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Influence of electric vehicle charging rates on transformer derating in harmonic-rich battery charger applications

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Abstract: A study on plug-in electric vehicle (PEV) charging load and its impacts on distribution transformers loss-of-life, is presented in this paper. The assessment is based on residential PEV battery charging. As the exact forecasting of the charging load is not possible, the method for predicting the electric vehicle (EV) charging load is stochastically formulated. With the help of the stochastic model, the effect of fixed, time of use, and real-time charging rates on the charging load and the resultant impact on transformer derating is investigated. A 38-bus test system is adopted as the test system including industrial harmonic sources. Test results demonstrate that uncontrolled EV charging might causes a noticeable change in the K-factor of the transformer, emerging the need for derating, while applying real-time rates for battery charging loads conquers this problem even in case of harmonic-rich chargers.

Key words: electric vehicle charging, charging rate, power quality, stochastic modeling, transformer derating

1. Introduction

Due to increasing gasoline prices, environmental concerns and depletion of fossil fuels, a growing concern for using electric vehicles has emerged. This is while, penetration of large residential loads such as electric vehicles (EVs), is a potential power quality problem. In order to suitably prepare for this problem, utilities must be able to predict the EVs battery charging loads. Since many distribution systems were designed decades ago considering the load levels at that time, major changes might be required in the distribution system components and load management strategies. Unbalanced conditions, reactive power requirements of the charger and the distorted currents drawn by the battery chargers are the power quality issues, which should be studied. Harmonics and overloading problems caused by vehicular battery chargers affect distribution equipment: transformers, cables, circuit breakers, and fuses [1]. Among these equipments, transformers as the vital and costly elements for proper operation of power distribution systems are most important.

Generally, distribution transformers are designed to supply loads with rated frequency. Therefore, much effort has been devoted for estimation of transformer losses and the required derating due to non-sinusoidal currents [2, 3]. A derating technique based on direct measurements performed at fundamental and harmonic frequencies is introduced in [4]. In [5], a finite element method is used for computation of the losses. A digital data acquisition method for measuring derating is proposed in [6]. Here, the derating method introduced in [7] will be used.

To carry out studies on electric vehicle battery charging load impacts on distribution grid equipments, the first step is forecasting the chargers (aggregate) load. Research on this issue goes back to the 1980s, reference [8] gives an account of some of these studies. In [9] quadratic and dynamic programming is developed to explore household EV charging impacts on power losses and voltage deviations in residential distribution systems. Recently, Mullan et al., in [10], set out that electricity suppliers can achieve significant benefits if vehicle charging patterns are controlled from the outset through structured tariffs.

Accordingly, there have been few studies about effect of EV battery charging on distribution transformers. In [11], authors conclude that there is a quadratic relationship between reduction of the transformer life expectancy and the total harmonic distortion of the battery charger current. They assumed that the statistical distribution of battery chargers currents has an exponential increase and decrease, for the fundamental as well as for the odd harmonics. This assumption neglects diversity factors to the current harmonic distribution, while this leads to overestimation of the harmonic problem [12]. Masoum et al., in [13], have presented their study on transformer derating emerged due to PEV penetrations, without considering the stochastic nature of the EV charging load. In [12, 14], prediction of the EV charging load and transformer derating procedure are done using a method that neglects the effect of charging rates on the start time of EV battery charging loads.

In this paper the uncertainties in load diversity duo to charging rate structures will be deliberated while, a model which takes into account the traffic habits, battery charging profile and the resultant stochasticity in the charging load will be used. Besides, the test system is divided into different industrial, commercial and residential areas for investigation of residential charging in presence of industrial harmonic sources.

The rest of the document is organized as follows: Section 2 introduces the current electric vehicle charging standards and power quality requirements. Section 3 presents the stochastic model used for EV charging load modeling. Section 4 deals with harmonic spectra of the loads. Section 5 discusses the effects of harmonics generated by chargers on transformers and formulates this impact. Section 6 presents the test system. Section 7 delivers the simulation results and their discussion. The last section concludes this paper.

