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Development of Demand Response Mechanism to Reduce the Impact of EV Charging on Power Distribution Transformers

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Abstract- the transportation industry, which contributes around 25% of overall carbon-dioxide emissions, has sparked concern about greenhouse gases emissions. The primary solution to this challenge is electric vehicles. However, large-scale integration of electric vehicles into distribution grid for charging raises significant concerns like increased ageing of costly grid equipment such as transformers. Therefore, this paper investigates the effects of high electric vehicle charging penetration on power distribution transformers and proposes a novel technique to mitigate their detrimental effects. The proposed technique is developed as an optimization problem, in which demand response is linked with time of use price to reduce the impact of EV charging on power distribution transformer. Simulation results obtained using the proposed methodology reveals that the transformer life expectancy increased as overheating of transformer decreased due to demand response.

Keywords: Electric vehicles, time of use tariff, demand response, loss of life, distribution transformer aging, Optimization.

Abbreviations

LoL	Loss of life of transformer.
SOC	State of charge.
SSE	Sum of squared errors.

Parameters

α_T	Spot electricity price in Tth hour
α_k	Spot electricity price in kth hour
ΔL_H	Winding hot-spot temperature rise over top-oil temperature
ΔL_{TOR}	Top-oil temperature rise over ambient temperature at rated load
ΔL_{TO}	Top-oil temperature of transformer
η	Efficiency of the charger
C_K^{SSE}	Successive difference of SSE
ε	Number of EVs per household
d	Oil thermal time constant at rated load
μ	Winding time constant for hotspot location in hours
L_A	Ambient temperature
L_{HR}	Winding hotspot temperature over top-oil at rated load
L_H	Winding hotspot temperature of transformer
B_K	Incentive in Kth hour
B_T	Incentive in Tth hour
K	Daily mileage driven in km
C	Energy consumption in kWh/km
F_{batt}	Capacity of battery in kWh
F_{cons}	Energy consumed by Electric Vehicle
F_{req}	Energy required to charge Electric Vehicle
$F_{T,K}$	Cross elasticity at Tth hour

F_T Self-elasticity at Tth hour
E_{AA} Accelerated aging coefficient of transformer
E_{EQA} Equivalent aging coefficient of transformer
E_{EQA}^{TOU} Equivalent aging coefficient based on proposed method
E_{EQA}^{un} Equivalent aging coefficient based on uncontrolled charging
θ_{EV} EV load
θ_{normal} Nameplate insulation life of transformer
θ_R Residential load
θ_{t-1} Ratio of initial load to the rated load
θ_T Total load on transformer
θ_t Ratio of ultimate load to the rated load
$Life_{exp}^{ToU}$ Based on proposed method Life expectancy of transformer
$Life_{exp}^{Un}$ Based on uncontrolled method Life expectancy of transformer
n Exponent of load squared vs winding gradient
M Number of EVs
m EV index
M_{EV} Number of EVs
M_{House} Number of household
$R_T^{offpeak}$ Off-peak price at time T
R_T^{peak} Peak price at time T
$R_T^{sdr\_1}$ Threshold-1 price at time T
$R_T^{sdr\_2}$ Threshold-2 price at time T
s Ratio of load loss at rated load to no-load loss
Q_{nom} Nominal apparent power of transformer
Q_T Apparent power of transformer at tth hour
SOC_{ini}^n nth EV initial SOC
SOC_{min} EV battery minimum SOC
SOC_t^n nth EV at time t SOC
t Time horizon
T Time slot index
β_{min} Transformer's temperature to start off-peak price
β_{peak} Transformer's temperature to start peak price
β_{sdr_1} Transformer's temperature to start shoulder-1 price
β_{sdr_2} Transformer's temperature to start shoulder-2 price
M_{EV} EV load
Y_{pen} Penetration level of EVs

1. INTRODUCTION

Due to global climate change and greenhouse gas emissions, electric vehicles (EVs) are becoming more popular. [1]. By 2040, about 28% of the world's passenger population will be riding in electric vehicles [2]. However, this is crucial in order to minimize the impact of electric vehicles integration on distribution transformers. Therefore, detrimental effects of electric vehicles on distribution systems are one of the most major barriers to their effective integration into current transportation infrastructure [3],[4]. Furthermore, due to heavy penetration of EVs, power loss could increase to 38%. As a result, the distributing system's holding capacity is necessary. In [5], a voltage-restricted approach to assess maximum hosting capacity and recommends regulated charging as an EV integration aid. [6] Calculates marginal holding capacity based on a linear power flow, which can be used to identify nodes that are substantially more effective at utilizing system capacity. In the absence of desecrate the channel's practical limits, the technique of electric car charging area optimizing network is presented in reference [7]. Unplanned EV charging occurred on the lower voltage level, therefore, undesirable consequences' are more in distribution grid especially in distribution transformers [8]. When transformers are over loaded, the temperature of the winding rises [9]. Overall, high EV adoption may result in under voltage limit deterioration, voltage limit degradation and 3-phase power supply distortion. As a result, the negative effects of EV integration on distributing grid remarkably increases which affects distribution transformer's life expectancy and cost of utilities [10].

