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Harmonic analysis of Electric Vehicle Loadings on Distribution System

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Abstract—With the increasing number of Electric Vehicles (EV) in this age, the power system is facing huge challenges of the high penetration rates of EVs charging stations. Therefore, a technical study of the impact of EVs charging on the distribution system is required. This paper is applied with PSCAD software and aimed to analyzing the Total Harmonic Distortion (THD) brought by Electric Vehicles charging stations in power systems. The paper starts with choosing IEEE34 node test feeder as the distribution system, building electric vehicle level two charging battery model and other four different testing scenarios: overhead transmission line and underground cable, industrial area, transformer and photovoltaic (PV) system. Then the statistic method is used to analyze different characteristics of THD in the plug-in transient, plug-out transient and steady-state charging conditions associated with these four scenarios are taken into the analysis. Finally, the factors influencing the THD in different scenarios are found. The analyzing results lead the conclusion of this paper to have constructive suggestions for both Electric Vehicle charging station construction and customers' charging habits.

Keywords—harmonics analysis; electric vehicle; smart grid; PSCAD simulation; total harmonic distortion; transient; overhead transmission line; underground cable; industrial area; transformer; photovoltaic system

I. INTRODUCTION

Nearly 30% of the total fossil fuel consumption in the world 2012 was in the transportation sector [1]. With the dramatically increasing demands, in the United States, the greenhouse gas emission from transportation is the second largest after the electric power industry [2]. Therefore, Electric Vehicles (EV) become the main solution to effectively reduce the pollution from transportation. The growing numbers of electric vehicles will burden the distribution grid and create a new peak demand. However, the utilities will benefit from efficient system utilization, the use of EVs as the energy storage and environmental benefits from the reduction of greenhouse emission. At the end of 2013, there are already more than 170,000 plug-in EVs and 20,138 charging stations in the United States.

The current electric distribution systems is not expected to able to accommodate high percentage of EVs penetration. Meanwhile, the introduction of EVs in distribution system create negative effects on the power quality due to harmonics created by the EVs. When the loads are nonlinear types drawing current with a non-sinusoidal and distorted wave while connecting to the grid, it negatively impacts the public networks which is designed to operate with a sinusoidal voltage at rated power. High non-linear loads cause harmonics, leading the voltage distortion to the customers, increasing mechanical stress, misleading protection equipment and degrading the system component efficiency [3].

In this paper, the main focus is to understand and investigate how EVs charging and discharging harmonics impact on the grid associated with different system components and different numbers of EVs at different selected places. The critical charging station allocation and design are obtained based on the result to avoid maximum harmonics and minimize the stress on the grid in future.

The paper is structured as the following: In Section II Model Setup, the base model IEEE34, EV charging level will be discussed. Four testing scenarios are introduced in Section III Testing Scenarios. In Section IV Charging Strategy, Total Harmonic Distortion (THD) and State of Charge (SOC) will be further demonstrated to bond closely with the modeling methodology in this paper. In Section V Results and Discussions, all results and comparisons will be presented from four testing scenarios. Section VI Conclusions concludes this paper and provide the further discussion.

II. MODEL SETUP

In this project, PSCAD/EMTDC is used. It is a general-purpose time domain simulation program for multi-phase power systems mainly focusing on the study

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of transients in power systems and seamlessly integrating the visual environment features of harmonics.

A. *Distribution Network*

This paper presents a study on the modeling of existing IEEE 34 radial distribution feeders. PSCAD model is built as the IEEE 34 Bus test system model which includes transformers, regulators with controls, induction generators, loads, distribution lines. [4]

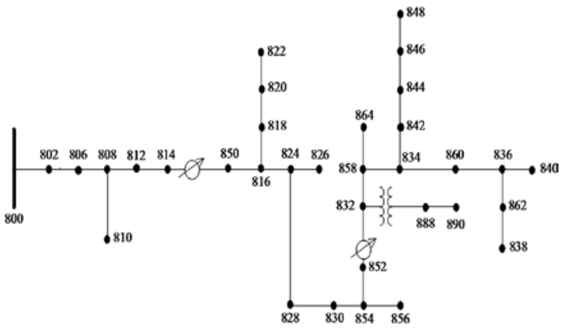


Fig.1. Structure of IEEE 34 radial distribution feeder

IEEE 34 model is built based on an actual system in Arizona and it includes different types of transmission lines and transformers. It is convenient to test the influence of harmonics on the distribution network by setting up different testing scenarios.