2. Electric vehicle charging and its standards

In 1991, the Infrastructure Working Council was formed by the Electric Power Research Institute in the direction of bringing together organizations that are involved in the electric vehicle industry to establish consent items about the methods and requirements of electric vehicle charging. Three charging levels were defined by the Electric Power Research Institute [15].

- level 1: 120 V, 15 A or 20 A: equipment typically installed on vehicle,
- level 2: for both private and public facilities 240 V, 40 A, single phase conductive or inductive connection,
- level 3: fast charging 480 V, 60-80 A, three phase circuit not considered as a requisite for the establishment of a rich charging infrastructure.

Besides, society of automotive engineers (SAE) J2894™ document, deals with power quality requirements for electric vehicle chargers. This document has three main sections: Charger power quality requirements, Characteristics of AC service, and Charging control [16].

According to IEEE standard 519-1992, for the case of loads such as EV battery chargers, current harmonic limit is 15% for harmonics order lower than 11th – values for other harmonic orders are also documented. Also, the guidelines set by National EV IWC, based upon IEC 1000-3-4, recommend a minimum total power factor of 95% and a maximum current THD of 20% [17].

Similar to the previous works on this issue massive three-phase PEV charger models – with all batteries connected in parallel, are presumed to represent the charging load (Principally, single phase charging units are more detrimental since they are more available to provide easy plug and charge, while they usually use PWM technology which harmonics are rich in lots of single phase chargers). Furthermore, non-linear loads are considered to be current sources of different frequencies.

3. Stochastic modeling of PEV charging loads

Considering that lithium-ion batteries are become more and more popular these days, a lithium-ion battery which is used in Nissan Altra EVs, is selected for our assessment [18].

Figure 1 illustrates the charging cycle for this battery [19].

The stochastic model is obtained from [18], a random variable with probability density function (pdf) $f(t)$, as the charging start time variable and another random variable with a probability density function $f_E(E)$, representing the initial state-of-charge SOC_i, are defined.

A) Initial battery state of charge

The variable E_i, initial battery SOC, has a linear relationship with the distance driven (d); i.e.,

$$E_i = \left(1 - \frac{\alpha d}{d_R}\right), \tag{1}$$

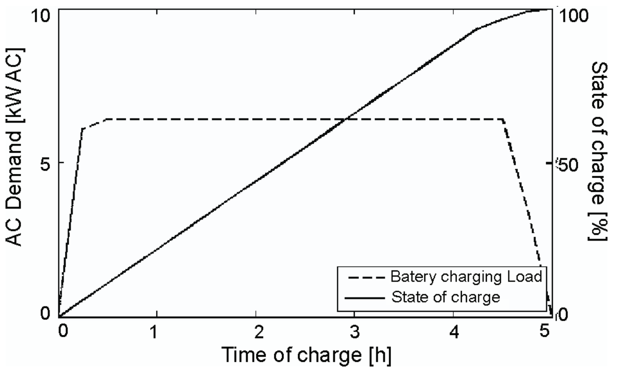

Fig. 1. Charging characteristics of a lithium-ion battery (Nissan Altra)

where d_R is the maximum possible range driven by a fully charged battery and α represents the number of days the PEV has traveled since last charging. Based on information available on private vehicle travel, the pdf for daily distance driven (d), in miles, is found to be of log-normal type [18]. Consequently, using the fundamental theorem introduced in [20], equation (2) will be derived for the pdf of E_i.

$$f_E(E) = \beta \frac{1}{(1-E)\sqrt{2\pi\sigma^2}} e^{-\frac{(\ln(1-E)-(\mu-\ln(d_R/\alpha)))^2}{2\sigma^2}} \quad 0 < E < 1, \tag{2}$$

where β is the coefficient used to eliminate the truncation of the pdf, and thus, justifying it as a density function. This pdf and battery charging profile (Fig. 1) will be used to evaluate the probability of the battery charger power demand.

