Harmonic evaluation of Plug-in Electric Vehicle on distribution network system

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Abstract. The significant development of plug-in electric vehicle (PEV) is a challenge for distribution networks. The PEV charger is a power electronic device that generates large amounts of power over a period of time to charge EV battery. In addition, the EV on board charger (OBC) also produces harmonics due to the process of converting AC grid voltage to DC voltage. Converter as OBCs main device is a source of harmonics which directly connected to the distribution network. In this study, harmonics from single OBC, multiple OBC and PEV penetration scenario were evaluated and compared with the SPLN standard D5.004-1: 2012. From the study results, THD injected to the distribution network is influenced by the percentage of the base load and PEV penetration. The worst possible condition is occurred under low load conditions while high PEV penetration happens. From the simulation results using the distribution network model especially in residential area, the low base load scenario (10.47%) and the high PEV penetration (90.01%) is generating TDD 6.59% and THDv 2.61%, respectively. Therefore, it is known that the harmonic effects generated by PEV charging to the distribution network still meet SPLN D5.004-1: 2012

1. Introduction
Nowadays, rapid growth of Plug-In electric Vehicle (PEV) are supported by some factors such as public awareness of global warming, reduce the carbon emissions, expensive price of gasoline [1,2], and government regulation (Perpres No.55/2019). Most PEVs are equipped with an on-board charger (OBC) as a battery charging device. OBC converts the AC voltage source from the grid to DC voltage so that the battery as the power source of electric vehicle (EV) can be recharged. OBC is a switching mode power supply (SMPS) consisting of an inverter and rectifier with a special topology. OBC based on power electronic device is a source of harmonics or a harmonic generator when connected to the network. The PEV is mostly charged overnight at home, so the EV owner can drive it in the morning with full battery condition. The PEV needs a large amount of energy for fully charge the battery overnight. This high amount of power for such a specific time will impact on the distribution grid [3]. Home charging EV will contribute significantly to the perceived harmonic, especially in distribution networks. Therefore, the harmonic value generated while PEV charging process needs to be evaluated.

There are some studies focusing on the PEV harmonic impact to the grid. Direct measurement shows that the maximum total harmonic distortion current (THDi) of level 3 charger is 17.3% on the end of charging cycle. Level 1 and level 2 generate maximum THDi 19.2%, they show higher THDi than the level 3 charger [4]. The other study is direct measurement on the constant charging stage, the result shows 11.6% average along the constant power charging state on the fast charging station [5,6]. Actually, the EV charger or OBC show variety of different harmonic patterns and values [7]. Some
low voltage nonlinear loads are possibly to make harmonic cancellation. The higher number of customer and the device will result the possibility of harmonic cancellation higher [8]. Some studies are focusing on harmonic amplitude because of the limitation based on the harmonic standard. On the other hand, if the diversity of the harmonic charger is not taken into account, there will be overestimated the harmonic problems [9]. In this study, direct measurement of 4 PEV types will be the delineated. Multiple OBCs connect to the single point of common coupling (PCC) will show the characteristic of multiple OBCs harmonic. Distribution network model are constructed to evaluate the PEV harmonic penetration impact. The diversity of the various type of OBC will be evaluated using single OBC, multiple OBCs, and penetration scenario evaluation in this study. The objective of the study is the comprehensive evaluation of PEV penetration focusing on the harmonic evaluation.

The rest of the paper is organized as follows. Section II describes the methodology for evaluating the harmonic characteristic of PEV and constructing PEV penetration simulation scenario. The SPLN D5.004-1: 2012 is described and some harmonic limitations that allowable in the grid are detailed. In section IV, the simulation result is analysed and evaluated based on the SPLN D5.004-1: 2012. Finally, the conclusion is given in Section V.

