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On the role of prosumers owning rooftop solar photovoltaic in reducing the impact on transformer's aging due to plug-in electric vehicles charging

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ABSTRACT

This paper investigates the synergetic effect of rooftop solar photovoltaic (PV) generation owned by residential prosumers (power producers and consumers) on reducing the distribution substation transformer's aging caused by charging plug-in electric vehicles (PEVs). Unlike previous work considering surveys based on internal combustion engine-based vehicle data (e.g., National Household Travel Survey (NHTS)) are used in estimating the charging demand of PEVs, this work considers actual PEVs charging data based on the 2015 Canadian Plug-in Electric Vehicle Survey (CPEVS). This work further quantifies the resultant aging seen on substation transformers when internal combustion engine-based National Household Travel Survey data as compared to plug-in electric vehicle driving data from the Canadian Plug-in Electric Vehicle Survey. Moreover, a comparison of the substation transformer aging is performed based on varying plug-in electric vehicle charging levels. Results of the scenarios have shown substation transformer loss of life is found to be at least 30% higher when vehicle data is based on plug-in electric vehicle studies versus conventional internal combustion engine vehicles with 0% PV penetration, up to twice as high at 100% PV penetration. Further studies have shown grouped plug-in electric vehicle charging using 3.3 kW at 7 pm results in twice the transformer aging seen versus plug-in electric vehicles charging beginning upon returning home. Finally, results have shown that the effect of rooftop solar PV owned by residential prosumers was found to reduce substation transformer loss-of-life by 75% in the case of 3.3 kW plug-in electric vehicle charging when 100% PV penetration was added to the system. Such reduction is due to a decrease in transformer's winding hot-spot temperature caused by PV generation despite the non-coincidence between the peak charging demand of plug-in electric vehicles and the peak power generation from rooftop solar photovoltaic.

1. Introduction

1.1. Background and problem statement

In an effort to reduce the carbon footprint of the transportation sector, the Government of Ontario has launched incentives such as the Ontario's Electric Vehicles (OEV) program and Green License Plates [1] in 2013. Such incentives currently allow Ontario drivers up to $14,000 in rebates for purchasing or leasing a new plug-in electric vehicle (PEV) [2]. The resultant PEV market has seen significant growth, resulting in double the total number of plug-in vehicles sales in Canada from 2013 to 2015 [3].

In response to the rapid PEV growth, previous work has tried to investigate the resultant impact in the distribution system due to plug-in electric vehicle charging [4–18], commonly considering transformer overload. The main limitation of such investigations lacked significant electric vehicle data, and required large assumptions such as the use of traditional internal combustion engine (ICE) vehicle data, which does not accurately represent the driving profiles of electric vehicle owners. Studies [4–10] considered the National Household Travel Survey (NHTS), which details travel data about conventional ICE vehicle habits. Similar ICE data was used in studies [11], [12] for France driving habits and [13] using Dutch travel. The work of Refs. [14,15] estimated impact using electric vehicle data as opposed to traditional NHTS data; however the data in Ref. [14] sources from electric vehicle charging stations, which do not accurately represent PEV owners likely to charge at home, and [15] considers a dataset of 9 electric vehicles, which is

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not a robust sample size. The work of Refs. [16,17] have investigated the impact of PEV charging in terms of reliability and transformer overload respectively, however both studies do not capture the habits of electric vehicle driving patterns through sampling ICE vehicle studies. Given that Ref. [18] suggests that vehicle driving patterns determine the time and duration PEV may charge, the importance of PEV sampling from proper datasets is emphasized. Moreover, studies [4–18] have not considered the growing penetration of rooftop solar photovoltaics (PV) on reducing the electric vehicle impact on distribution systems. To date and to the best knowledge of the authors, there is a lack of actual plug-in electric vehicles charging data in estimating the impact on the substation transformer's aging in the electric power distribution system.

In 2009, the Government of Ontario launched the micro feed-in-tariff (microFIT) program [19], allowing homeowners to generate up to 10 kW power typically through rooftop PV installation. Providing financial incentive to residential consumers, the microFIT program has steadily increased rooftop PV generation at homeowners, with 20 MW installed in Ontario in 2015 [20]. Such incentive programs have changed the role of residential consumers to be also power producers (i.e., prosumers). Studies [21–24] aimed to determine the resultant effects of distribution system impact with electric vehicles including rooftop PV generation. Studies [21.22] further report that PV generation is unable to mitigate PEV charging on transformer loading due to a lack of chronological coincidence. The analysis presented in Refs. [21,22] was limited only to estimate the transformer's overload and did not consider the transformer loss of life and its thermal model. Furthermore, such studies did not investigate the time-damped heating and cooling due to the thermal time constant of the transformer and, therefore, the synergetic effect between rooftop solar photovoltaic and plug-in electric vehicles charging on the transformer's aging has not been considered. Lastly, the works of Refs. [23,24] have reported distribution transformer loss of life considering both plug-in electric vehicle charging and rooftop PV generation, however these studies both neglected to detail an investigation into the thermal performance of the transformer when considering actual plug-in electric vehicles data.