B) PEV battery charger load demand

According to the charging profile of a lithium-ion battery a vector (**P**) is assigned, in which each item at index j represents a power demand. Assuming that initial state of charge and charging start time are independent variables, the expected value for the charging load at time instant t for an individual battery will be:

$$\mu(\mathbf{P}) = \sum_{j=1}^{n_c} \mathbf{P}_j \Phi(\mathbf{P}_j, t), \tag{3}$$

where, n_c represents the length of the power demand vector for each battery and $\mathbf{\Phi}(P_j, t)$ is the probability of a charging load with operating power demand $\mathbf{P}_j$ at time instant t. Besides, $\mathbf{\Phi}(P_j, t)$ can be expressed as:

$$\Phi(P_j, t) = \sum_{k=1}^{j} f(t-(j-k))\mathbf{H}(k), \tag{4}$$

where $f(t)$ is the charging start time function and is defined in the next part for different scenarios. Furthermore, in Equation (4), $\mathbf{H}(k)$ is the probability of charging power $\mathbf{P}(k)$.

Each element of the vector, $\mathbf{H}$, can be evaluated using Equation (2) and the charging profile shown in Figure 1.

Equation (3) will be used to estimate fundamental current drawn by the chargers, and by using the harmonic spectrum, other harmonic orders currents can be determined. Total load demand at each bus will be μ(P), derived from Equation (3), multiplied by number of vehicles at that bus – since similar batteries and battery chargers for all the PEVs are assumed.

1) *Charging start time for a fixed electricity rate scenario*

When the charging rate is fixed all day long, the vehicle owners do not have any incentive to avoid charging during peak load hours. Therefore, this case might result in a worst case scenario. Hence, for our test system the charging start time function, $f(t)$, is a partly uniform pdf:

$$f(t) = \begin{cases} 1 & t = 18 \\ 0 & t = \text{anyothertime} \end{cases} \quad 1 \le t \le 24, \tag{5}$$

i.e., it is assumed that charging is done at the peak load hours – justifying a worst-case scenario.

2) *Charging start time for a TOU charging rate scenario*

In structures that provide encouragement for EV owners to recharge their vehicles during off-peak times, the following uniform discrete distribution can be employed as a representative for the possible charging start time pattern. (It is assumed that for the times between 21 p.m. and 7 a.m. the charging rate is lower than the other daily hours).

$$f(t) = \begin{cases} 0.33 & t = 21,\ 22,\ 23 \\ 0 & t = \text{anyothertime} \end{cases} \quad 1 \le t \le 24. \tag{6}$$

3) *Charging start time for a real time charging rate scenario*

As a general common sense rule, the higher the price of charge, the fewer the tendencies to charge (at that time) and the higher the traffic at a time, the less the availability of a vehicle to be charged in a station. Therefore by plotting the reciprocal of the product of the curves shown in Figure 2(a), an insight to the shape of the distribution of the charging start time can be gained. Accordingly, it has been demonstrated in [18] that the distribution of charging start time for this scenario can be a Gaussian distribution due to its bell-shape.

$$f(t,\mu,\sigma) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(t-\mu)^2}{2\sigma^2}}. \tag{7}$$

Figure 2(b) depicts the resultant distribution of charging start time represented by Equation (7).

