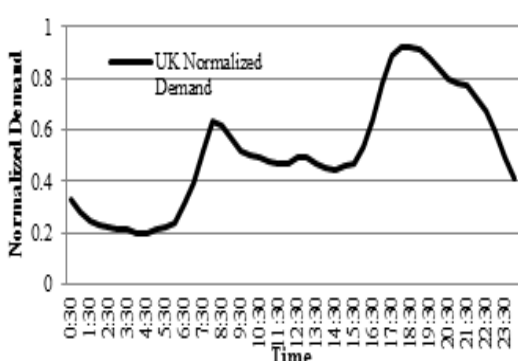


Figure 3. Domestic unrestricted users' demand pattern on week days during winter in UK¹⁴.

4. EV and Charging Profile Modeling

Nissan Leaf with 24kWh battery capacity and 3.3kW on board charger was chosen in this case study. This is because Leaf has been recently launched in Malaysia and has the highest battery capacity among the other EVs launched in Malaysia. The state of charge of the battery is controlled between 20% and 80% in light of the longer battery longevity¹⁵. Besides, the research¹⁶ shows that Average Annual Kilometers Travelled (AAKT) for male driver and female driver in Malaysia are 16,059.80km and 15,425.35km, respectively. This translates into an average of 44km and 42.6km daily commute distance for male and female drive respectively in Malaysia. With the assumption of 160km travel distance by Leaf on a fully charged battery¹⁵, male driver and female driver will consume approximately 27.5% and 26.4% of the energy stored in the battery on a daily basis. Four charging scenarios are considered in term of battery's

state of charge and required charging times are shown in Table 3. With the assumption of people might start to charge their EV any time after come back to home after 5pm¹⁷, 6 different start charging time is selected, which is 6pm, 7pm, 8pm, 9pm, 10pm and 11pm. Based on the 6 different start charging time, a total of 24 different EV charging profiles are created where every starting time consist of 4 different scenarios which is shown in Table 3.

Table 3. Battery charging scenarios

Scenarios	Battery state of discharge, %	Charging Time Required
Maximum Discharge	20%~80%	4hours 21minutes
Male Driver	52.5%~80%	2hours
Female Driver	53.6%~80%	1hour 55minutes
Partial Discharge	50%~80%	2hours 10minutes

5. Monte Carlo Simulation and Network Impact Analysis

Monte Carlo method is a technique of model resolution using repeated random sampling to obtain numerical results and is commonly used to deal with power system calculation problems involving uncertain parameters¹⁸. By using Microsoft Excel VBA and OpenDSS, power flow simulation based on the developed demand profile and LV distribution network model is repeated 1000 times for each different EV penetration level (0 to 100% in steps of 10%) as well as both newly developed network and matured network. In each time of repeated simulation, the following actions are performed:

- Random allocation of EV to the house base on EV penetration level.
- Random connection of single phase EV load to any one phase if the house is of 3 phase connection.
- Random assign of one EV charging profile from 24 different profiles which has discussed in section IV to each EV.

The detail of the Monte Carlo approach is shown in Figure 4. The penetration level (PL) of EV is defined in (1).

$$PL, \% = \frac{\text{unit of house with one EV}}{\text{total houses in a feeder}}$$

A number of network performance criteria are considered here for network impact assessment as following:

5.1 Voltage Drop

Voltage drop studies were carried out to determine the effects of EV charging on the LV system voltage levels. According to TNB's standard^{11,19}, the statutory tolerance for voltage excursion on the low voltage distribution network is -6% and +10% of the nominal value which is in the range of 252V to 216V. The voltage drop across the feeder is equal to the product of total impedance of the feeder times the line current²⁰.