B. *Electrical Vehicle Model(Charging level 2)*

Batteries, as the most important part in the Electric Vehicle industry, the characteristic of the battery directly determines the charging behavior and the impact on power grid. In modern electrical storage industry, there are four main cell chemistries in use of rechargeable batteries, Lithium-ion battery is the best choice for EVs. Thus, this paper will model Li-ion battery and use it to simulate the charging and discharging impact on the power grid.

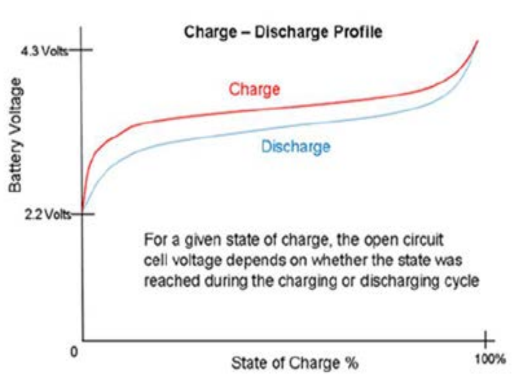


Fig. 2. Charge and discharge characteristic of a typical battery cell

In the simulation, all EVs charging are based on level 2 charging. Level 2 charging equipment offers charging through a 240V, AC plug and requires installation of home charging or public charging equipment. These units require a dedicated 40 amp circuit. Level 2 chargers are commonly found in residential settings, public parking areas, places of employment and commercial settings. [5] This paper, therefore, will use 240V and 32A as the input standard.

Battery model is built according to the charging and discharging characteristics. There are several parameters to be set in the battery model such as rated capacity(Ah), reserved battery(Ah), maximum voltage(V), voltage at exponential point(V), charge current(A), efficiency, battery combination, nominal voltage(V), SOC: state of charge (%). After setting all the parameters correctly and running the battery model in PSCAD, the simulation result, shown in Fig3, is nearly seamless. The charging and discharging characteristics are the same following with the typical battery cell characteristics. It works at 240V rated voltage and the charging current is 32A.

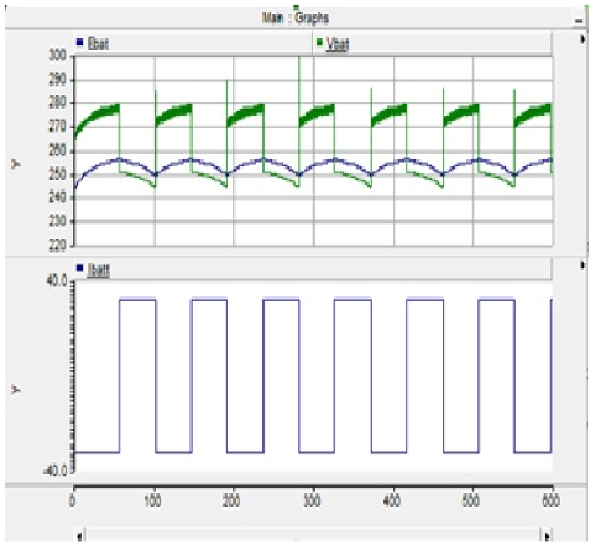


Fig. 3. PSCAD simulation result of battery model charge and discharge process

Besides, during the charging time, the battery voltage is not a smooth curve, showing certain fluctuations. The reason behind is power electronic devices in the inverter, which connecting the battery to grid and converting the AC current to DC current. These power electronic devices are also known as harmonic sources. This further proves the accuracy of the model.

