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Application of Distribution Transformer Thermal Life Models to Electrified Vehicle Charging Loads Using Monte-Carlo Method

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Abstract— Concentrated purchasing patterns of plug-in vehicles may result in localized distribution transformer overload scenarios. Prolonged periods of transformer overloading causes service life decrements, and in worst-case scenarios, results in tripped thermal relays and residential service outages. This analysis will review distribution transformer load models developed in the IEC 60076 standard, and apply the model to a neighborhood with plug-in hybrids.

Residential distribution transformers are sized such that night-time cooling provides thermal recovery from heavy load conditions during the daytime utility peak. It is expected that PHEVs will primarily be charged at night in a residential setting. If not managed properly, some distribution transformers could become overloaded, leading to a reduction in transformer life expectancy, thus increasing costs to utilities and consumers.

A Monte-Carlo scheme simulated each day of the year, evaluating 100 load scenarios as it swept through the following variables: number of vehicle per transformer, transformer size, and charging rate. A general method for determining expected transformer aging rate will be developed, based on the energy needs of plug-in vehicles loading a residential transformer.

Keywords—Distribution transformer, smart grid, Monte-Carlo, plug-in hybrid, PHEV

1. Introduction

It is expected that plug-in hybrids (PHEVs) will be introduced to the public by auto manufacturers in late 2010 and early 2011 [1]. Based on the adoption pattern of standard hybrids in the early 2000s, we anticipate that early adopters of PHEVs will be similarly clustered in residential neighborhoods – that is, as one neighbor purchases a PHEV, neighbors on the same street, and same transformer, become more likely to purchase a PHEV. The non-homogeneous distribution of PHEVs plugging into the power grid means that some distribution transformers may see several PHEVs, whereas a distribution transformer in another part of the neighborhood may see none [2]. An example of the non-uniform distribution of PHEVs, even at a city-wide level, is shown on the Southern California Hybrid Vehicle registration map in Figure 1.

Electric utilities are already looking forward to PHEV implementation and are conducting capacity and operations studies of their distribution networks. This analysis is an overview of distribution transformer life modeling, with a focus on the application of existing transformer life models to determine the unique characteristic of PHEV loading impacts. The transformer life models used in this analysis are dependent solely upon thermal loading characteristics, as developed in IEC 60076. Non-fundamental harmonic currents are excluded from the thermal model.

The focus of this work is to develop hotspot temperature (HST) duration curves that may be integrated to evaluate transformer wear. Sensitivity to increasing plug-in fleet penetrations and varying geographical climate will be evaluated based on real-world drive cycle and meteorological data. Over one year, 36,500 travel-days were simulated for each scenario. A charge-delay algorithm was implemented in the simulator to show how grid communication may preserve transformer life without significantly impacting service to the utility consumer.

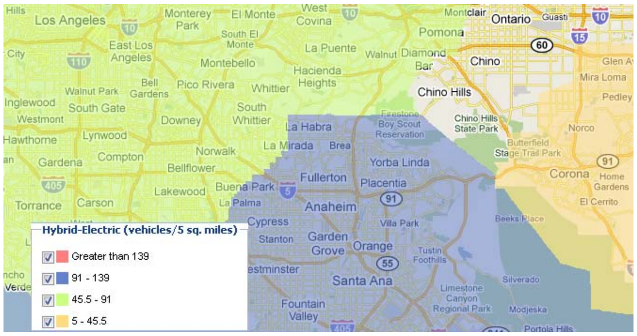

Figure 1: Hybrid vehicle registrations – number of vehicles per 13 km^2 [3]

2. Distribution Hardware Model

According to [4, 5, 6, 7, 8], the primary degradation mechanism in transformers is elevated HST. *Hotspot temperature* is defined as the hottest temperature of any location in the transformer winding. At large electrical loads, elevated core-winding temperatures cause chemical breakdown of insulating paper and insulating oil [8]. When the dielectric properties of the insulation change, the voltage isolation within the transformer is compromised, leading to failure.

