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A Comprehensive Simulation Study of PEV Penetration Impact on Residential Area Distribution Network

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ABSTRACT

Abstract **-** Nowadays, rapid growth of electric vehicles is one of the breakthroughs for the future. Electrical utility with first stage of EV ecosystem adoption has to prepare for the impact of high demand of PEV penetration especially in residential area. The increase of EVs and charging points are challenge for the grid network. High number of private charging points in residential area is a big future demand that needs to be considered. This study aims to create a comprehensive model of electric vehicle charging penetration impact in residential area with the worst possible conditions and specific data in Indonesia. PEV charging profile and real residential load profile in Indonesia are recorded and used in this study. Driving behavior survey, distribution network modelling and PEV charging profile modelling are constructed. High PEV penetration Feeder loading and voltage drop are evaluated. High PEV penetration would impact on overloading and voltage drop on the network. Peak shifting in distribution network could possibly happen following the EV user charging behavior. However, for the first stage EV ecosystem development, the time shifted strategy including varying the PEV charging location near the transformer could resulting valley filling and reducing the network loses.

Keywords: Distribution Network, Driving Behavior, Electric Vehicle, Penetration, Residential

1. INTRODUCTION

The growth of electric vehicles has increased significantly in recent years [1][2][3]. Electric vehicles are becoming a trend for environmentally friendly transportation that provide solutions to pollution problems and reduce the use of fossil fuel [4][5]. In 2019, it was recorded that electric car-type vehicles in the world reached 7.2 million units, an increase of 40% compared to 2018. The world's electric car market share reached 2.6% in 2019, the highest compared to previous years. The increase in the number of electric vehicles must be followed by an increase in the infrastructure for charging electric vehicles. At the end of 2019 there were 7.3 million charging units spread throughout the world. Of note, 6.5 million units or reaching 90% of them are slow charging for private users [6]. The majority of private charges are in residential areas [7][8]. Therefore, the large penetration of plug-in electric vehicle (PEV) charging in residential areas is a new opportunity and challenge, especially for the distribution network. Currently the Government through Presidential Regulation (Perpres) No. 55 of 2019 concerning "the acceleration of the battery-based electric motor vehicle program for transportation", has appointed PT PLN (Persero) for the first time as a provider of electricity charging infrastructure for both Private and Public Electric Charging Stations (SPKLU). The government also provides fiscal and non-fiscal incentives as a stimulus for program acceleration. This is an opportunity as well as a challenge for PT. PLN (Persero) as a provider of electrical energy in Indonesia. Based on global trends, the increase in loads due to charging electric vehicles in the distribution network, especially in residential areas, will increase significantly during the charging period for private electric vehicles. Therefore, it is necessary to study the penetration impact of charging electric vehicles to the distribution network in the residential area.

Several studies discuss the impact of PEV penetration to the network using modeling and typical data for analysis. Loading models in industrial and residential areas as well as the stochastic approach to form a typical model are used to determine the impact of penetration to age and stress of distribution transformers [9]. Coordinated and uncoordinated charging scenarios are created assuming drive times to go and back. PEV is modeled into a pure resistive constant load to determine the voltage stress and losses in the feeder [10]. Private drivers will charge as soon as possible after arriving home in the afternoon so that the next day their electric vehicle can be used again [11][12][13][14][15]. The uncontrolled condition of charging private electric vehicles in residential areas will be a burden to the network, especially if it intersects the peak load time (WBP).

This study aims to create a comprehensive model of PEV penetration impact on residential area distribution network. A survey of driving behavior in Indonesia was conducted to determine the estimated use of stored energy and the need for charging electric vehicle batteries. The network model used represents the characteristics of the load distribution in the distribution network. Household load profile data and electric vehicle charging power profiles are obtained from direct field measurements. The impact of penetration with direct measurement profile data and a worst-case scenario in the distribution network will help grid operators to do network planning and anticipate the growing demand of PEV charging, especially in residential area distribution networks.

The structure of this paper will then be structured as follows. Chapter II describes other related studies. Chapter III is a research method which consists of driving behavior survey, distribution network modeling, PEV penetration load profile modeling and distribution network PEV penetration scenario elaboration. Chapter IV is the results and discussion of the impact of PEV penetration and evaluation of mitigation. Then in Chapter V the conclusions will be presented.