III. TESTING SCENARIOS

In this model, four testing scenarios are chosen to investigate the harmonic impact of EVs on the distributed system. The details of every scenario will be introduced.

A. *Overhead transmission line and underground cable*

This scenario analyzes the difference of the impact delivered by overhead transmission lines and underground cables during the plug in and plug out actions. The area between node 834 and node 840 is selected as the testing node. The IEEE 34 model offers the standard overhead transmission scenario in this area, which can be used directly for the tests. As for the underground cable scenario, the Fre-Dep (Phase) Model in PSCAD will be chosen to simulate the model since it is the most advanced time domain model available as it represents the full frequency dependence of all line parameters (including the effect of a frequency dependent transform).It is useful for any study involving the transient or harmonic behavior of the line or cable.

B. Industrial area

Several precise instruments are located in the industrial area. This leads to a high demand for power quality in this area. Then, the effect of Electric Vehicle charging stations in this area needs to be studied. Industrial areas are usually located at suburban areas with frequent transportation where factories consume a large amount of electricity. [6] In IEEE34, bus 890 follows this requirement exactly. It has a large spot load, which can be regarded as an industrial station, and it is far from other loads.

C. Transformer scenarios

This scenario analyzes the harmonic impact brought by Electric Vehicles charging stations which is near to the transformer. First, power quality problems, such as harmonic distortion, have negative effects on the energy system components. Transformers contribute such problems the most and may need to be de-rated to as much as 50% capacity when feeding loads with extremely distorted current cause the reduction in their service life. [7].Second, transformer is also a harmonic source. Harmonics are produced by nonlinear loads or devices that draw non-sinusoidal currents. A good example is a saturated transformer, whose magnetizing current is no sinusoidal. [8] All these make the paper devoting more effort on the transformer scenarios. The transformer between node 832 and node 888 is selected.

D. PV modules

In this scenario, the PV model will be included. Tests focus on analyzing the performance of EV charging near the renewable resources - PV, known as the relatively high harmonic generated. For the simulations, The PV model used in this report was developed by Dr. Athula Rajapakse of the University of Manitoba, and was provided by the PSCAD technical support team. The model offers two custom library components, the PV array and the Maximum Power Point Tracker (MPPT). [9] This advanced model could give precise simulation results and will be located in Node 840.

IV. STRATEGY

The strategies extend the analysis of harmonics in this section. In part A, the method to analyze the harmonic during a complete EV charging period will be involved. In part B, the method to set the initial values of EV battery will be discussed.

Part A

Based on the simulation results, the waveform of system current near to the EV charging point is demonstrated as the following.

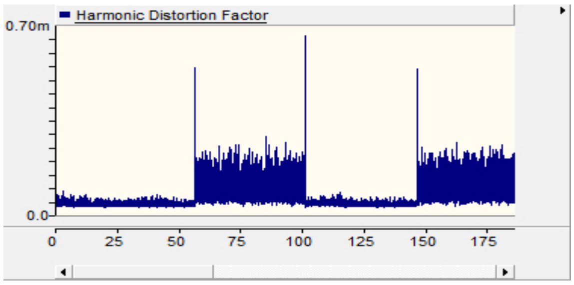


Fig. 4. harmonic distortion factor of current in charging period

In Fig 4, the system current waveform can be divided into four periods. Period1 (57s) is the Plug-in Transient (PIT). It is the moment when EVs are plugged in, a transient will be created. The current will be much higher than the system value at the steady state. Period2 (57~101s) is the Steady-state Charging Period (SSCP). It is the period when EVs are on the process of charging. The oscillating current in period is much larger than the current before period 1 and smaller than the transients. Period3 (101s) is the Plug-out Transient (POT). It is the moment when EVs are plugged out, another transient will be created. Period4 (101~146s) is the period that no EVs are charging, therefore, it is no need to study. The first three periods will be discussed in details.