The HST of transformers has been observed in the field and modeled in a variety of ways. The transformer heating model used in this analysis is based on standard IEC 60076-7:2005 "Loading guide for oil-immersed power transformers" [4]. Difference equations C.6–C.11 (Annex C of IEC 60076) were used as the basis to numerically calculate the HST. The calculations were performed in MATLAB and Microsoft Excel. IEC 60076 develops the HST equations in the following way:

$$\theta_{h(n)} = \theta_{o(n)} + \Delta\theta_{h(n)} \qquad (1)$$

where θ_h is the HST in degrees Celsius, θ_o is the top-oil temperature at the current load, and $\Delta\theta_h$ is the total HST rise at the *n*th timestep, where $\Delta\theta_h$ is calculated in (2):

$$\Delta\theta_{h(n)} = \Delta\theta_{h1(n)} + \Delta\theta_{h2(n)} \qquad (2)$$

$\Delta\theta_{h1(n)}$ and $\Delta\theta_{h2(n)}$ come from the difference equations for HST rise, and can be calculated:

$$\Delta\theta_{h1(n)} = \Delta\theta_{h1(n-1)} + \frac{Dt}{k_{22}\tau_w} \times \left[k_{21} \times \Delta\theta_{hr}K^y - \Delta\theta_{h1(n-1)}\right] \qquad (3)$$

where Dt is the timestep in minutes, k_{22} and k_{21} are experimentally-derived constant related to the thermal recovery of the transformer, τ_w is the winding time constant in minutes, $\Delta\theta_{hr}$ is hotspot-to-top-oil gradient at rated current in Kelvin, K is the load factor (current load/rated load), and y is the exponential power of current versus winding temperature rise (winding exponent). Similarly, $\Delta\theta_{h2}$ can be evaluated:

$$\Delta\theta_{h2(n)} = \Delta\theta_{h2(n-1)} + \frac{k_{22}Dt}{\tau_o} \times \left[(k_{21} - 1) \times \Delta\theta_{hr}K^y - \Delta\theta_{h2(n-1)}\right] \qquad (4)$$

where τ_o is the average oil time constant in minutes. The top-oil temperature must be calculated and substituted back into (1):

$$\theta_{o(n)} = \theta_{o(n-1)} + \frac{Dt}{k_{11}\tau_o}\left[\left[\frac{(1+K^2R)}{1+R}\right]^x \times (\Delta\theta_{or}) - \left[\theta_{o(n-1)} - \theta_a\right]\right] \qquad (5)$$

where k_{11} is another experimentally derived thermal Baseline constant of the transformer, R is the ratio of load losses at rated current to no-load losses, $\Delta\theta_{or}$ is the top-oil temperature rise at rated load, and θ_a is the ambient temperature in degrees Celsius. The HST equations were validated using the test case given in Annex C – the model calculates the HST over a 120-minute period, based on the load factor and ambient temperature. The model followed the results of the test case within 0.05%.

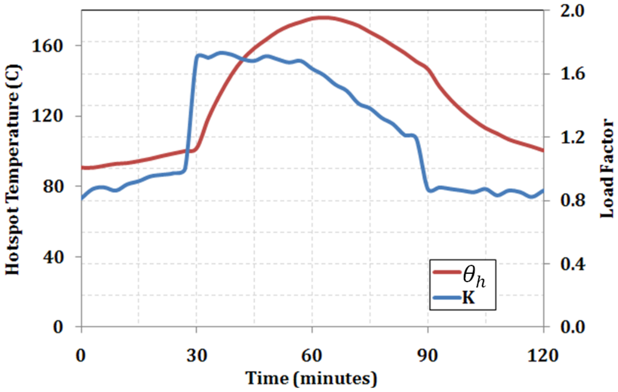

Figure 2: Simulated hotspot and transformer load factor as a function of time. From IEC60076 Annex C example, used for validating the numerical model implementation.

2.1 Transformer Aging Characteristics

The goal of this analysis is to define the limits of HST increase and aging due to PHEV charging loads for a specific transformer type. The distribution transformer's properties used in the analysis for this paper are shown in Table 1.

Table 1: Distribution Transformer Properties

Symbol	Property	Value	Units
g_r	Average winding-to-average-oil temperature gradient at rated current	14.5	Ws/K
H	Hot-spot factor	1.4	
k_{11}	Thermal model constant	1	
k_{21}	Thermal model constant	1	
k_{22}	Thermal model constant	2	
P_{rated}	Transformer rated power	25 or 37.5	kW
R	Ratio of load losses at rated current to no-load losses	8	
Dt	Simulation timestep	1	minutes
x	Exponential power of total losses v. top-oil temperature rise (oil exponent)	0.8	
y	Exponential power of current v. winding temperature rise (winding exponent)	1.6	
$\Delta\theta_{hr}$	Hot-spot-to-top-oil gradient at rated current	20.3	K
$\Delta\theta_{or}$	Top-oil temperature rise at rated load	38.3	K
τ_0	Average oil time constant	180	minutes
τ_W	Winding time constant	10	minutes