1.2. Key contributions

Unlike previous work in which surveys based on internal combustion engine vehicle data (e.g., National Household Travel Survey (NHTS) [25]) are used in estimating the charging demand of plug-in electric vehicles, this work compares the resultant impact seen between traditionally employed NHTS data and actual plug-in electric vehicles charging data based on the 2015 Canadian Plug-in Electric Vehicle Survey (CPEVS) [26]. The synergetic effect of charging plug-in electric vehicles from rooftop solar photovoltaic on the substation transformer's aging is analyzed using both NHTS and CPEVS datasets. The work in this paper provides further insight on the transformer winding hottest-spot temperature change due to the synergy between rooftop solar photovoltaic and plug-in electric vehicles charging considering high level 2 power chargers rated 3.3 kW, 6.6 kW and 10 kW.

1.3. Difference between this work and the authors previous work

The main contributions with respect to the authors' previous work are as follows:

1) The synergetic effect of charging plug-in electric vehicles in the presence of rooftop solar photovoltaic on the loss-of-life of the substation transformer is investigated taking into consideration the thermal characteristics of the transformer. While previous research determined insignificant synergy due to non-coincidence between peak hours of PV generation and PEV charging, the thermal time constant of the transformer allows PV generation to reduce the transformer temperature when PEV are charging.
2) This study provides a comparison of the electric vehicle charging demand using actual Plug-in Electric Vehicle driving data and driving data previously obtained from NHTS which are based on conventional ICE vehicles. The comparison is performed in terms of the daily driving distance and home arrival time expected using each dataset.
3) This work considers Level 2 charging with up to 10 kW, which nearly doubles the power drawn with respect to previously performed research in which the rated power of the chargers was limited only to (6.6 kW).

2. Plug-in electric vehicles charging demand: NHTS versus CPEVS data

This section provides a comparative overview of NHTS and CPEVS datasets, as sampled to determine probabilistic charging impact on the transformers loss of life.

2.1. NHTS and CPEVS datasets

The NHTS periodically surveys transportation habits of residents throughout the United States as a means of recording the change in transportation mediums and driving habits over time. The most recent NHTS survey was performed in 2009 and consists of approximately 150,000 households and transportation data of 300,000 respondents throughout April 2008–April 2009. The NHTS raw dataset reports the vehicle type used by driving respondents, the majority of which are labelled "Automobile/car/station wagon" as defined in the NHTS Codebook [27] and as such, do not report plug-in electric vehicles driving data.

2.2. Vehicles daily driving distance

The CPEVS 2015 similarly contains driving data from 110 PEV car owners in British Columbia, Canada throughout June 2014–February 2015, representing approximately 10% of all British Columbia PEV purchasers in the year 2015 [26]. Data obtained in the CPEVS includes daily driving distance and home arrival time of PEV owners, needed to sample PEV charge duration and time.

Plug-in electric vehicle charging demand is estimated in this study using the model developed in Ref. [28], which considers the initial state-of-charge (SOC) of the vehicles battery and the charger's efficiency in estimating the total energy required, assuming final vehicle SOC of 100%. The driving distance for each vehicle for each day is sampled from one of two considered studies: The Canadian Plug-in Electric Vehicle Study (CPEVS) 2015 [26], and the National Household Travel Survey (NHTS) 2009 [25]. The daily distances travelled using NHTS were obtained by dividing annual mileage (ANNMILES) by 365, representing the total days in the surveyed year. Furthermore, to convert to vehicle specifications in mileage, the CPEVS driving distance data measured in kilometers was multiplied by 0.6214. A resultant comparison of the driving distance distribution between CPEVS and NHTS studies is given in Fig. 1. From inspection of Fig. 1 it may be seen that driving distances in the NHTS study are less than those of the CPEVS study, and suggest that vehicle initial state of charge may be higher in studies using NHTS versus that of CPEVS, as the median daily distance driven is 21 miles in NHTS and 29 miles in CPEVS. Given the work of Ref. [29] reports electric vehicle driving distances as 10% higher than those of non-electric vehicle owners; the significant increase in driving distance from CPEVS with respect to NHTS is attributed towards a combination of electric vehicle drivers tending to travel