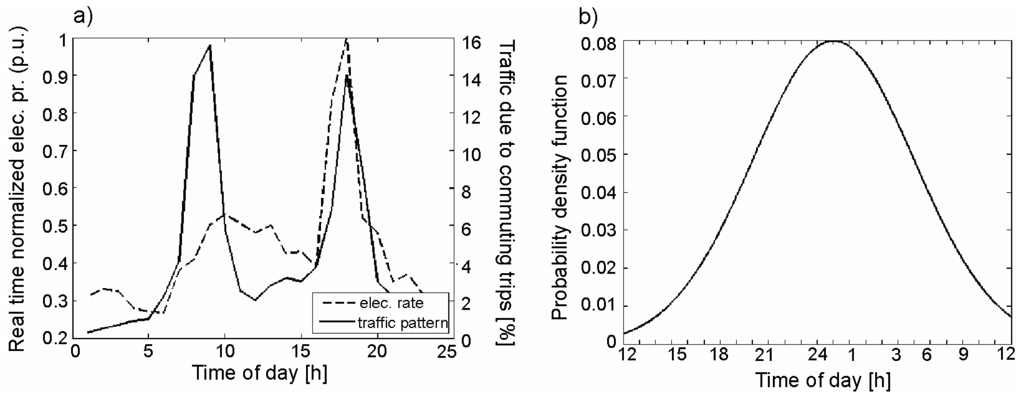

Fig. 2. Real time price and traffic pattern (a), distribution of battery charging start time for the real time rate scenario (b)

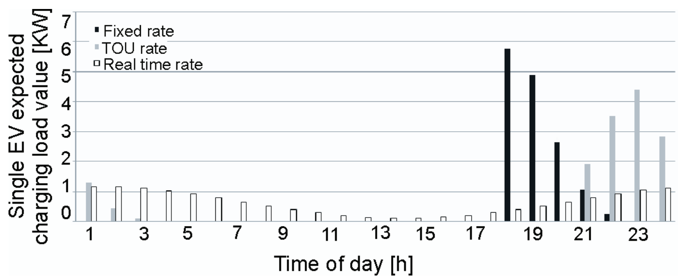

Fig. 3. Impact of scenarios on expected charging load during a day for a single EV

To gain a better insight into the influence of the scenarios on the expected charging load during the day see Figure 3.

4. Harmonic spectra of the loads

A. Non-linear non-EV loads

An industrial area is included in the test case system which involves using of variable frequency drives and adjustable speed drives.

The harmonic current spectra of these VFD and ASDs [21] are used to model their nonlinearity as harmonic current sources – see Table 1.

B. Battery chargers harmonic spectra

As it is mentioned in [11], although some manufacturers and researchers claim of having designs with extremely low THD, but commercial chargers with THD values as high as 60% could be found. Therefore, no general agreement exists among the THD values generated by different battery chargers. Accordingly, some researchers consider the charger as highly contaminating load, with suggested average THD value of about 30%. Staats et al., [12] performed an elaborate statistical study based on Monte Carlo simulations that investigate uncertainties in load diversity due to different start times, variable initial battery state-of-charge and different charging profiles. Typical harmonic current content of PEV chargers obtained from [12] is shown in Table 2.

Table 1. Harmonic current spectra for non-linear industrial loads

h	Variable frequency drive		PWM adjustable speed drive	
	magnitude %	phase (deg)	magnitude %	phase (deg)
1	100	0	100	0
5	23.52	111	82.8	−135
7	6.08	109	77.5	69
11	4.57	−158	46.3	−62
13	4.2	−178	41.2	139
17	1.8	−94	14.2	9
19	1.37	−92	9.7	−155
23	0.75	−70	1.5	−158
25	0.56	−70	2.5	98
29	0.49	−20	0	0
31	0.54	7	0	0

Table 2. Harmonic spectrum used to model the non-linearity of the charging load

Order of harmonic	Magnitude p.u.	Phase (deg)
1	1	0
5	0.25	−68
7	0.17	−41
11	0.09	−41
13	0.05	−20
THD%	31.9%	