2. Methodology
Harmonic is sinusoidal signal of voltage or current with a frequency value of a multiple of its fundamental frequency (f = 50Hz). Periodic non-sinusoidal waveform can be decomposed by Fourier transform which is the sum of fundamental components and harmonic components. The source of harmonics in power systems is nonlinear load such as electronic equipment, welding machines, furnaces, and electronic power devices. Most PEV is equipped with an OBC for charging battery. OBC is a switching mode power supply (SMPS) consisting of an inverter and rectifier with a special topology. Electronic-based OBC is a source of harmonics when connected to the network. The harmonic generated by PEV have to comparing it to the standard range of allowable current and voltage harmonics. In addition, PEV chargers should fulfil the harmonic limit and DC current injection standard on the allowed grid according to the following standards: IEEE-519, IEEE-1547, SAE-2894, and IEC-1000-3-6. In this study, SPLN D5.004-1: 2012 [9] is used as a reference to evaluate the harmonic value generated by PEV against the harmonic value allowed on the distribution network especially in Indonesia. Table 1 and Table 2 show the voltage and current harmonic limits that must be maintained in the electric power system. This standard sets limits on the value of harmonics per component of the harmonic order and the total harmonic distortion (THD) allowed in the system. The voltage harmonic distortion limit is seen based on the system voltage level. While the current harmonic limits see the value of the voltage level and short circuit ratio. Short circuit ratio is the ratio of the maximum short circuit current at the connection point to the maximum load current of the transformer used.

The scenario used in this study is the worst possible condition of PEV penetration in distribution networks, especially in residential areas. The characteristics of PEV harmonics are evaluated by looking at the values of voltage harmonic distortion and current harmonic distortion in single PEV and multiple PEV measured at one node or point of common coupling (PCC). Comparison of the value of the basic load to the penetration of PEV is varied to get the worst possible harmonic conditions that can be injected into the PEV network.

| Voltage at PCC | Individual Harmonic Voltage Distortion (%) | Total Harmonic Voltage Distortion THDVn (%) |
|----------------|------------------------------------------|------------------------------------------|
| $V_n \leq 66kV$ | 3                                        | 5                                        |
| $66kV < V_n \leq 150kV$ | 1.5                                      | 2.5                                      |
| $V_n > 150kV$  | 1                                        | 1.5                                      |
Table 2. Harmonic current limitation.

| Ihs/IL | Maximum Harmonic Current Distortion in % of IL | Total Demand Distortion |
|-------|-----------------------------------------------|------------------------|
|       | Individual Harmonic Orde "h" Odd Harmonic     |                        |
|       | h < 11                                       | 11≤h≤17                |
|       |                                              | 17≤h≤23                | 23≤h≤35              | 35≤h                  |
| <20   | 4.0%                                         | 2.0%                   | 1.5%                 | 0.6%                  | 0.3%                  | 5.0%                  |
| 20 - 50| 7.0%                                         | 3.5%                   | 2.5%                 | 1.0%                  | 0.5%                  | 8.0%                  |
| 50 - 100| 10.0%                                        | 4.5%                   | 4.0%                 | 1.5%                  | 0.7%                  | 12.0%                 |
| 100 - 1000| 12.0%                                       | 5.5%                   | 5.0%                 | 2.0%                  | 1.0%                  | 15.0%                 |
| >1000 | 15.0%                                        | 7.0%                   | 6.0%                 | 2.5%                  | 1.4%                  | 20.0%                 |

3. Results and Discussion

In the distribution network model used, the nominal voltage level was 400V and the value of the short circuit ratio was 35.11 so that the THDv limit was <5% and the total demand distortion (TDD) limit was <8%. Figure 1 and Figure 2 showed the value of current and voltage harmonics generated during the PEV charging process which measured directly from each OBC connection point. The fundamental current per OBC was 13A and the harmonic order was evaluated up to the 39th order. It was known that the total current harmonics or THDi generated had varying values in the range 4.37%-10.92% and the generated THDv had range 0.189%-0.222%. Each OBC was known to generate different harmonic value. This result was influenced by OBC technology selection such as converter topology, switching frequency, and filters used. To found out the characteristics of harmonic penetration from various sources, a simulation was carried out by combining several OBCs at one connection point. Multiple OBC charging together through one PCC will generate the resultant harmonics that were injected into the distribution network.

\[
U_{\text{har}} = \sqrt{U_{\text{h1}}^2 + U_{\text{h2}}^2 + 2U_{\text{h1}}U_{\text{h2}} \cos(\theta_{\text{h2}} - \theta_{\text{h1}})}
\]  

(1)

When the four OBCs were combined to one connection point or PCC, the values of current harmonics and voltage harmonics were obtained as shown in Figure 3. THDi and THDv values resulting from multiple OBC harmonics are 3.1% and 0.13%. This shows that the resultant harmonic values did not
add up perfectly to each other depending on the phase value per order of harmonic values. From the simulation results and referring to equation (1) an illustration was made to make it easier to understand the characteristics of harmonizing summation in the system if there were multiple sources of harmonics in the network being evaluated. Figure 4 shows an illustration of the characteristics of the sum of harmonics with the assumption that the two harmonics sources had the same magnitude. So it was known that if there were several sources of harmonics in a network, the harmonics components would add up to each other if the angle difference per order of harmonics values was below 90°, add up perfectly if the angle difference value was exactly 0°, and will subtract if there were more than 90° and harmonics would be cancel each other if the harmonic component has a 180° angle difference.