2. METHODS

2.1. Survey of Driving Behavior in Indonesia

In this study, cluster sampling and purposive sampling methods are used to determine the driving behavior in Indonesia. Purposive sampling is used to determine the criteria for respondents who can fill in the required question, such as length of domicile and age, with these two criteria being considered to represent the respondent's knowledge of the area they live in. Meanwhile, cluster sampling is used to determine samples based on regions, in this case Yogyakarta and its surroundings, Denpasar and its surroundings, Makassar and its surroundings, and the last is Jabodetabek. After the area to be sampled is determined, then the sampling is carried out randomly. The equation (1) is an empirical equation to determine the number of populations that are commonly used in studies for sample sizes greater than 30 and the number of populations is unknown.

$$n=\left(\frac{\frac{Z_{\alpha}}{2}\cdot\sigma}{e}\right)^2 \tag{1}$$

Where $Z_{\alpha}/2$ is the confidence coefficient (generally 95% or more), σ is the standard deviation (generally 5-25%), and e is the margin error (generally 1-5%). Sampling in this study used the value of the level of confidence, standard deviation and a margin of error of 95%; 25%; and 2.5% in order to obtain a sample rate of at least 384.16 respondents. So that the required sample size is 400 respondents. The number of samples that have been obtained is then divided proportionally into the four research locations.

2.2. Modelling of Distribution Network

Distribution networks generally supply loads of different values to each network segment and random load locations. In this research, three load distribution models are made that can be used to simplify the problem, namely the load at the end of the feeder (Model 1), the load is evenly distributed (Model 2), and the distributed load increases evenly (Model 3) [16]. Fig.1 illustrated the model, Model 1 end-centered load is a distribution network topology model where the load is concentrated at a point and is connected to a long express feeder. Model 2 evenly distributed load is a distribution network topology model where the load is spread evenly along the distribution network feeder. Model 3 multilevel distributed load is a distribution network model where the load is spread out and increases in value to the end of the network or vice versa. The equations used to calculate the voltage drop for model 1, model 2, and model 3 is given in equations (2), (3), and (4) respectively.

$$V_d=\frac{\sqrt{3}I.l(r\cos\theta+x\sin\theta)}{10V_{ll}} \tag{2}$$

$$V_d=\frac{\sqrt{3}I.l(r\cos\theta+x\sin\theta)}{20V_{ll}} \tag{3}$$

$$V_d=\frac{2\sqrt{3}I.l(r\cos\theta+x\sin\theta)}{30V_{ll}} \tag{4}$$

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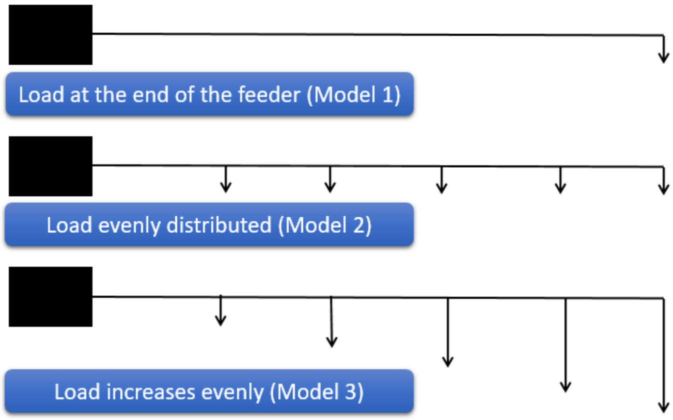

Figure 1. Model of distributed load in distribution network

The three distribution network models will be evaluated with varying the PEV penetration level. The distribution network model used will focus on voltage drop analysis and network loading. The load profile used is the average load value of household customers in Jakarta. The load is sampled every 15 minutes for 24 hours using a smart meter, then the customer load profile data can be downloaded via the web meter data management system (MDMS). The average load of household customers will be the base load model used in the simulation. In the power system simulation software, the load model will be converted into a composite model that represents the customer load profile relative to the time or time domain.