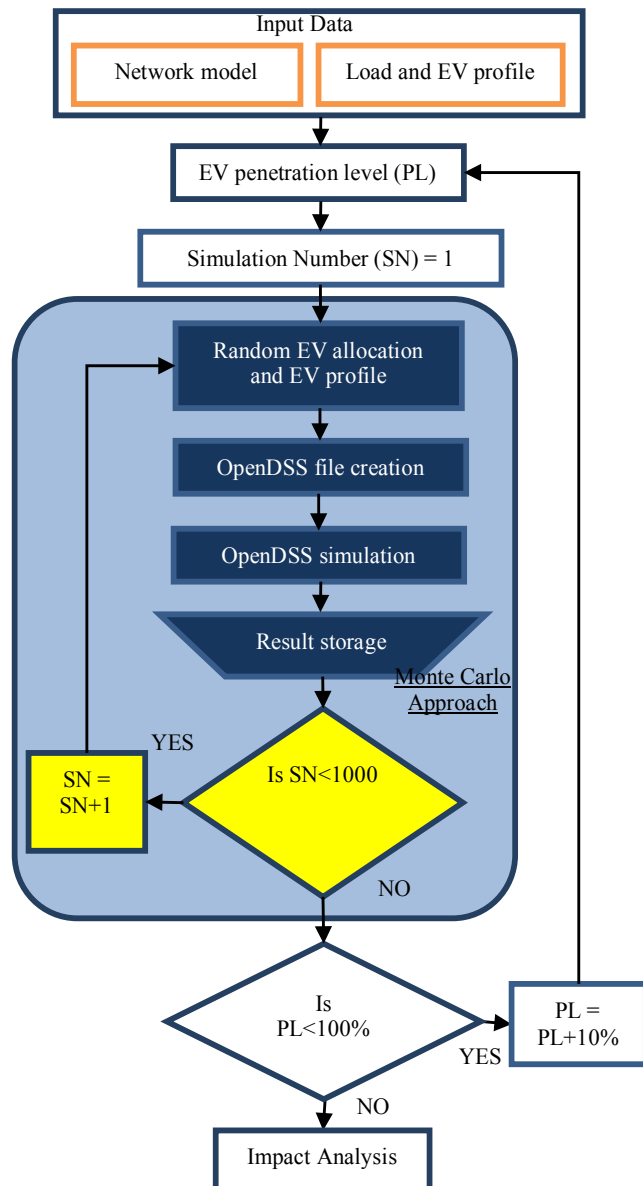


Figure 4. The adapted Monte Carlo procedure.

5.2 Voltage Unbalance

Integration of uncontrolled single phase EV charging is likely to increase the LV

system's voltage unbalance level. The mathematical model of voltage unbalance, also known as the Line Voltage Unbalance Rate (LVUR) at the load using the NEMA definition is shown in (2)²¹:

$$\%LVUR = \frac{MV}{V} * 100 \quad (2)$$

Where,

= Max voltage deviation from average line voltage

= Average line voltage

In Malaysia, the statutory limit of the voltage unbalance factor is 1.0%¹¹.

5.3 Feeder and Transformer Thermal Loading

The thermal loading of transformers and feeders are determined by the maximum current carrying capacity of each component; and, with high penetration of EV charging, the thermal limit of the feeders and transformer might be violated. In Malaysia, TNB has set a criterion that under both normal and contingency operating condition, electrical equipment such as transformers, switchgears, overhead lines and cables must not operate beyond their thermal limits²².

5.4 Network Losses

Power losses in the distribution network are mainly due to cable resistance and the magnitude of the loss depends on amount current flow and the line resistance. The line loss on a distribution feeder is equal to the product of line current squared times the line resistance²³. Integration of EV charging will increase the current flow which will lead to higher losses. The impact of network losses assessment can be described by formula (3):

$$\% \text{ of losses} = \frac{EL}{BC} * 100$$

Where,

= Network energy losses

= Energy consumption of base case

6. Result and Discussion

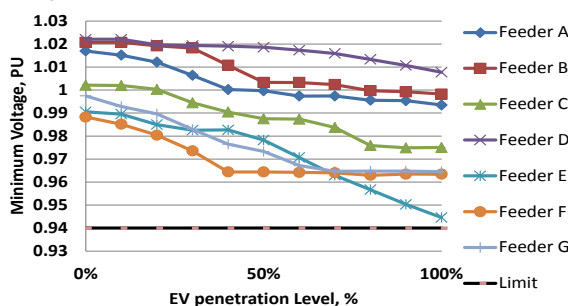
With 1000 runs of Monte Carlo simulations where EV connection and EV charging profile assignation were performed randomly in every runs, results were generated and analysis were performed. These results and analysis consist of indicators, such as voltage, current (which is discussed previously in Section V.1-V.4)

were generated. Results of the simulation are discussed in section below based on different indicators for both newly developed network and matured network.