Several variables will be used to measure the characteristic of the harmonic brought by EVs. THD, namely Total Harmonic Distortion (or Distortion Factor), of current is the main variable to be measured in this paper. It is a measurement of the harmonic distortion and is defined as the ratio of the sum of the power of all harmonic components to the power of the fundamental frequency. THD is used to characterize the linearity of audio systems and the power quality of electric power systems. [10] Besides, the maximum harmonic, the damping time, the mean of the THD value in different periods will also be analyzed to understand the characteristics of the harmonic better in every period.

Part B

State of Charge (SOC) is the equivalent of a fuel gauge for the battery pack in a battery Electric Vehicle (BEV), Hybrid Vehicle (HEV), or Plug-in Hybrid Electric Vehicle (PHEV). The units of SOC are percentage points (0% = empty; 100% = full). In this study the SOC value is set to be the same due to the reason that different values of SOC will have an influence on the harmonics. For level 2 charging, different SOCs will produce different starting charging points. In other words, it also means various voltage when charging starts that leads to different voltage between battery and grid. Due to the same internal resistance in the same battery model, different voltage result in different charging current and the harmonics. To justify that, run the model with two different set SOC values to get from the fundamental maximum harmonics to the 7th step harmonics.

TABLE I. Harmonic test information under different SOC

SOC value	0.2	0.3
Fundamental harmonic	0.000595239	0.000567526
2nd	0.000443216	0.000386339
3rd	0.000221102	0.000238714
4th	0.000149677	0.000143943
5th	0.000118645	0.000139764
6th	0.000102062	0.000115007
7th	8.24E-05	9.42E-05

From the test results above, different SOC values will have an influence on harmonics. Thus, in order to control the variables, this study uses the same SOC value under all testing scenarios.

V. RESULTS AND DISCUSSIONS

A. Industrial area

Industrial area is full of all kinds of industrial equipments. Some are precise instruments, having high demands for power quality. Harmonics in this area caused several problems for system components, such as additional losses and hence additional heating. [11]This group of tests aims to obtain factors influencing the maximum THD and damping time in the PIT and the POT, and the average THD in the SSCP. This helps to find out the cause of harmonics brought by EVs in this area.

TABLE II. THD in different charging periods with different EV number and testing point

THD in different charging periods with different EV number and testing points				
EV number	**Test point**	**Max value in PIT**	**Mean in SSCP**	**Max value in POT**
one	800	5.50E-03	2.00E-03	1.80E-02
	890	2.30E-02	5.30E-03	7.70E-02
two	800	1.50E-02	3.60E-03	3.50E-02
	890	5.50E-02	8.40E-03	1.30E-01
three	800	1.90E-02	4.90E-03	5.10E-02
	890	7.50E-02	1.00E-02	1.80E-01
four	800	2.60E-02	6.10E-03	6.20E-02
	890	1.10E-01	1.20E-02	2.10E-01
five	800	3.00E-02	7.30E-03	6.90E-02
	890	9.90E-02	1.40E-02	2.20E-01