2.3. Modelling of PEV Charging Profile

Charging batteries of electric vehicle generally uses the constant current constant voltage charging (CC-CV) [17] technique. The battery capacity of an electric vehicle or the State of Charge (SoC) value that has been reduced due to driving has to be recharged. The CC-CV method at an early stage will perform a constant current charging technique to speed up charging. The value of the charging current is kept at a constant value by adjusting the value of the charging voltage. This phase is maintained until the terminal voltage value of the battery reaches the maximum allowable charging voltage in accordance with the specifications of battery type. In the battery charging process, the initial constant current technique is needed to limit the charging current to a certain value so as not to exceed the maximum allowable charging current value. The large difference in the value of the charging voltage and the value of the battery terminal voltage due to the small SoC value of the battery can cause large inrush currents and potentially damage the battery. Equation (5) shows the acceptable current curve equation or limit of allowable charging current [17]. Where i is the fill current, I0 is the largest charge current when t equals 0, and A is the allowable charge current ratio.

$$i = I_0 \; e^{-At} \tag{5}$$

After reaching the maximum charging voltage value, the charging method will change to constant voltage technique. Contrary to the constant current technique, the constant voltage technique will maintain the charge voltage value at a certain level and the charging current will decrease accordingly adjusting the SoC of the battery to keep the voltage value constant. The constant voltage technique prevents over charging until the charging current reaches the value of C/10A [19].

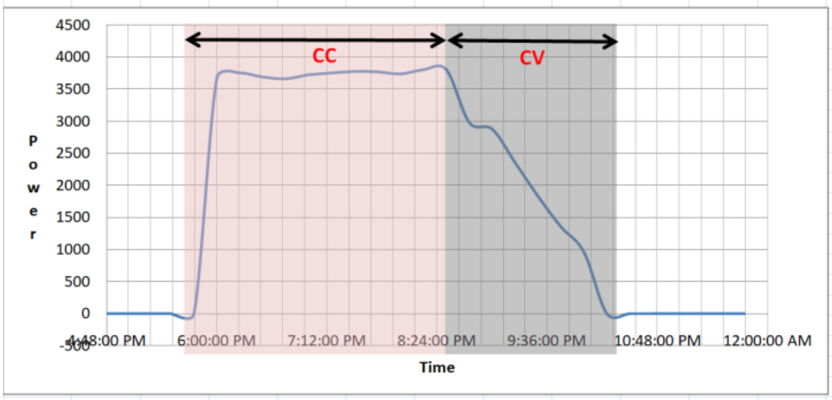

Figure 2. Power profile of PEV charging

To find out the value of the PEV charging power profile, it is necessary to know the output power of the charger used and the length of time for charging. The charger output power can be determined by looking at the standard level of charging allowed while the length of time for charging is influenced by the level of charging and the amount of the battery capacity. The distribution network in the residential area has limited power rating, so the residential area will apply SPLN level 1 for charging electric vehicles. As per SPLN D3.030.2017, the allowable charging current limit is 16A with an AC voltage of 230V. The SPLN also regulates the type of plug-in connector used is IEC 62916-2 or commonly known as IEC type 2. Fig. 2 shows the PEV charging power profile. The profile of electric vehicle battery charging using the CC-CV technique will be used as a load model for PEV and SPLN D3.030.2017 as a reference for electric vehicle battery charging levels in this study.

2.4. PEV Penetration Scenario

The simulation scenario in this study uses the assumption of the worst possible conditions of PEV penetration in the residential area and based on the survey result of driving behavior in Indonesia. When the electric vehicle returns home with depleted battery, the electric vehicle user will charge the PEV as soon as possible so that it can be used again tomorrow. The condition of charging an electric vehicle as soon as possible after reaching the house without charging time management is called uncontrolled overnight charging. The electric vehicle battery used has a capacity of 16 kWh and is at 20% SoC when it reaches the house. The charging time of electric vehicle batteries refers to the results of a survey of driving behavior in Indonesia, which is 18:00. Electric vehicles are spread across 5 distribution network connection points. The charging power profile of the CC-CV by adjusting the charger level 1 specification in the residential area distribution network will be used to charge PEV under the uncontrolled overnight charging scenario with the explained assumptions. The amount of PEV penetration is determined by the number of electric vehicles at each connection point or point of common coupling. The PEV penetration value will be varied to see its impact on the voltage profile and network loading.