Although, according to IEEE standard 519-1992, such a charger with this harmonic content is not an acceptable one, but it would suffice our goal that is to study the case using the stochastic models derived for different charging rates while harmonic-rich chargers are used. As an assumption, this harmonic spectrum will be used for the 29.07 kWh lithium-ion (Nissan Altra) battery charger current, drawn from the utility side line. Furthermore, similar to our modeling for other non-linear loads, current sources with the aforementioned harmonic spectra will represent the non-linearity of the charging load in our harmonic load flow. As additional points, it should be mentioned that differences in the phase angle of current harmonics result in phase cancellation phenomena. Furthermore, when considering the impact of harmonic currents on transformer deration, the THD is a misleading factor, since the magnitude at each order of harmonic current, is more important when thermal effects are concerned. Also, due to unavailability of the required data, in our study, the harmonic content of the charger (in percentage of the fundamental current) is assumed to be constant during the whole charging period but in fact, as the fundamental frequency current drawn by the charger changes during the charge cycle, there is no significant change in harmonic current magnitudes.

5. Effect of EV charging on transformers

Higher heating by fundamental current and additional heat by harmonics (due to losses) are effects of battery charging load on transformer. The non-uniform current distribution in the windings (skin and proximity effects) and stray losses from electromagnetic flux in areas where it was not intended, result in extra losses [11]. Thus, life span reduction by higher hot-spot temperature is introduced. The decrease in the life span can be mitigated by appropriate load reduction, known as required transformer derating. The IEEE standard C57.110 standardizes this transformer life reduction or the derating factor. Making use of the winding eddy-current loss, harmonic current magnitudes, and harmonic order values the derating factor can be evaluated. In general a transformer in which the current distortion exceeds 5% is usually considered for derating for harmonics [17].

A) Dry-type transformer capability equivalent calculation using design eddy-current loss data

Conventionally, a single number to determine the capabilities of a transformer in supplying power to a load is defined. The term F_{HL} is a proportionality factor applied to the winding eddy losses. It represents the effective rms heating caused by the harmonic load current. Equation (8) formulates this term, in which P_{EC} is the total winding eddy current losses due to the harmonics, and $P_{EC\text{-}o}$ is the winding eddy current losses at the power frequency, when no harmonic currents exist. Equation (9) defines the K-factor which can be obtained from F_{HL} in Equation (8). A higher K-factor indicates that the eddy current loss in the transformer will be K times the value at the fundamental frequency.

$$F_{HL} = \frac{P_{EC}}{P_{EC-O}} = \frac{\sum_{h=1}^{h_{\max}} I_h^2 h^2}{\sum_{h=1}^{h_{\max}} I_h^2}, \tag{8}$$

$$K - \text{factor} = F_{HL} \frac{\sum_{h=1}^{h_{\max}} I_h^2}{\left(I_1^{rms}\right)^2}. \tag{9}$$

In order to maintain normal life of the transformer, IEEE std C57.110 recommends that the transformer loaded under non-sinusoidal conditions, shouldn't be loaded at its rated capacity.

Equation (10) derives the factor that must be multiplied by the rated current for determination of the recommended maximum load current that can be continuously drawn from the transformer under standard conditions (the maximum permissible rms non-sinusoidal load current under rated conditions) [7].

$$I_{\max}\text{p.u.} = \sqrt{\frac{1 + P_{EC-R}\ \text{p.u.}}{1 + F_{HL} \times P_{EC-R}\ \text{p.u.}}}\,. \tag{10}$$

Consequently, the needed derating in percentage of the rated VA of the transformer will be:

$$\text{Derating} = \left(1 - I_{\max}\ \text{p.u.}\right) \times 100\%. \tag{11}$$

Operating at load currents below the term defined in Equation (10), ensures that the losses in the highest loss density region of the windings do not exceed the design value of losses under rated frequency operating conditions [7]. Note that for the transformers in the test system, the average winding eddy-current loss under rated conditions, $P_{EC\text{-}R}$, at the point of maximum loss density is assumed to be 8% of the local RI^2 loss [17].