The current condition of battery charger harmonics is summarized in [11]. Harmonic distortion's influence on the distribution system, particularly distribution transformers, is explored. Electric utilities may confront challenges, particularly at the distribution level, when plug-in hybrid vehicles (PHEVs) obtain a bigger share of the personal car market [12]. Impact of electric vehicles on transformers and underground cables was discussed in [13-16]. Model of smart charging system and its impact on distribution grid was shown in [17]. Price based charging of EVs and its impact on distribution system is studied in [18-20].

From the literature survey, it is observed that it is critical to charge electric vehicles without endangering the network. To address the afore mentioned problem, this study proposes a system for charging electric vehicles that rely on transformer heating, with demand set by a time-of-use pricing.

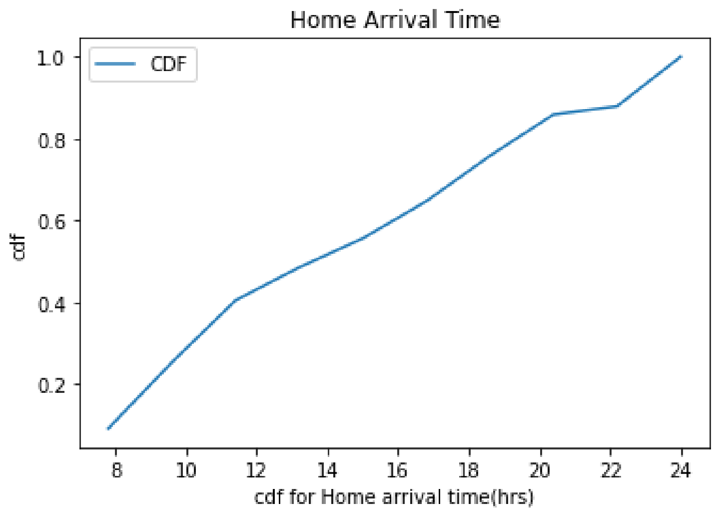
2. Modeling of EV load, ambient temperature & residential Load, and distribution transformer

To reduce distribution transformer loss of life, this research proposed Time of Use (ToU) pricing mechanism. For implementing the proposed mechanism, change in physical infrastructure does not required. Further, modeling of EV load, ambient temperature, residential load, and distribution transformer is carried out in subsequent sections to implement the proposed mechanism.

2.1 Electric Vehicle Load Modeling

The Jupyter Notebook is used to assess the EV vehicle's overall load demand during the 24 hours. Because EV charging is a stochastic process, Jupyter Notebook may be required to correctly approximate cumulative EV load requirements. For 129,695 users, NHTS (2017) estimated the charge completion time and charging start data [21]. More than 75% of electric vehicles are charged at home [22], hence, the period during which car customers begin charging was determined using the most recent household arrival statistics for electric vehicles. The charging time is determined by the daily distance travelled. The continuous distribution function is also used to determine the home departure duration and daily mileage, figure-1 & 2.

Figure- 1. Home arrival time.



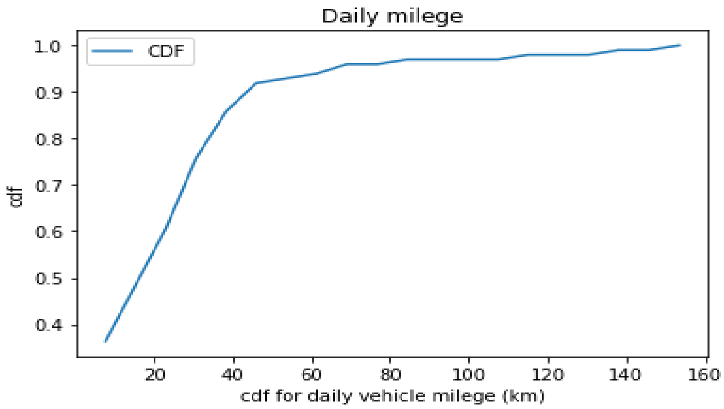


Figure -2. Daily mileage.

The number of EVs linked with distribution system can be determined using (1).