3. RESULTS AND DISCUSSIONS

3.1. Network Loading and Voltage Profile

Line loading was measured at the closest conductor to the outgoing transformer (secondary side) while the voltage drop was measured at the end node of the distribution feeder. The penetration value would be increased from 0-100% with each step increasing by 20%. Zero percent penetration was the same initial loading condition in all three distribution network models. Hundred percent penetrations were defined as each house has 1 EV per unit in charging condition. Penetration of PEV used the scenario of uncontrolled overnight charging, which is assumed when the PEV arrives at home after being used for daily activities, PEV would immediately charge according to the scenario described in the PEV load model. In the initial condition, peak loads and voltage drop at the largest end terminal were occurred at 17:45. Notation [s] in the figure represent time in minutes.

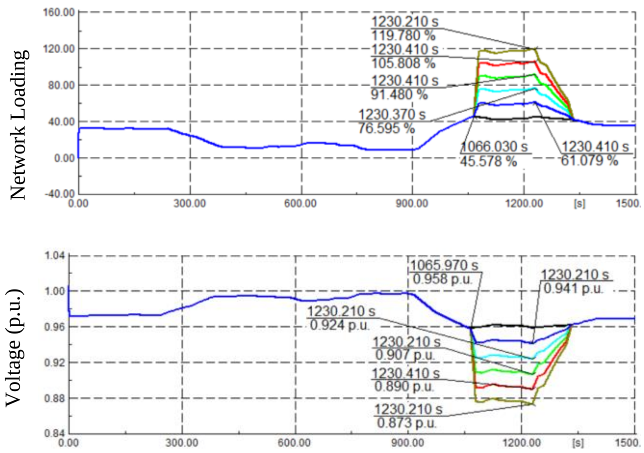

Figure 3. Feeder loading and voltage drop of distribution network model 1

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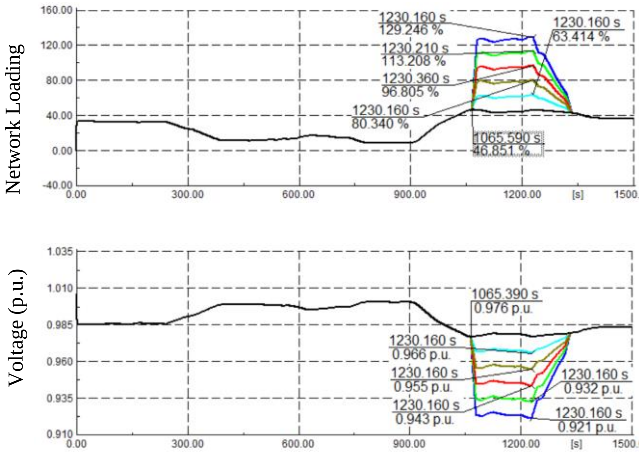

Figure 4. Feeder loading and voltage drop of distribution network model 2

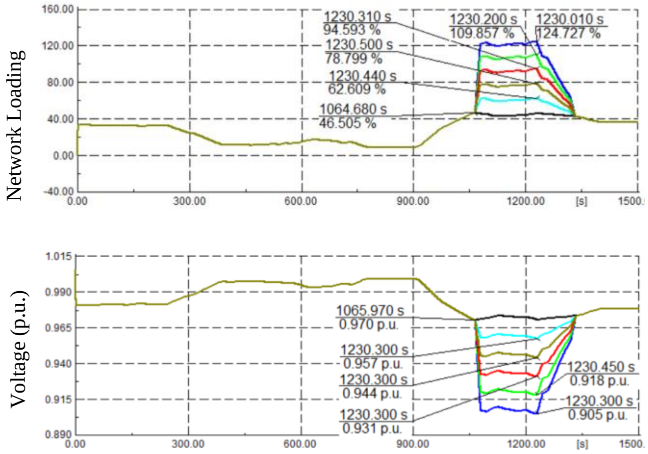

Figure 5. Feeder loading and voltage drop of distribution network model 3

Table 1. Network loading and voltage model 1

Number of EV	**Load at the end of the feeder**			
	% Penetration	Max Line Loading (%)	Voltage Drop (%)	Voltage End (p.u.)
Initial	0%	45,7	4,2	0,96
15	20%	61,2	5,9	0,94
30	40%	76,8	7,6	0,92
45	60%	91,8	9,4	0,91
60	80%	106,2	11,0	0,89
75	100%	120,0	12,7	0,87