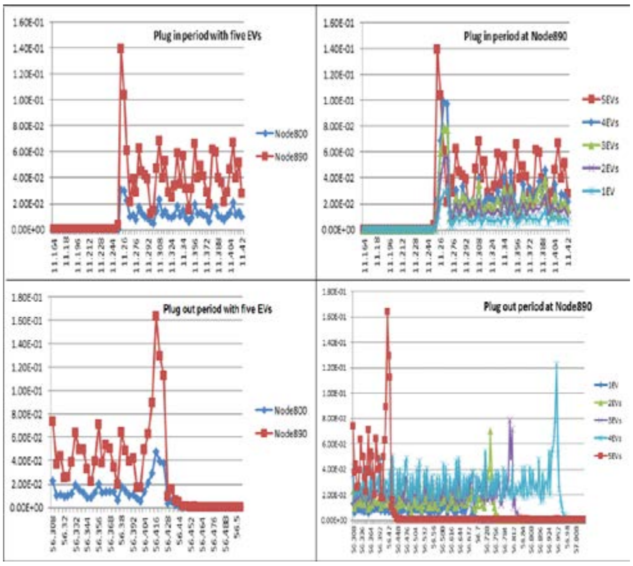


Fig. 5. Harmonic comparisons in industrial scenarios

From Table 2 and Fig 5, a trend can be found that, in most cases, increasing EV numbers will increase maximum THD and average THD. However, exception does exist. In Node 890, it's different. The reason is that the maximum THD is not only determined by a single reason, it is mainly determined by the number of EVs, the distance to the EV bus, the testing start time in the cycle and the structure of the grid. Among the factors, the EV number is one of the dominant factors. Besides, THD values near the testing point are all higher than those in the further point. This means that the charging point on the grid suffers the largest THD than other points. As the result, the factories near the large-scale charging station needs more protective methods for the power quality.

The damping time between two nodes is the same that will not be influenced by the selecting node and the numbers of EVs. Because the IEEE34 node system consists of a large amount of RCL, it is relatively much larger than what five EVs have which can be considered negligible. Thus, even with five EVs the damping time is still the same.

B. Transmission line and underground cable comparison

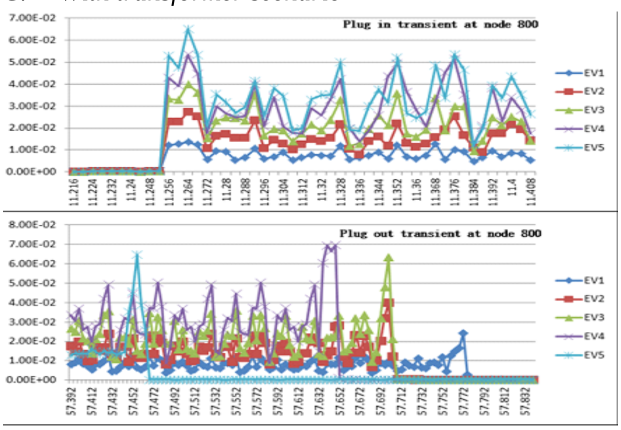
In this scenario, the maximum value of harmonics are obtained before and after the overhead transmission lines are changed to cables under the condition of different EV unumber and different testing points.

TABLE III. Harmonic comparison in transmission line and underground cable

Charging starting time max harmonic			
Number of EV	**Bus**	**T/line**	**Cable**
One	800	0.0256	0.0335
	834	9.17E-02	0.122
	840	6.71E-01	0.789
Two	800	4.89E-02	0.0621
	834	1.60E-01	0.2036
	840	8.73E-01	1.1053
Three	800	7.01E-02	0.088
	834	2.17E-01	0.279
	840	9.04E-01	1.204
Four	800	9.15E-02	0.1103
	834	2.89E-01	0.3504
	840	7.36E-01	1.2925
Five	800	1.06E-01	0.0785
	834	0.2818	0.2354
	840	0.9713	1.1531

As shown in Table 3,in different testing scenarios, during the charging time, maximum values of harmonics in cables are always higher than the one in overhead transmission lines. The main reason of the difference between transmission lines and cables is the cable surge impedance tended to be significantly lower than surge impedance for overhead lines because the closer proximity of the conductors increases the capacitance and reduces the inductance. [11] The increasing harmonic can cause the cables more vulnerable to temperature rise as compared to overhead lines. Several cases of premature failures of power cables due to power system harmonics are reported all over the world. [12] Therefore, the cable suffers more damages than the transmission line from the harmonics.