$M_{EV}= Y_{Pen}*M_{House}*\varepsilon$ (1)

In this work, Chevy volt (24-kwh) and Nissan Leaf (18- kwh) EV models are considered. To determine the power required by the batteries, charging level 2 with a charged ability of 3.7 Kilowatt was used. Steps for computing the EV load are as :

Input: F_{batt}: Capacity of battery in kWh
K: Daily mileage driven in km
e: Energy consumption in kWh/km
η : Efficiency of charger
i: Set minimum state of charge

$$SOC_{min}=\begin{cases} 30\% & if\ EV\ is\ Chevy\ Volt \\ 5\% & if\ EV\ is\ Nissan\ LEAF \end{cases}$$

ii: Compute the energy consumed by the vehicle

$$F_{cons} = \frac{K*e}{F_{batt}}$$

iii: Compute the state of charge (SOC) of the battery

$$SOC_{ini}^{m} = \max\ [SOC_{min}, (1 - F_{cons}\frac{K}{F_{batt}})]$$

iv: Calculate the energy required to charge the vehicles

$F_{req} = (\frac{1-SOC}{\eta})*F_{batt}$

Output: Required energy to charge the vehicle(F_{req}).

2.2 Ambient Temperature And Residential Load Modeling

Most of the researchers have used a load curve that provides a typical load demand to describe actual load. However, variations in load over time were not considered in this model. In this work, the Commonwealth Scientific and Industrial Research Organization's (CSIRO) Australia load profile data and Australian Government's Bureau of Meteorology [23-24] ambient temperature data have been used. Equations-2 and 3 solved to get the correct number of clusters. The upper limit of C_K^{SSE} was utilized to calculate the most appropriate amount of clusters.

$$SSE=\sum_{i=1}^{K}\sqrt{\sum_{p\epsilon C_i}(C_i - p)^2} \quad (2)$$

$$C_K^{SSE}=SSE_{K-1}+SSE_{K+1}-2 * SSE_K \quad (3)$$

2.3 Modeling of Distribution Transformer LoL

The IEEE standard C68.81 is considered to create the temperature ageing equation. The loss of life of a transformer was calculated using (4), where 't' is the number of time intervals, which is usually 24 hours, and θ_{normal} is the transformer's insulation life under standard load, which is usually 18000 hours.

$$LOL\ (\%) =\frac{E_{EQA}*t*100}{\theta_{normal}} \quad (4)$$

E_{EQA} is the average ageing factor, which is calculated by (5). The real accelerated ageing factor E_{AA} for each time phase is used to calculate the transformer's lifespan decline by (6). In this empirical calculation, the transformer's hotspot temperature is employed. When the hotspot's temperature was higher than the prescribed hotspot's temperature (usually 120C), the E_{AA} was larger than 1, and vice versa.

$$E_{EQA} = \frac{\sum_{m=1}^{M} E_{AA,m} * \Delta T_m}{\sum_{m}^{M} \Delta T_m} \quad (5)$$

$$E_{AA} = e^{\frac{15000}{383} - \frac{15000}{L_H + 283}} \quad (6)$$

The ageing of a transformer is determined by the hotspot temperature using equation -7.

$$L_H = L_A + \Delta L_{TO} + \Delta L_H \quad (7)$$

The rise in hotspot temperature caused by winding as well as oil is computed using (8) and(9), respectively.

$$\Delta L_H = L_{HR} * \{(\theta_T^{2n} - \theta_{T-1}^{2n})(1 - e^{\frac{\Delta T}{\mu}})\} + \{\theta_{T-1}^{2n} * L_{HR}\} \quad (8)$$

$$\Delta L_{TO,T} = \Delta L_{TOR} * \{(\frac{\theta_T^2(S+1)}{S+!}) - (\frac{\theta_{T-1}^2(S+1)}{S+!})\} * (1 - e^{\left(\frac{S(\delta_T^{m-1} - \delta_{T-1}^{m-1})\Delta T}{d(\delta_{T-1}^{m} - \delta_T^{m})}\right)} \quad (9)$$

Where,
$\delta_T = \theta_T(S-1)$
$\delta_{T-1} = \theta_{T-1}(S-1)$
T=1, 2……………, 24
m=1, 2............…..., 24

Loss of life of the distribution transformer is calculated using the function' of the distribution system demand as well as the ambient' temperature. Except ϴt and ϴt-1 all the symbols in (8) & (9) are constants.