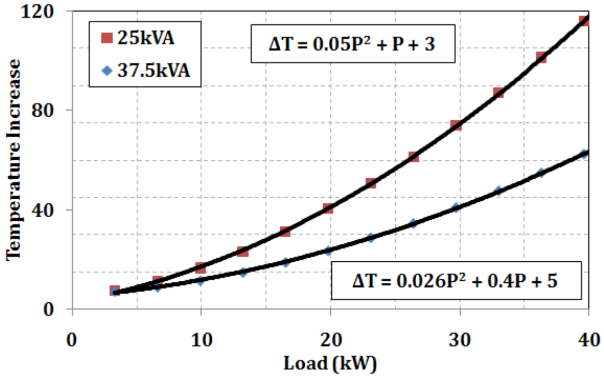

Figure 3: Hotspot temperature increase as a function of load. Square and diamond markers indicate each additional PHEV loading the transformer at 3.3 kW.

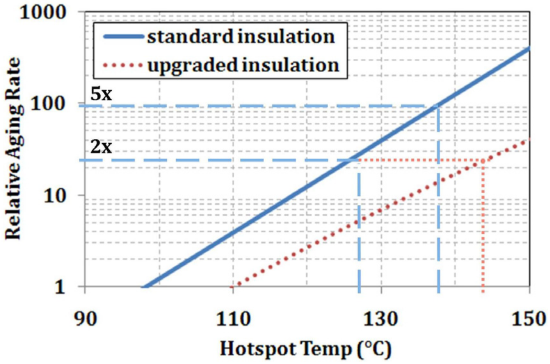

Figure 4: Relative aging rate as a function of hotspot temperature. Upgraded and non-upgraded insulation curves are included, as defined in IEC 60076 [8]. The horizontal dashed lines correspond to the daily max loading for one hour per day. Text above the line indicates the averaged aging rate.

Table 2: Net Aging Rate Summary: Based on 1-Hour Daily Peak Load

Insulation Type	Peak HST (°C) (1 hour duration)	Net Aging Rate
Standard	127	2x
Standard	137	5x
Upgraded	144	2x

Using the validated model implementation, the increase in HST from PHEV loading was calculated. Battery charging profiles for each PHEV are assumed to be a square wave from 0 kW to 3.3 kW. Figure 3 shows the relationship between load and temperature increase, which is nearly linear below rated load – once above the rated load, the elevated HST results in a rapid increase in aging rate, as shown in Figure 4. The labels above the horizontal lines indicate the daily-averaged aging rate, assuming a one-hour peak HST. The average aging rate is calculated:

$$V_{daily} = \frac{V_{peak}+23}{24} \qquad (6)$$

Upgraded insulation is a figure of merit defined by IEEE/ANSI, which states that thermal insulation paper is considered upgraded if it exhibits "50% retention in tensile strength after 65,000 hours in a sealed tube at 100°C" [9]. Replacing older distribution transformers with upgraded-insulation models on known PHEV-loaded transformers appears to be one immediate solution for preventing accelerated transformer replacement. However, grid communication networks may provide additional opportunity for utilities to sufficiently offset PHEV charging loads, in addition to other valuable services provided by an intelligently operated power grid [10, 11, 12, 13, 14, 15, 16].

3. Analysis

Two analyses were conducted to demonstrate the capabilities of the model: a baseline analysis and a Monte-Carlo analysis. The baseline analysis demonstrates a worst-case scenario, assuming a 3.3-kW charging rate, where all PHEVs plug in at the same time during peak load. The Monte-Carlo analysis utilizes data that reflect actual driver behavior, load characteristics, and weather data to determine how actual operating conditions affect a transformer from the base scenario.

3.1 Baseline Analysis

The goal of the base scenario analysis is to define the maximum limits of transformer aging rate due to additional PHEV charging loads. The base scenario analysis makes the following assumptions:

1. Ten houses are served by a 25-kVA or 37.5-kVA transformer.
2. Vehicle charging loads are summed with an existing customer peak representing 80% of the transformer rating.
3. Ambient air temperature is 30°C.
4. Vehicles charge at a rate of 3.3 kW.