6. System under study

An 11-kV 38-bus system, Figure 4(a), with base power of 1 MVA is selected as the case study system. It is assumed that laterals 2-19, 3-23, 7-8, 6-26 supply commercial loads, industrial loads, composite loads and residential loads, respectively. The daily load curves for the aforementioned load types are depicted in Figure 4(b), where the load curve for composite loads is assumed to be the mean of the three other curves. With reference to Table 1, for industrial loads a VFD is placed at bus 23, and two ASDs at buses 24 and 25. For the parameters of the system and the loads (excluding the battery charging loads) refer to [18].

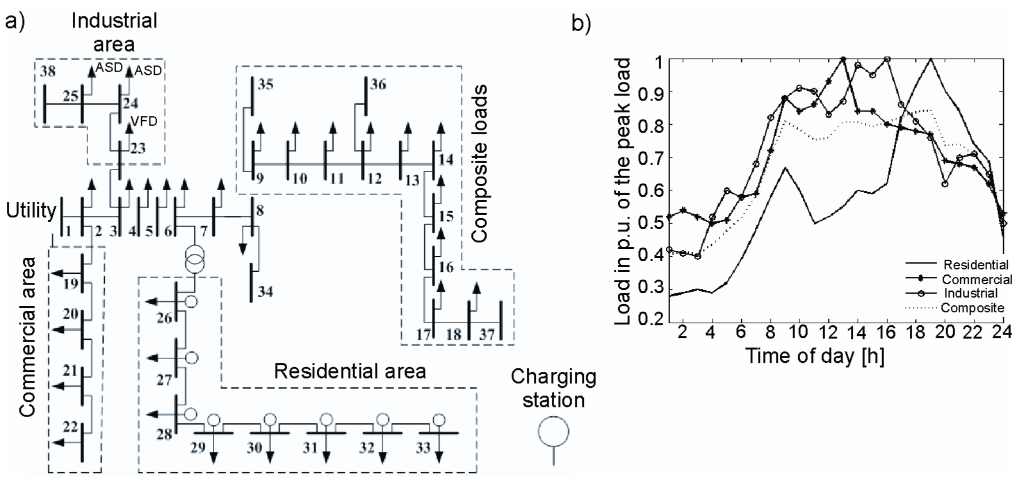

Fig. 4. Test system, schematic (a), test system, (b) daily load curves

The number of vehicles is considered to be 2840 with a penetration level of 20%, i.e. the charging PEVs percentage of the total number of vehicles. Besides, all of the charging cars are assumed to be charged at the residential area and are spread evenly between the residential buses. Note that the daily load curves, charging rates, traffic pattern and the number of vehicles are all selected from [18] and none of the system constraints (bus voltages and line limits) have been violated.

7. Simulation results and discussion

A backward/forward sweep-based harmonic load flow using the method presented in [22] was developed in MATLAB for a symmetrical three phase harmonic analysis for distribution systems.

Our study will be focused on the impact of non-sinusoidal PEV charging load on transformer standard loading, using the stochastic model developed in section 3-B. Note that in reality most of the EV charging is done at residential areas, therefore the charging is presumed to be done at this area. Besides, it is taken for granted that a distribution transformer supplies the residential area. Therefore we will use the harmonic distribution of the corresponding currents drawn from the residential transformer, to illustrate our points. Figures 5-7 depict the changes in the K-factor, total harmonic distortion and the recommended derating of the transformer current for the fixed charging rate (worst case scenario), respectively. Similarly, Figures 8-10 and 11-13 illustrate the previous points for the TOU and real time rate (RTR) scenarios, respectively. In these figures the filled bars represent the case where the charging load generates harmonics and the non-filled bars stand for the case assuming that the charger currents are free of harmonics (i.e. only background harmonics from industrial area are present).

As can be seen from Figures 5-7, by introducing the nonlinear charging load a noticeable rise will occur in the transformer K-factor and current THD, resulting in a negative effect on the transformer life. This effect may become devastating when higher penetration of EVs is considered.