3. PROPOSED MECHANISM TO REDUCE IMPACT OF EV CHARGING ON DISTRIBUTION TRANSFORMER

The focus of this work is to figure out the best ToU pricing based on the ambient temperature. Relation between load and energy cost [25] is shown in (10).

$$\theta_T = \theta_{T-1} + F_T \frac{\theta_{T-1}}{a_o}[a_T - a_o - B_T] + \sum_{\substack{k=1 \\ K \neq T}}^{24} F_{T,K} \frac{\theta_{T-1}}{a_o}[a_T - a_o - B_T] \quad (10)$$

Where, T, k = 1…….24

This work used time of use price based Demand Response (DR) mechanism to reduce the accelerating aging of distribution transformer. The mechanism is developed as an optimization problem with the objective to minimize E_{AA} which is the function of household load and EVs load subject to equality and inequality constraints.

$$\text{Min } F(E_{AA}) = \sum_{T=1}^{24} E_{AA}(\theta_{R,T} + \theta_{EV,T})\,\Delta T \quad (11)$$

s.t.

Limit on Transformer Capability:

$$Q_T \leq Q_{nom} \quad (12)$$

Transformer demand:

$$\theta_{Total,T} = \theta_{R,T} + \sum_{m=1}^{M} \theta_{EV,T}^{m} \quad (13)$$

Electric Vehicle SOC:

$$SOC_T^m = SOC_{T-1}^m + \left(\eta \theta_{EV,T}^m \frac{\Delta T}{F_{batt}}\right) \quad (14)$$

$$SOC_{ini}^m = \max\,[SOC_{min}, (1 - F_{cons} \frac{k}{F_{batt}})] \quad (15)$$

$$SOC_{dep}^m = SOC_{req} \quad (16)$$

Lithium-ion Battery Charging Characteristic:

$$\theta_{EV,T}^{m}=\begin{cases}\theta_{EV}^{max} & if\ 0 \le T \le T_1 \\ \theta_{EV}^{max}\left(\frac{T_2-1}{T_1-1}\right) & if\ T_1 \le T \le T_2\end{cases} \quad (17)$$

To avoid increased ageing owing to increased temperature, the overall apparent energy after the inclusion of EVs must not exceed the transformer's capability limit (12). The total required load that the transformer is subjected to at any particular time T is presented as a limitation (13). Constraints provides the State of charge of nth electric vehicle at period T for an amount of interval ΔT (14). From (15), the initial nth EV is determined based on the prior traveling range The charging power of an electric vehicle is determined using a common charging pattern as a restriction (16).

Peak price at time T (R_T^{peak}) and transformer temperature at peak price (β_{peak}) are the decision variables. The table 2 shows the relation between four distinct threshold temperatures and the ToU tariffs. Relation between time of use price and transformer temperature is shown in (18). Solution of (10) will provide the ToU tariff, as well as the self and cross elasticity used among the various rates [26].

$$R_T^{peak}=\begin{cases} R_T^{peak} & if\ L_H \le \beta_{peak} \\ R_T^{sdr\_1} & if\ \beta_{sdr\_1} \le L_H \le \beta_{peak} \\ R_T^{sdr\_2} & if\ \beta_{sdr\_2} \le L_H \le \beta_{sdr\_1} \\ R_T^{peak} & if\ \beta_{min} \le L_H \le \beta_{sdr\_2}\end{cases} \quad (18)$$

Where,

$\beta_{sdr\_1} = (\beta_{peak} - \beta_{min})\frac{2}{3} + \beta_{min}$

$\beta_{sdr\_2} = (\beta_{peak} - \beta_{min})\frac{1}{3} + \beta_{min}$

$R_T^{sdr\_1} = (R_T^{peak} - R_T^{off\_peak})\frac{2}{3} + R_T^{offpeak}$

$R_T^{sdr\_2} = (R_T^{peak} - R_T^{off\_peak})\frac{1}{3} + R_T^{offpeak}$

Table 1 shows the self and cross elasticity used between the various tariffs.

Table 1. Self and cross elasticity

	Peak	Shoulder-1	Shoulder-2	Off-peak
Peak	-0.1	0.009	0.009	0.01
Shoulder_1	0.009	-0.1	0.009	0.01
Shoulder_2	0.009	0.009	-0.1	0.01
Off-peak	0.01	0.009	0.009	-0.1

4. SIMULATION RESULTS AND DISCUSSIONS

Proposed methodology has been implemented considering EVs load and household load. Distribution transformers parameters considered in this work are given in table 2.