C. *With transformer scenario*



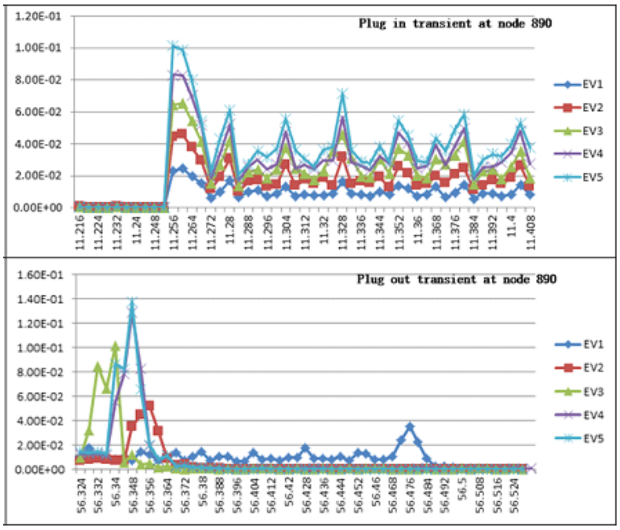


Fig. 6. Harmonics comparison in transformer scenario

This experiment focus on testing the THD value in PIT and POT in node 800, far away from the transformer, and node 890, near the transformer, under different EV number. As in shown in Fig 5, in node 800, THD is far lower than that of node 890.Besides, the damping times in PIT and POT are longer than that of normal scenario, which usually damps quickly and has been shown in Fig4. It shows that transformer exhibits the inrush phenomenon during the saturation. Because of the over fluxing breaking the flux symmetry, the charging and discharging process gives the large current on the transformer core. The saturation of transformer core creates high magnitudes of current and voltage as shown in the figure above then the undamped harmonics keeps oscillating till EVs plug out. As a result, EV charging stations are not suggested to be installed next to the transformer. Otherwise, they tend to suffer more harmonic impact and reduce their service life.

D. *PV model*

Renewable resources, such as PV and wind turbines, are known for the relatively lower power quality generated. PV system performance in terms of power quality strictly depends on the use of the inverters, the solar irradiance and the temperature that may affect the power generated, voltage and current profile. Therefore, a large amount of harmonic is inevitable. [13] This group of tests targets to analyze the performance of EV, also known as a harmonic source, near the PV position.

First, the THD of different EV numbers and distances to the charging position in the system will be tested. The results are shown in the table below.

TABLE IV. THD in a PV, EV system

Average THD Value in Steady-State Charging Period at Different Testing point			
Node	800	834	840
One EV	1.30E-02	3.61E-02	9.34E-02
Two EV	1.13E-02	2.84E-02	5.96E-02
Three EV	9.67E-03	2.38E-02	4.34E-02
Four EV	8.57E-03	2.01E-02	3.36E-02
Five EV	7.65E-03	1.91E-02	2.96E-02

Table 4 shows that the PV produces huge harmonic in the system, with an average value much higher than the previous three scenarios. However, with the increasing number of EVs, The THD in different testing points decreases correspondingly. Besides, the THD value increases to 2.45E-02 in average, a much higher value than that in the previous three scenarios. This shows that the harmonic produced by the PV has absorbed during the charging of nearby EVs.

This means the electric vehicle charging station located near to renewable sources can mitigate the harmonic in the system, to some extent. However, these absorbed harmonics may also cause damages to EV charging. The charging station must have some protective methods, such as installing proper filter, in such location.

VI. CONCLUSIONS

In this paper, harmonic effects of electric vehicle loading and impacts on a distribution system have been studied. The total harmonic distortions brought by electric vehicle loadings in the grid have been tested and analyzed.

The simulations results present the implications and suggestions in engineering practices and customer habits. Some of the key findings of this research are:

- For the customers, charging the EV battery with higher SOC could cause less damage to both the grid and the battery.
- For the EV charging station installation, the locations should be chosen far away from transformers, which are not only suffering the harmonic impact of EVs but are also acting as a harmonic source.
- EV charging stations near industrial areas should have limits on the number of EVs and be equiped with protective systems to guarantee high power quality.
- Underground cable is more susseptable to EV harmonics impacts than the overhead transmission line. This also requires higher requirements and standards for charging stations in this area.
- EV charging station near the renewable resource, which itself is a harmonic sources, would need to include mitigation from the harmonic in the system. However, system metigation, such as installing filters, should be considered to guarantee the power quality from the charging station.

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