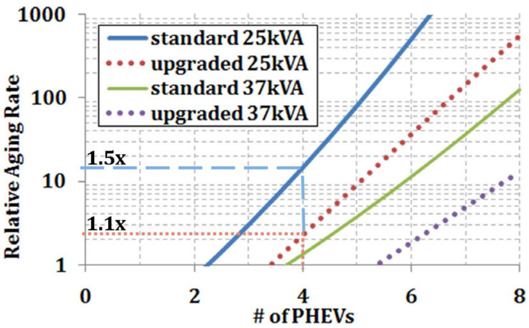

Figure 5: Base Scenario: relative aging rate vs. number of PHEVs on a distribution transformer, assuming an initial peak load of 80% of the transformer rating, ambient temperature of 30°C, and 3.3 kW level-2 charging.

Figure 5 shows the effect that simultaneous battery charging will have on aging rate for a transformer already operating at 80% of the rated load during its peak hour. The dashed horizontal lines indicate the peak aging rate for 1 hour of the day, while the number above the line indicates the daily averaged aging rate, based on the peak load. Assuming four PHEVs are served by a 25-kVA transformer, this scenario suggests a service life decrement of 10–50%. However, the 37.5-kVA distribution transformer saw a negligible decrease in expected service life. Real-world PHEV loading is less than this base scenario due to the diversity of vehicle arrivals.

3.2 Monte-Carlo Analysis

GPS travel survey data from the Southern California Association of Governments (SCAG) shows all of the arrival times for 1,150 drivers to their homes, superimposed on top of a single-phase distribution transformer load, shown in the green curve of Figure 6 [17, 18]. The behavior of PHEV owners will be a primary factor faced by distribution networks. For consumers wishing to charge their 18-kWh battery pack (PHEV40) within 2 hours of arriving home, SAE J1772 level-2 charging will provide the 6.6-kW charging power necessary to meet this need. However, overnight vehicle charging may not need the full power capabilities of the circuit, and so a 3.3-kW charging scenario is compared to the 6.6-kW maximum.

All of the vehicles have 11.6 kWh of useable energy storage and have a charging efficiency of 81%. The simulated vehicles' electric motor provides 100% of the traction power when in charge-depleting (CD) mode. The vehicles drive in CD mode until the battery reaches a 35% state-of-charge (SOC), at which time an auxiliary gasoline engine runs a generator that maintains the battery's SOC for the duration of the trip. The ambient temperature data come from the typical meteorological year data set for Los Angeles [19].

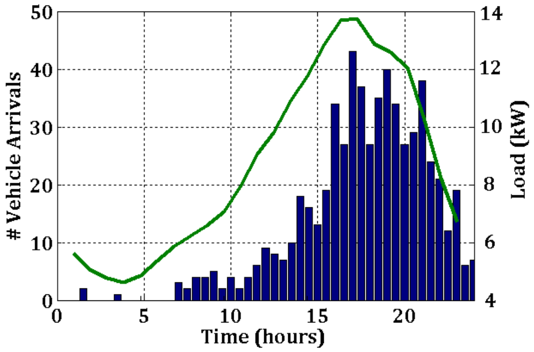

Figure 6: Expected transformer load and number of arrivals as a function of time. Driving data come from SCAG GPS travel survey data and represents 1,150 drivers in the Los Angeles area. The green curve is an averaged residential transformer load and does not include PHEV charging.

Figure 7 shows the MATLAB simulation inputs and outputs – standard residential load profiles, meteorological data, and GPS travel data are combined to calculate the HST rise and corresponding transformer wear acceleration. The year-long baseline increase in aging rate due to PHEVs was calculated by running the data through a one-year simulation period. Each day was simulated 100 times, using unique sets of driving profiles for each simulated day. The simulation assumes that PHEV owners immediately plugged in upon arrival home.

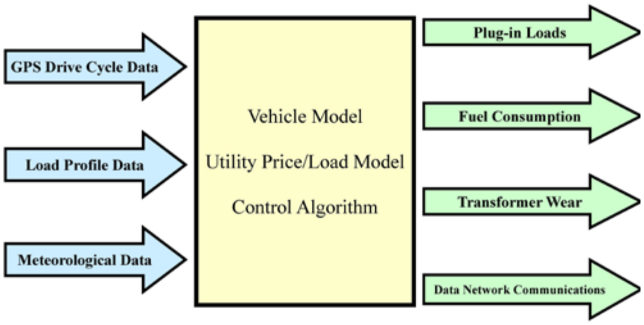

Figure 7: MATLAB model data inputs and outputs for Monte-Carlo analysis.