Table 2. Distribution Transformer Parameters

Parameters	Type
Thermal time constant of oil at rated load	6.86 hr.
Winding time constant at hot-spot location	0.08 hr.
Average Ambient temperature	30^0 C
Top oil rise over ambient temperature under rated condition	53^0 C
Hottest-spot conductor rise over top-oil temperature under rated condition	27^0 C
Ratio of load loss at rated load to no-load loss	4.87
Exponent of load function versus top-oil rise	0.8
Exponent of load squared versus winding gradient	0.8

The proposed mechanism simulated under MATLAB environment considering residential load and uncoordinated and coordinated EVs charging. Impact of EVs penetration on transformers' life expectancy has also been analyzed. Total load, comprised of residential and EVs load, ToU price signal, ToU price based load shifting and incentive based load shifting for 24 hours are shown in figure 3. From the simulation results it can be seen that for uncoordinated charging of EVs, the hot-spot temperature of transformer rises over the threshold temperature between 14:00 and 22:00 hours. However, due to demand response, load has been shifted from high price to low price periods, therefore, peak load has been reduced from 1.22 pu at 18:00 hr to 0.94 p.u. at 24:00 hr. The ToU rate ranges from 0.2 to 0.5 dollars per kWh. The demand response presented here can transfer the load to off-peak hours while keeping the transformer temperature within safe limits

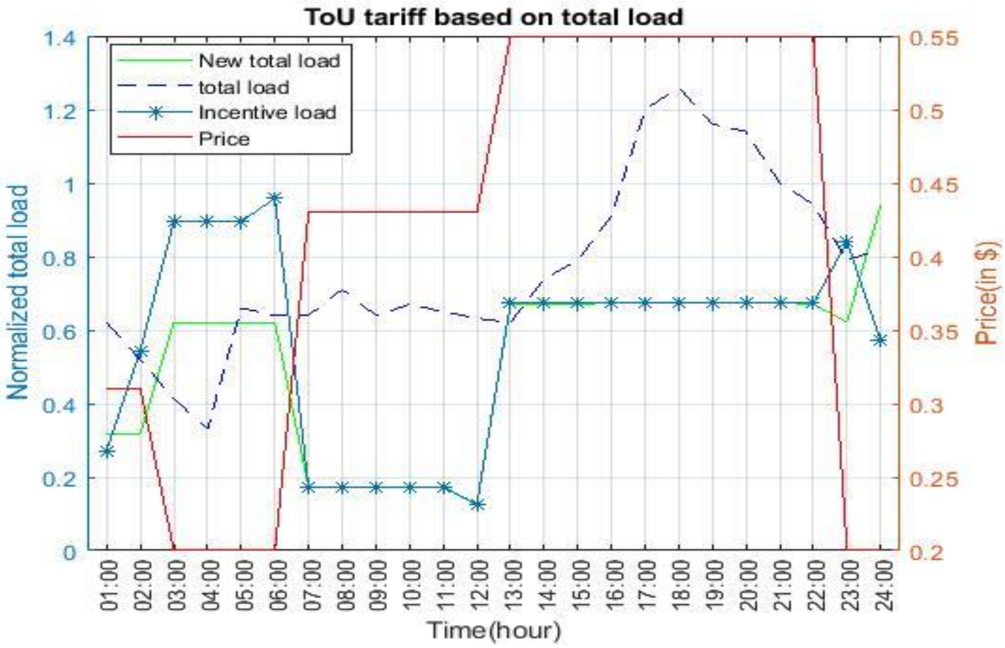


Figure-3. Shifting of load considering price based and incentive based demand response.

Data given in table 2 were included in the thermal simulation of the transformer for the EVs load model. Three scenarios considering 10, 25, and 50 EVs penetration level were tested. Results obtained with proposed mechanism considering coordinated charging strategy has also been compared with uncoordinated charging strategy.

Table 3. Aging of transformer

EV Penetration	R_T^{peak}	β_{peak}	E_{EQA}^{un}	E_{EQA}^{smart}	$Life_{exp}^{un}$	$Life_{exp}^{smart}$
10	0.55	87.5	0.216	0.015	20.55	20.55
25	0.55	85	1.169	0.017	17.58	20.55
50	0.55	84.5	10.149	0.051	2.02	20.55

From the simulation results, it is observed that in case of coordinated charging strategy the transformer's life expectancy is 20.55 years for all the penetration levels of EVs. However, in case of uncoordinated strategy, it is decreasing with high penetration of EVs.

5. CONCLUSIONS

In this work, impact of EVs load on the distribution transformers has been analyzed. A novel demand response mechanism has been developed to reduce temperature of distribution transformer to enhance distribution transformer life expectancy. From the simulation results it is established that the proposed demand response strategy effectively reduces distribution transformer temperature by transferring electric vehicle load from peak hours to off peak hours. Further, coordinated charging of EVs is more effective compared to uncoordinated strategy to enhance the life expectancy of distribution transformers.

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