6.1 Voltage Drop

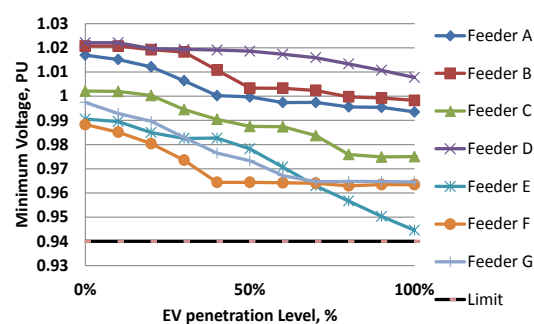
With regards to the voltage drop issue, the minimum voltage in every repeated simulation is recorded at the end of every feeder where worst voltage drop experienced²⁴. Average value of the recorded minimum voltage is shown in Figure 5(a) for newly developed network and Figure 5(b) for matured network. From these figures, there is no violation of voltage limit recorded for newly developed network throughout the simulation. This is because most of the feeders have around 50% margin, except Feeder E with 41% margin as mentioned in Table 2. Figure 9(a) shows that most of the feeders' thermal loading still below rated value even with high EV penetration level, except Feeder E.

However, for matured network, the network starts experience voltage violation for Feeder E at 80% of EV penetration level. From the simulation, matured network accommodate less EV penetration level than the newly developed network. This is due to the higher load level in the matured network as compared with the newly developed network. Figure 6 shows the percentage of cases with voltage drop issues versus various EV penetration level for both newly developed and matured network respectively. Approximate only 15% of total cases having voltage violation problem for matured network when the EV penetration level higher than 80%. The violation problem only occurs in Feeder E, which has lowest feeder margin.



6.2 (a) Voltage Unbalance

With the voltage value recorded in section 6.1, voltage unbalance analysis was carried out by using formula (2) stated in section 5.2. Figure 7(a) and Figure 7(b) show the average voltage unbalance value occur throughout various EV penetration level for newly developed network



(b)
Figure 5. Minimum voltage vs. EV penetration level; (a) newly developed network, (b) matured network.

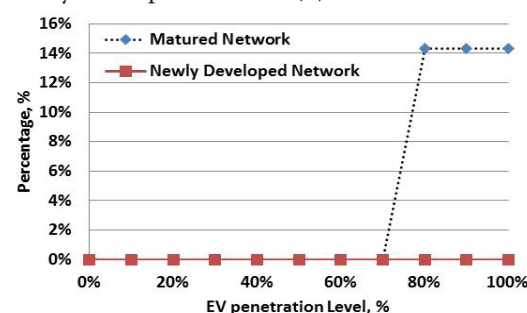
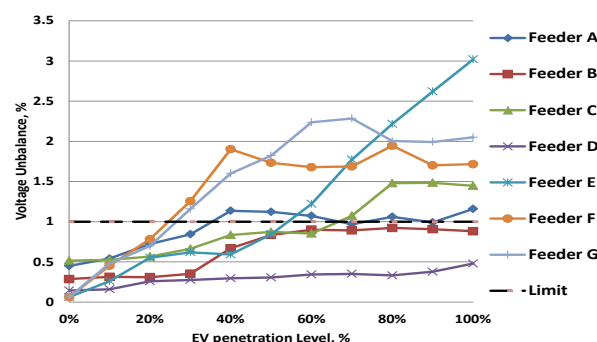
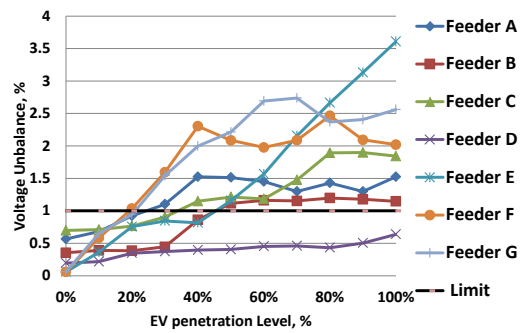


Figure 6. Percentage of cases violated voltage drop limit vs. EV penetration level.

and matured network respectively. With connection of single phase EV charging, newly developed network start experience voltage unbalance violation at around 30% EV penetration level. However, for matured network, voltage unbalance violation start experienced at around 20% EV penetration level. Figure 8 shows the percentage of cases with voltage unbalance issue versus various EV penetration level for both newly developed and matured network. Higher load demand in matured network cause the voltage unbalance occur earlier with respect to EV penetration levels compared to newly developed network.