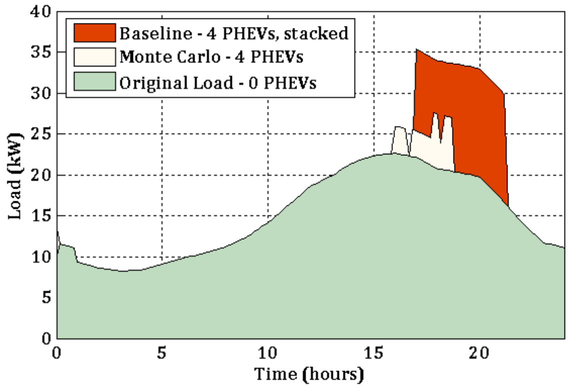

Figure 8: Transformer load as a function of time, before and after PHEV charging load contribution. Transformer serves 4 PHEVs charging at 3.3 kW. The baseline assumes each vehicle travels 40 miles per day; a random monte-carlo simulation was plotted, illustrating the temporal diversity in charging events.

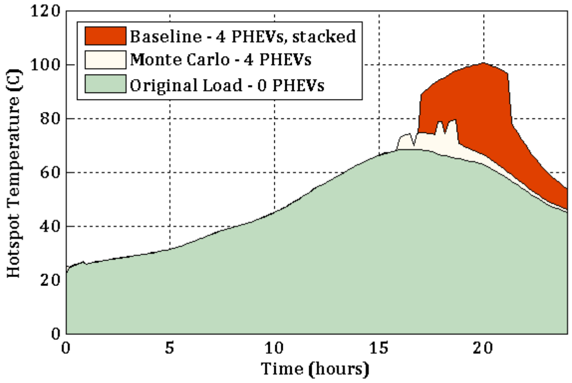

Figure 9: Hotspot temperature as a function of time, corresponding to the example in Figure 8.

Table 3: Summary of PHEV charging events from the daily example in Figure 8

Vehicle	Charging Start Time	SOC (%)	Energy Needed (kWh)	Duration (minutes)
2	16:00	83	3.0	55
3	16:50	63	6.6	120
4	17:50	90	1.8	36
2	18:20	87	2.3	42

A daily load and HST profile are shown in Figure 8 and Figure 9. Under this scenario, there are four separate PHEVs charging at various times. The plug-in loads are obvious spikes in load for two-hour periods, and contribute a significant additional load onto the transformer. The transformer thermal response can be seen in Figure 9, and a summary of PHEV charging events can be found in Table 3. In this example, the PHEVs typically arrive on an empty battery, except for one early-evening trip by vehicle 4, which promptly went back out until later in the evening. The other vehicles arrivals were distributed between 5 p.m. and 8 p.m., giving the transformer sufficient time to thermally recover from the previous charging events.

Table 4: Monte-Carlo simulation case definition

Test Case	Transformer Rating (kVA)	Number of PHEVs
Base	25	0
Base	37.5	0
1	25	1
2	25	3
3	25	6
4	37.5	1
5	37.5	3
6	37.5	6

The year-long maximum increase in aging rate due to PHEVs was calculated by running the simulation over a one-year period, taking the maximum aging per day based on 100 daily simulations. The maximum case was chosen because the averaged load data do not reflect periods of elevated load that would accelerate the aging process. Additionally, the typical meteorological year data do not reflect prolonged heat waves during the summer time, which would also contribute to accelerated transformer aging. The natural diversity of vehicle arrivals still provided sufficient time for the transformers to cool down in nearly all cases.

The resulting HST-duration curves from the six test cases described in Table 4 are shown in Figure 10 and Figure 11. In the most extreme Monte-Carlo scenario, where six PHEVs were loading a 25-kVA transformer at 6.6-kW each. The addition of PHEV charging loads reduced the transformer nominal lifetime by 12%; all other simulations yielded life reductions less than 1%.