Table 2. Network loading and voltage model 2

Number of EV	**Load evenly distributed**			
	% Penetration	**Max Line Loading (%)**	**Voltage Drop (%)**	**Voltage End (p.u.)**
Initial	0%	46,9	2,3	0,98
15	20%	63,5	3,4	0,97
30	40%	80,4	4,5	0,95
45	60%	97,1	5,7	0,94
60	80%	113,4	6,8	0,93
75	100%	129,4	7,9	0,92

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Table 3. Network loading and voltage model 3

Number of EV	Load increase evenly			
	% Penetration	**Max Line Loading (%)**	**Voltage Drop (%)**	**Voltage End (p.u.)**
Initial	0%	46,5	3,0	0,97
15	20%	62,7	4,3	0,96
30	40%	79,0	5,6	0,94
45	60%	94,8	6,9	0,93
60	80%	110,0	8,2	0,92
75	100%	124,7	9,5	0,90

Figure 3 shows the increase in loading value on the feeder and the value of the voltage drop that occurs at the end terminal for 24 hours on the load network model at the end of the line. Line loading increases with maximum loading varying from 45.66% to 119.99% during the charging period. The line loading value has reached 92% for 60% PEV penetration into the network. The voltage profile at the terminal end increases with the voltage drop value varying from 2.34% to 7.88% during the charging period. If seen in Figure 3 it is also known that the peak load shifts following the peak power needed by the PEV charging process at 20:30. Table 1 shows a summary of voltage and load data in model 1.

Figure 4 shows the increase in loading value on the distribution network feeder and the value of the voltage drop that occurs at the terminal end for 24 hours on a uniformly distributed load model. Line loading increases with maximum loading varying from 46.89% to 129.43% during the charging period. The line loading value has reached 97% for 60% of PEV penetration. The voltage profile at the terminal end increases with the voltage drop percentage value varying from 2.34% to 7.88% during the charging period. If seen in Figure 4 it is also known that the peak shifting occurred following the peak power needed by the PEV charging process at 20:30. Table 2 shows a summary of voltage and line loading data in model 2.

Figure 5 shows the increase in loading value on the feeder and the value of the voltage drop that occurs at the terminal end for 24 hours in a distributed load network model that increases evenly. Line loading increases with maximum loading varying from 46.55% to 124.74% during the charging period. The line loading value has reached 95% for 60% of PEV penetration. The voltage profile at the terminal ends increases with the percentage value of the voltage drop varying from 2.97% to 9.52% during the charging period. If seen in Figure 5 it is also known that the peak load shifts following the peak power needed by the PEV charging process at 20:30. Table 3 shows summary of voltage and line loading data in model 3.

3.2. PEV Charging Location

In the next simulation scenario variation of PEV charging location is performed relative to the transformer position in the network. The value of the voltage profile and the network load will be evaluated based on the PEV charging location. The voltage profile will be seen at the terminal end of the network. The values of the percentage voltage drop against the nominal value of the system voltage are evaluated. Network loading can be seen from the percentage loading value at the closest feeder conductor to the transformer.