![Figure 3. PCC Voltage and current harmonic distortion of single OBC (red, green, and blue are phase A, B, and C).](image)

![Figure 4. Harmonic summation characteristic.](image)

Next penetration simulation is carried out in the distribution network. Harmonics generated by the PEV charging process will be penetrated into a typical distribution network model to get the harmonics impact on the distribution network, especially in residential area. Analysis will be carried out by looking at THD value, the evaluated THD value is at the PCC closest to the terminal of transformer secondary side. The model used in this simulation is a uniformly distributed distribution network with variations in PEV penetration values and base load conditions. In this simulation we want to know the effect of PEV penetration on generated THD by varying the value of penetration and loading under initial conditions. Figure 5 and Figure 6 showed the THDv and THDi value generated on the network due to variations in PEV penetration and base load value. The biggest THD value in this simulation is shown by the orange block with PEV penetration value reaching 100%. It can be seen that the greatest THDi and THDv occur when the base load is low while maximum PEV penetration occur, the THDi and THDv are 6.73% and 3.08%. The most significant harmonic was
happened when the PEV penetration was high while the base load was low. It can also be seen from the blue block, when high PEV penetration and base load was high, THDi and THDv felt by the tissues are 3.22% and 1.52%. Therefore, it is known that the worst harmonic conditions occur when the basic network load is low while the non-linear load in this case the PEV penetration is high. From the simulation results above then a scenario was formed to evaluate the TDD and THDv. The worst scenario used was using some assumption, firstly the base load were 10.47% and the PEV penetration was 90.01% equal to around 99EVs. Specification of the distribution transformer was 400kVA/400V; 3% (%Z).

![Voltage Harmonic](image1)

**Figure 5.** THDv with varying PEV penetration.

![Current Harmonic](image2)

**Figure 6.** THDi with varying PEV penetration.
To evaluate harmonics based on the SPLN standard D5.004-1: 2012 it is necessary to know the short circuit ratio and the evaluated system voltage. The network short circuit ratio in this simulation is 33.35 while the system voltage level evaluated is at <= 66kV so it is known that the allowable TDD limit is <= 8% and the allowable THDv is <= 5%. By using equations (2) and (3) measured at the PCC in the transformer secondary terminal, the generated TDD value is 6.59% and the THDv value is 2.61%. Based on the SPLN standard D5.004-1: 2012, it is necessary to know the short circuit ratio and the evaluated system voltage. The network short circuit ratio in this simulation is 33.35 while the evaluated system voltage level is at <= 66kV so it is known that the allowable TDD limit is <= 8% and the allowable THDv is <= 5%. From the simulation results using the residential area distribution network model, the low base load scenario (10.47%), and the high PEV penetration (90.01%), the TDD values generated were 6.59% and THDv 2.61%, respectively. So, it is known that the harmonic effects generated by PEV charging to the distribution network still meet SPLN D5.004-1: 2012. Even in some references [10,11] it is mentioned that PEV can be modelled as constant power sources regardless of the harmonics.

4. Conclusion
Harmonics from single OBC, multiple OBC and penetration scenarios to the distribution network model have been evaluated and compared with the SPLN standard D5.004-1: 2012. The evaluation not only focus on the amplitude of the harmonics generated by OBC of PEV but also diversity of harmonic charger including multiple source harmonic characteristic and worst case of distribution network penetration scenario. From the study results, THD felt by the distribution network was influenced by the percentage of the base load and PEV penetration. The worst possible condition was occurred under low load conditions while high PEV penetration happens. The worst scenario has been constructed and evaluated using low base load condition 10.47% and high PEV penetration 90.01%, the TDD values generated were 6.59% and THDv 2.61%. Thus, it has been known that the harmonic effects generated by PEV charging to the distribution network still met SPLN D5.004-1: 2012.

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