(a)



(b)

Figure 7. Voltage Unbalance vs. EV penetration level; (a) newly developed network, (b) matured Network.

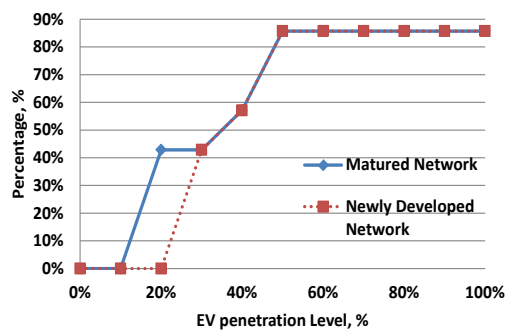
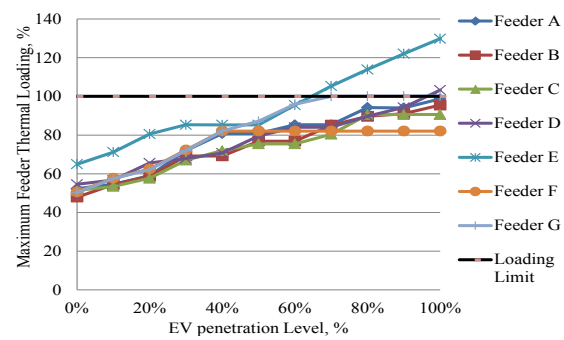


Figure 8. Percentage of cases violated voltage unbalance limit vs. EV penetration level.

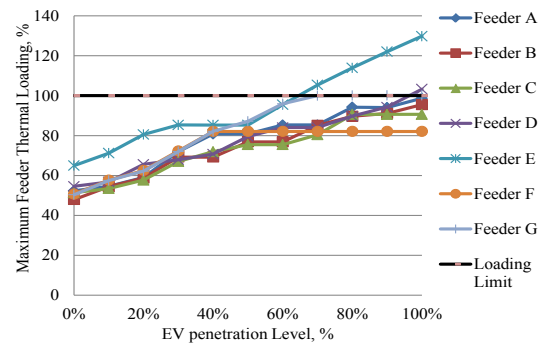
6.3 Feeder and Transformer Thermal Loading

Transformer and feeders' maximum thermal loading throughout the every repeated simulation was also recorded in this work. The violation of thermal limit of transformer and feeders were due to the additional new high load demand caused by EV charging. Figure 9(a) and Figure 9(b) shows that feeders start experience thermal loading overload at approximately 70% and 20% EV penetration level for newly developed and matured networks, respectively. Moreover, the transformer thermal loading condition for newly developed network and matured network are shown in Figure 10(a) and (b) respectively. The transformer start to experience thermal loading overload at around 80% and 40% EV penetration level for newly developed and matured networks, respectively. Figure 11 and Figure 12 show the percentage of cases with feeder thermal loading issues, as well as transformer thermal loading issues versus various EV penetration level for both newly developed and matured networks.

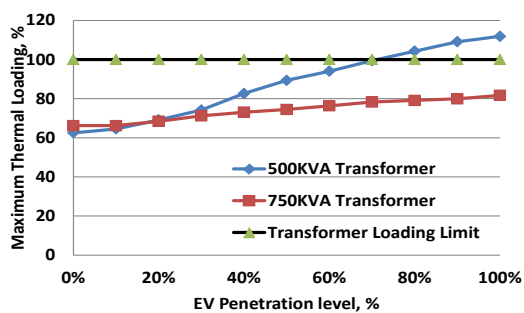


(a)

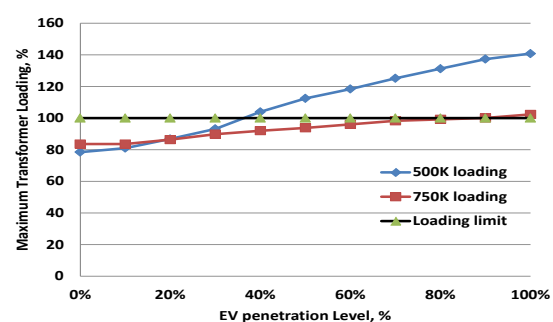
Figure 9. Maximum Feeder Thermal Loading vs. EV Penetration Level; (a) newly developed network, (b) matured Network.