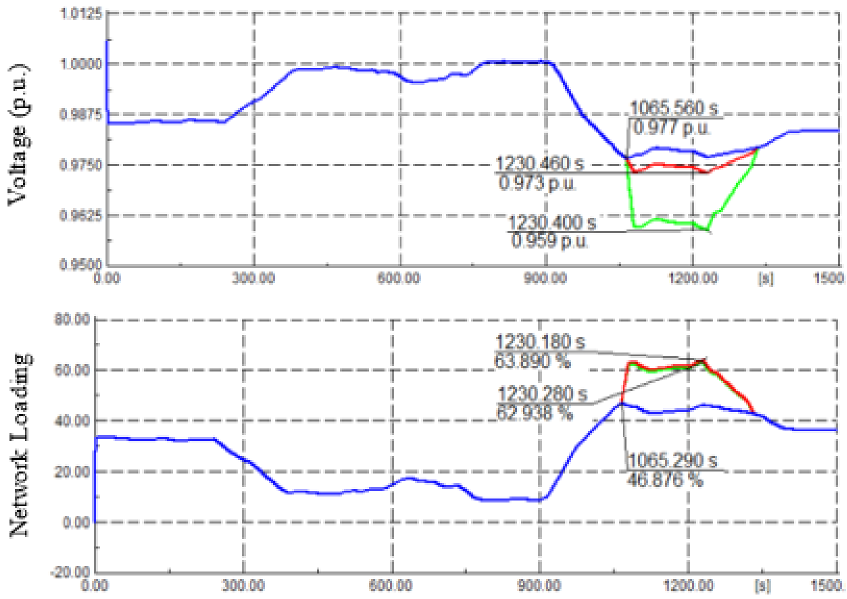

Figure 6. Voltage and feeder loading impact of PEV charging location

Table 4. Feeder loading and voltage drop of varying PEV charging location

	Initial	Closest	Farthest
Voltage End Terminal (p.u.)	0,98	0,97	0,96
Voltage Drop (%)	2,30	2,70	4,10
Maximum Line Loading (%)	46,88	63,89	62,94

Fig. 6 shows the simulation results of the network voltage profile and the value of the conductor loading with variations in the PEV charging location. The blue line shows the initial condition of the system, the red line shows the voltage profile and conductor loading when the PEV is penetrated at the node or terminal closest to the transformer. While the green line shows the voltage profile and network loading when the PEV is penetrated at the end node or at the terminal furthest from the transformer. Table 4 shows a summary of simulation results. It is known that PEV charging at the closest node to the transformer can reduce the risk of voltage drop from 0.959 if it is placed the furthest node to 0.973 when the PEV is penetrated the closest node to the transformer. On the other hand, network loading is not significantly affected. The discussion section is where the article interprets the results to reach its major conclusions. This is also where the author's opinion enters the picture. The discussion is where the argument is made. Common features of the discussion section include comparison between measured and modelled data or comparison among various modelling methods, the results obtained to solve a specific engineering or scientific problem, and further explanation of new and significant findings.

3.3. Loses Impact of PEV Penetration

Controlled charging strategies need advanced metering infrastructure (AMI) to automatically controlling and monitoring the charging process [20][21]. It needs to upgrade the conventional meter reading so that enabling the two ways communication of the grid operator and the end users. However, for the first phase to developing EV ecosystem, time shifting strategy are evaluated. Utility company PLN encourage the EV user to shifted the charging time into of peak period overnight charging by giving incentive.

Table 5. Time shifting and charging location impact

	Uncontrolled Overnight	Time Shifted	Uncontrolled Overnight + Near Transformer	Time Shifted + Near Transformer
Peak	9.26%	8.88%	6.99%	6.59%
Average	9.09%	8.28%	6.87%	5.67%
Peak (kW)	28.776	26.457	19.979	18.092
Average (kW)	28.265	24.661	19.646	15.566

Table 5 shows the summary of loses simulation result. Uncontrolled overnight charging of PEV generating 9.26% at peak period and 9.09% average loses. The time shifted strategy including placing the PEV charging location near the transformer could reduce loses 2.67% at peak period and 3.42% average. High PEV penetration were generating voltage drop and overloading in the distribution network especially at residential area. Thus loses of the network increases. Incentive is needed to encourage the user behavior to charge the PEV at off peak load period. The time shifted strategy including varying the PEV charging location near the transformer could resulting valley filling of the residential area load profile and decreasing the average network loses.

3.4. Discussion

The rapid growth of EV will become electrical utility challenge for the future. Global trend shows the highest number of EV charging points are private charging. Private charging means the EV user will charge the battery of PEV in the house or residential area. The charger standard follows the SPLN D3.030:2017 where residential area would use level 1 16A/230VAC using IEC 62916-2 type 2 as charging plug connector. In this study, the worst possible condition of PEV charging in residential area has been constructed. The assumption was the EV user would directly charge the battery as soon as it arrives at home thus it could be used in fully battery condition in the next day. If some PEVs uncontrolled charge the battery together at almost the same time in residential area, it would generate such a very high power from the grid and would impact the distribution network system.

