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Impacts of plug-in hybrid electric vehicles on a residential transformer using stochastic and empirical analysis

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HIGHLIGHTS

- Catastrophic failure of distribution transformers due to PEV charging is unlikely.
- Uncontrolled Level 1 charging has little effect on transformer life time.
- Off-peak charging results in prolonged transformer life.
- Smart charging and load management is critical for high load factor transformers.
- PEV demand is manageable for transformer even if multiple vehicles exist.

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ABSTRACT

Plug-in electric vehicles (PEV) have been identified as an option that can reduce criteria pollutant and greenhouse gas emissions associated with the transportation sector. The electricity demand of one of these vehicles is comparable to that of a typical U.S. household and thus clustering of PEVs in a neighborhood might have adverse effects on the transformer and disruption of service. In this paper, the electricity demand of a neighborhood is modeled based on measured vehicle and household data. The electricity demand profile of the PEVs is modeled based on the vehicle type, arrival and departure times and the daily miles traveled, all taken from the National Household Travel Survey (NHTS). A thermal model is developed to calculate the hot spot temperature and loss of life of the transformer.

Results show that Level 1 charging has a small impact on the transformer aging and that only in one case, with Level 2 charging, the transformer might fail due to excessive temperatures. Overall addition of a significant number of PEVs is manageable for the transformer. The negative effects on the life time can be mitigated by properly designing the transformers and using smart charging scenarios.

1. Introduction

Concerns about greenhouse gas emissions and global climate change have led governments to put more stringent regulations in place to reduce emissions from both mobile and stationary sources. Power generation and transportation sectors are major contributors to GHG emissions in the state of California [1] and significant reduction in these sectors is required to meet the state's AB32 regulation [2].

Among various technologies, plug-in electric vehicles (PEV) have been identified as a feasible transportation option for the near future and may pave the way for longer term solutions such as fuel cell vehicles, better public transit, and mixed-use transit oriented development. These vehicles have various advantages including reduced liquid fuel usage, lowered criteria pollutant emissions resulting in better air quality, utilization of the generation capacity that is idle during off-peak hours, reduced GHG emissions, and providing a cheaper source of mobility than gasoline on a per mile basis [3,4]. Vehicle-to-grid (V2G) capability and the use of battery packs as storage for peak shaving and flattening the electricity demand curve have been extensively studied. Overcoming the technological barriers and with a smart communication link between the grid and vehicle, V2G can help improve the grid efficiency, stability, reliability, and maximize the intermittent renewable energy integration [5–11].

The majority of previous studies focus on the impact of PEVs on the generation side of the electricity grid [11–21], concluding that with the addition of PEVs with controlled charging, building new power generation infrastructure will not be required [17–21]. The impact of PEVs on the distribution grid has not been as rigorously

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Nomenclature

AAF	aging acceleration factor
EAF	equivalent aging factor
LOL %	loss of life percentage
K	load factor (ratio of the load to the rated load)
R	ratio of power loss at rated load to no load condition
τ_{oil}	oil time constant
τ_w	winding time constant
θ_{HST}	Winding's hot spot temperature (°C)
θ_{amb}	ambient temperature (°C)
$\Delta\theta_{oil}$	top oil's temperature rise over ambient (°C)
$\Delta\theta_{HST}$	Winding's temperature rise over oil (°C)
$\Delta\theta_{oil,R}$	Top oil's temperature rise over ambient at rated power (°C)
$\Delta\theta_{HST,R}$	Winding's temperature rise over oil at rated power (°C)

studied, mostly because it was believed that the number of these vehicles in a particular area would not be high enough to have a significant influence on the transmission or distribution grids. However, recent support of plug-in hybrid electric vehicles (PHEV) by the United States government, with a goal of having one million PHEVs on the road by 2015 [22] combined with the fact that clustering of these vehicles can occur in a particular neighborhood [23], hints that the impacts of these vehicles on the local grid might not be as far in the future as previously anticipated.

The addition of a PEV to a household can result in doubling the household electricity demand peak [24], and having a cluster of these vehicles on a distribution transformer can result in an increase in the transformer temperature, undesirable harmonics, and consequently loss of the transformer life. These effects depend on the charging profile, vehicle penetration, driving pattern, and time of charging of vehicles [25] with the key factor being the charging profile, voltage and power level [26]. The number of overloaded transformers will increase linearly as the penetration of PEVs increases [26].