(b)



(a)



(b)

Figure 10. Maximum Transformer Loading vs. EV Penetration Level; (a) newly developed network, (b) matured Network.

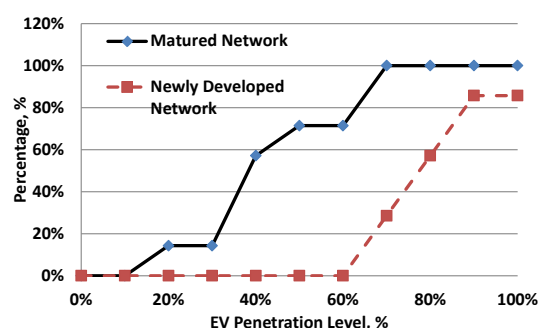


Figure 11. Percentage of cases violated maximum feeder loading limit vs. EV penetration level.

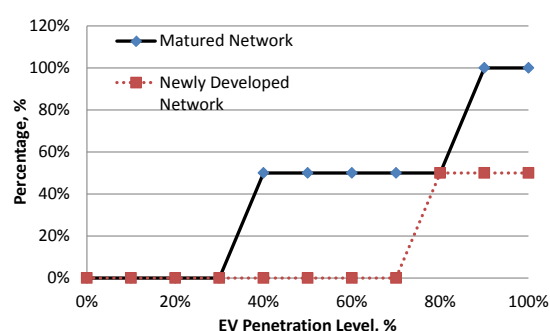


Figure 12. Percentage of cases violated maximum transformer loading limit vs. EV penetration level.

6.4 Network Losses

The average network losses throughout the all repeated simulations are presented in Figure 13 for both newly designed network and matured network. The result shows that the network losses increase linearly with the increase of EV penetration level for both types of networks. Matured network shows higher network losses compared to newly designed network due to higher load demand as discussed in Section II.

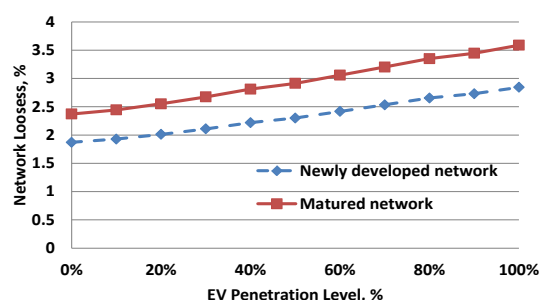


Figure 13. Network energy losses vs. EV penetration level for both newly developed network and matured network.

Generally, the increase of EV penetration levels will have a significant impact on the operation of LV network to certain extend, depending on the penetration levels. From the presented study, voltage unbalance is the main issue which mainly caused by the single phase EV charging. Summary of safe EV penetration level with respect to different network impact assessment criteria for both newly developed network and matured network is shown in Table 4.

Table 4. Proposed safe level of EV penetration

Network impact assessment criteria	Proposed safe level of EV penetration	
	Newly developed network	Matured Network
Voltage drop limit	100%	80%
Voltage unbalance limit	30%	20%
Feeder thermal loading limit	70%	20%
Transformer thermal loading limit	80%	40%

7. Conclusion

This paper has implemented Monte Carlo methodology to assess the impact of EV charging toward a sample of a newly developed and matured LV network in Malaysia. Different metrics have been used to quantify the impact of EV charging, with emphasis on voltage drop limits, voltage unbalance limit, thermal limit and network losses, according to TNB standards which had mentioned in Section 5.1 to Section 5.3.

The results from the studies indicate that voltage unbalance problems are likely to arise at much earlier penetration levels than other network problems for both newly developed and matured network. Although the results cannot be generalised to all situations, however, it does point out where problems could arise, so that network replacement with higher margin or other solutions can be put in place such as restriction of EV charging up to certain level. Further research can progress in optimum EV charging placement, controlled EV charging, demand response and Vehicle-to-Grid application.

8. Acknowledgement

The authors would like to thank TNB Distribution Melaka for providing the LV network sample. The funding support provided by the Ministry of Higher Education Malaysia under the research grant MTUN/2012/UTEM-FKE/7 M00015 is gratefully acknowledged.

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