3.3 Communication-Enabled Analysis

Based on the analysis above, a simulation using a PHEV demand-control scheme was performed. In this scenario, the communication system may delay an individual PHEV charger in order to prevent coincident charging during peak load. The charge-delay scheme requires that vehicles wait for 10-minutes intervals until the transformer HST drops below 98°C

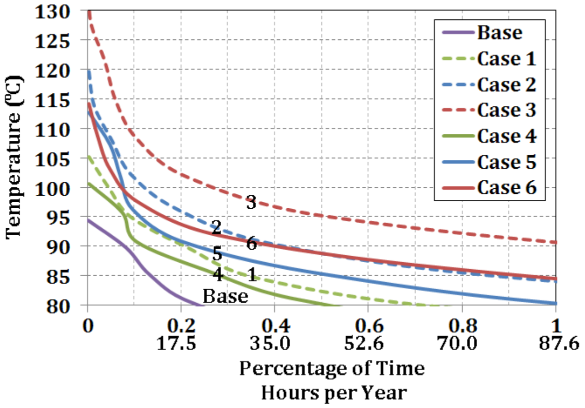

Figure 10: HST duration curves for 6 test cases using a 25 or 37.5 kVA transformer, and 1-6 PHEVs for the maximum 1% of the time, or 88 hours per year. Assumes 3.3 kW charging.

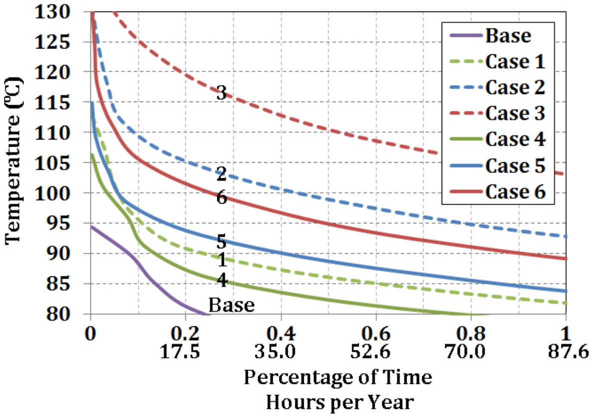

Figure 11: HST duration curves for 6 test cases using a 25- or 37.5-kVA transformer, and 1-6 PHEVs for the maximum 1% of the time, or 88 hours per year. Assumes 6.6 kW charging.

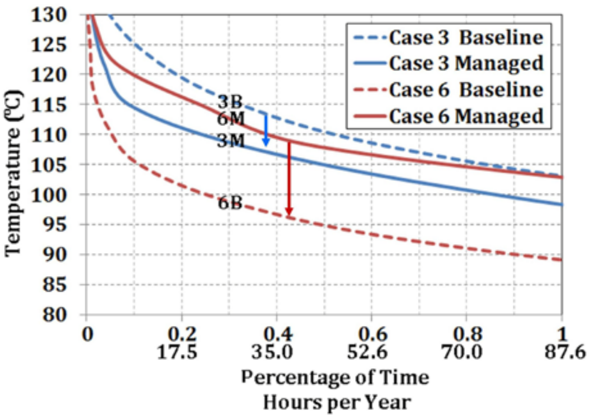

Figure 12: HST duration curves for 6 test cases using a 25- or 37.5-kVA transformer, and 1-6 PHEVs for the maximum 1% of the time, or 88 hours per year. Assumes 6.6-kW charging and a charge-delaying scheme where charging is stopped if the HST rises above 98° C.

This particular scenario demonstrates how often vehicle charging might need to be controlled in the most extreme case, when six vehicles are sited on a single transformer. A total of 1,200 charge delay periods were requested by the utility for the 25-kVA transformer – in other words, a PHEV owner might expect to have their vehicle's charging delayed by about 33 hours per year. For the 37.5-kVA transformer, 240 charge delay periods were requested, totaling 7 hours per year per car. The change in HST duration before and after grid communication is shown in Figure 12. Even with the charge-delay scheme, peak loads on hot summer days may still occasionally push the HST above 98°C.

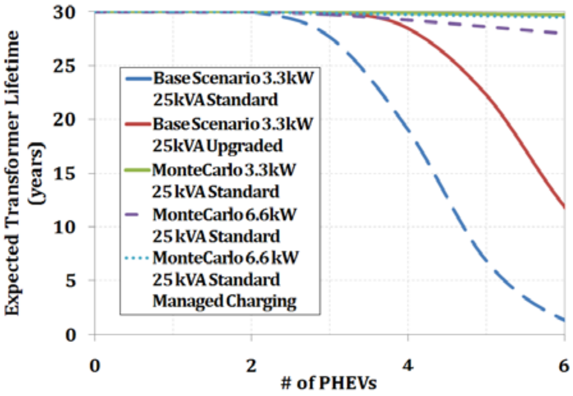

Figure 13: Expected Transformer Lifetime as a Function of the Number of Vehicles on the Transformer, and the Scenario Type.