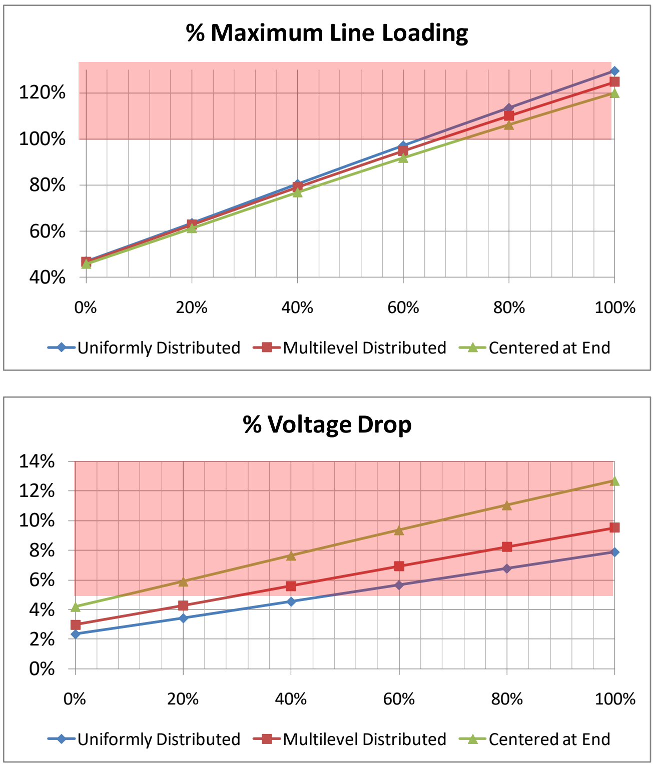

Figure 7. Impact of PEV penetration on maximum line loading and voltage drop

The three distribution network models (model 1, model 2, and model 3) were constructed to simplify and represent the condition of load distribution in the real field and evaluate the impact of PEV penetration on residential area distribution network. The objectives of the simulation were focus on the voltage profile and feeder loading evaluation. Figure 7 was summarizing the result analysis. The biggest load change occurs in model 1 or the uniformly distributed load distribution model. Feeder loading increased to 129.4% when each house had a PEV. This result shows that the impact of uncontrolled overnight charging PEV can increase the loading up to 72.5% from the initial loading. The biggest voltage drop occurs in model 3 or distribution model with a centralized load at the end of the feeder. Voltage drop increases to 12.7% or 0.87 p.u. if maximum PEV penetration occurs. The change in voltage drop when all houses have a PEV reaches 8.5% of their initial conditions. In addition, this loading condition and voltage drop occur outside the initial peak load time. In this simulation, the initial condition of the peak load occurs at 17:45 and when the PEV was penetrated the peak load shifts to 20:30. Peak shifting could possibly happen as the impacted of PEV penetration. PEV penetration could significantly affect the voltage drop and feeder loading conditions also shift the peak load time.

Variation position of PEV charging to the distribution transformer has also been done. Longer distance of PEV charging placement tend to cause higher voltage drop. On the other hand, the shorter distance of PEV charging placement to the distribution transformer was causing higher loading condition. However, the PEV charging position is more significantly affecting the voltage drop condition. To reduce voltage drop, EV Charging can be placed in the terminal closest to the transformer. Moreover, incentive is needed to encourage the user behavior to charge the PEV at off peak load period. The time shifted strategy including varying the PEV charging location near the transformer could resulting valley filling of the residential area load profile and decreasing the average network loses. However, when the PEV penetration happens, the distribution network has to be reevaluated. The transformer cable and topology has to be recalculated to anticipate the impact of PEV penetration.

4. CONCLUSIONS

In this study a comprehensive simulation of PEV penetration has been done. The worst possible condition of PEV charging penetration in residential area has been constructed and evaluated. The three distribution network models (model 1, model 2, and model 3) have been designed to represent the condition of distribution network on the field and to evaluate the impact of PEV penetration on residential area distribution network. The distribution network household and PEV charging profile were based on the direct measurement on the field. The maximum charging level were based on the SPLN D3.030:2017 level 1 charging standard using IEC

62916-2 type 2 as charging plug connector. The driving behavior survey has been done to construct the worst possible condition of PEV charging scenario. The result shows that high PEV penetration would impact on overloading and voltage drop on the network. Peak shifting in distribution network could possibly happen following the EV user charging behavior. However, the time shifted strategy including varying the PEV charging location near the transformer could resulting valley filling and reducing the network loses.

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