Shao et al. [27] conducted a study including 5 homes with 2 PHEVs and showed that no scenario results in transformer overload except all charging at peak time with 220 V charging (Level 2). Mosheni et al. [28] conducted similar simulations and only in a small number of these simulations the transformer was overloaded with the addition of PHEVs. Other studies have been conducted to identify the possible effects of PEVs on power losses, power quality, service and residential transformers, and 3-phase primary lines [26,29,30]. One conclusion that seems to be common in most studies is that in order to operate a more reliable and economic grid, and to prevent transformer loss of life and outages, smart communication between the vehicle and the grid would be necessary [7,31–33].

In this paper, the electricity consumption of a neighborhood including ten houses in Southern California is simulated based on measured electricity consumption data. A virtual PHEV with a 60 km (40 miles) all electric range and charging characteristics of a Chevrolet Volt, is added to each household. The electricity required to fully charge each vehicle is calculated for each scenario using National Household Travel Survey (NHTS) data [34] which include the times each driver leaves in the morning and returns in the evening, and also travel distance such that the state of charge (SOC) of the battery when the driver returns home can be calculated. In order to study a case with more possible negative impacts on the transformer, each scenario is also conducted with a battery electric vehicle (BEV) with 160 km (100 miles) range and characteristics of a typical BEV; 0.193 kWh km^{-1} (0.31 kWh min^{-1}) (DC) consumption and 0.85 charging efficiency [35].

A suitable transformer is chosen based on the number of customers that it serves and also the peak demand. In this study, 37.5 and 50 kVA transformers are found to be most appropriate based on the analysis. The load on the distribution transformer serving this neighborhood is then calculated and the transformer hot spot temperature (HST) is modeled. The IEEE C57.91 standard [36] is used to calculate the transformer's loss of life based on the dynamic temperature calculations.

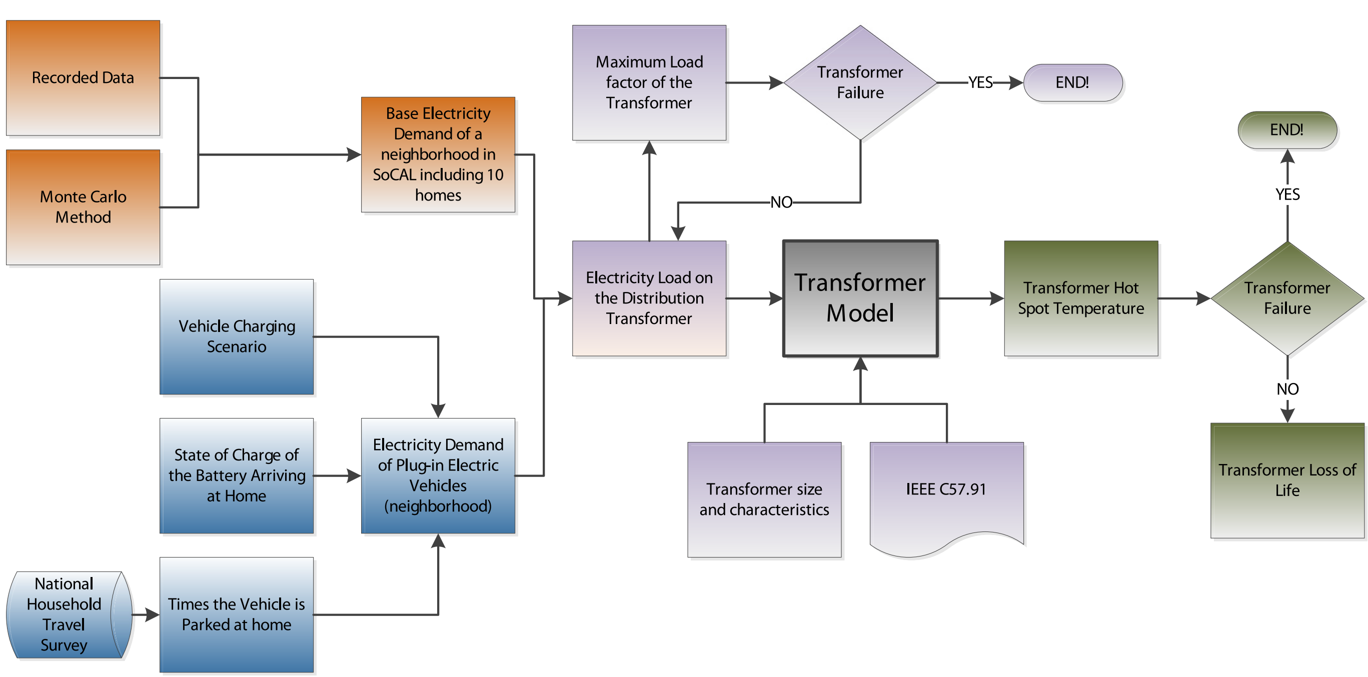

Fig. 1. Model flowchart.