The HST curves were integrated and the annual aging rate was calculated to determine expected transformer lifetime. A summary of expected lifetimes for a 30-year rated transformer is shown in Figure 13. The baseline scenario, where all vehicle coincidentally charge at 3.3 kW on a 25-kVA transformer, shows what may happen if four PHEVs simultaneously charge on a daily basis – the transformer's life would be reduced by 37%. Using the same rating transformer with upgraded insulation would produce an expected lifetime loss of only 8%. However, arrival distribution of drivers show that stacked PHEV loads would be infrequent enough to impact transformer life by more than 3%, given the simulated Monte-Carlo scenarios.

5. Conclusion and Future Work

This paper developed a method for determining lifetime wear on a residential distribution transformer due to plug-in vehicles. Driver behavior data shows that the natural distribution of vehicle arrivals is sufficient to eliminate a majority of stacked PHEV charging. For the occasional situation where stacked charging does occur, one-way grid communication could provide valuable charging-offset services. Because increasing the diversity of times when people physically arrive at home is not possible, additional grid communication capabilities at the distribution level could be used to increase the diversity of charging between PHEVs connected to the same distribution transformer. Further upstream in the power system, this same communication network would allow the PHEVs to provide ancillary services to the utility [20, 21, 22]. Basic one-way communication could ensure that transformer overheating does not occur and utility service continues uninterrupted during extreme HST excursions. A preliminary example showed that PHEV charging would need to be managed for fewer than 33 hours per year in the most extreme case, to mitigate PHEV-induced degradation.

These results are specific to parts of the Southern California system. Differences in load shape, weather, and number of houses per transformer vary substantially depending on region, as well as within the same region. Future work will include:

- Validating the model's hotspot temperature predictions with actual data collected in the field
- Run the model using non-averaged transformer data that includes extreme load excursions seen on transformers in the field
- More detailed transformer thermal modeling, including harmonic currents [23, 24]
- Collecting large sets of field data to evaluate sensitivity of different types of regional characteristics, including transformer load shape, climate, and transformer sizing
- Using this model, in collaboration with higher-level models, to develop control schemes that enable PHEV ancillary services and greater integration of renewable energy generation

In summary, a simulation process was developed to predict the impact of PHEV charging on a particular residential transformer. This simulation:

- Utilized the IEC 60076 standard to develop a transformer aging model that can be applied to PHEV loads on a distribution transformer
- Combined transformer load profile data, GPS travel survey data, and meteorological data
- Provides graphical outputs to predict transformer life based on different PHEV control scenarios.
- Shows that the natural distribution of vehicle arrivals sufficiently prevents most stacked charging events, reducing periods excessive hotspot temperature that degrade transformer life

In conjunction with the higher-level power system benefits of grid communication and renewables integration, low-bandwidth one-way communication with PHEVs appears to be a simple solution for ensuring reliable operation of the distribution system throughout PHEV deployment.

6. Acknowledgements

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14. ABSTRACT *(Maximum 200 Words)*

Concentrated purchasing patterns of plug-in vehicles may result in localized distribution transformer overload scenarios. Prolonged periods of transformer overloading causes service life decrements, and in worst-case scenarios, results in tripped thermal relays and residential service outages. This analysis will review distribution transformer load models developed in the IEC 60076 standard, and apply the model to a neighborhood with plug-in hybrids. Residential distribution transformers are sized such that night-time cooling provides thermal recovery from heavy load conditions during the daytime utility peak. It is expected that PHEVs will primarily be charged at night in a residential setting. If not managed properly, some distribution transformers could become overloaded, leading to a reduction in transformer life expectancy, thus increasing costs to utilities and consumers. A Monte-Carlo scheme simulated each day of the year, evaluating 100 load scenarios as it swept through the following variables: number of vehicle per transformer, transformer size, and charging rate. A general method for determining expected transformer aging rate will be developed, based on the energy needs of plug-in vehicles loading a residential transformer.

15. SUBJECT TERMS
Distribution transformer; smart grid; Monte-Carlo method; plug-in hybrid; PHEV

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