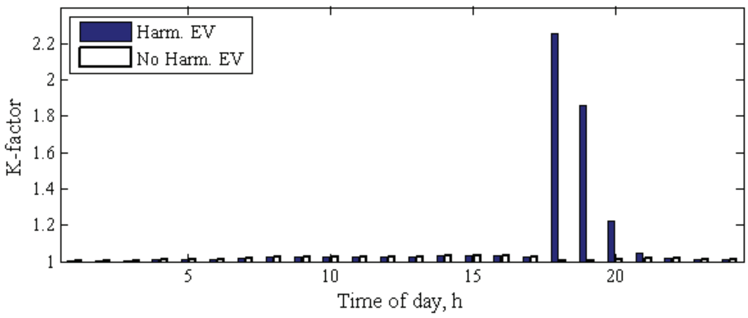

Fig. 5. Daily residential transformer K-factor, fixed rate scenario

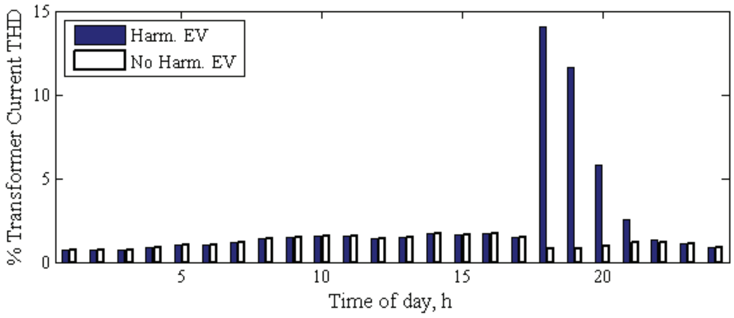

Fig. 6. Daily residential transformer current THD, fixed rate scenario

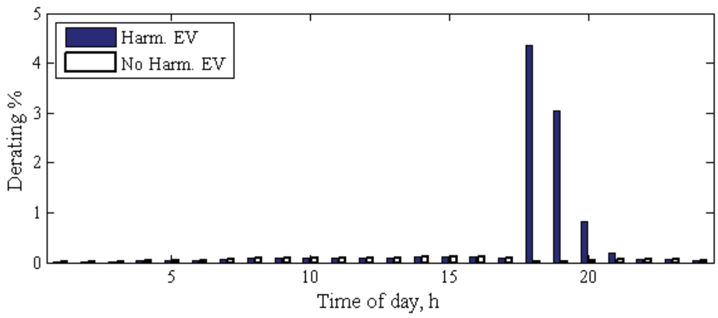

Fig. 7. Residential transformer recommended derating in percentage of the rated load capability, fixed rate scenario

For the TOU charging rate scenario, Figures 8-10 show that although the resultant current THD is less than the fixed rate scenario but still derating should be performed for utilization of the transformer life span. The improvements are due to the direct impact of charging start time pattern on the expected value for the charging load $\mu(P)$, which is, in equation form, the influence of substitution of Equation (4) in (3).

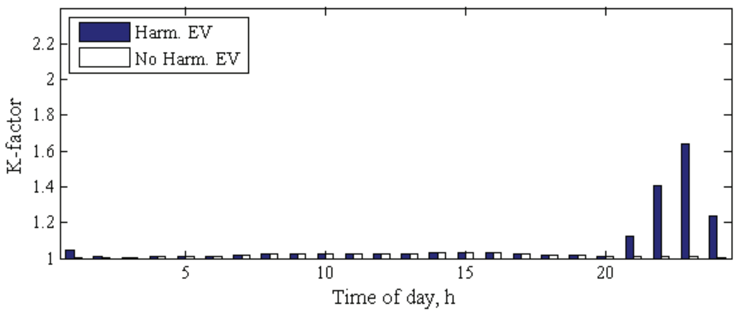

Fig. 8. Daily transformer K-factor TOU scenario

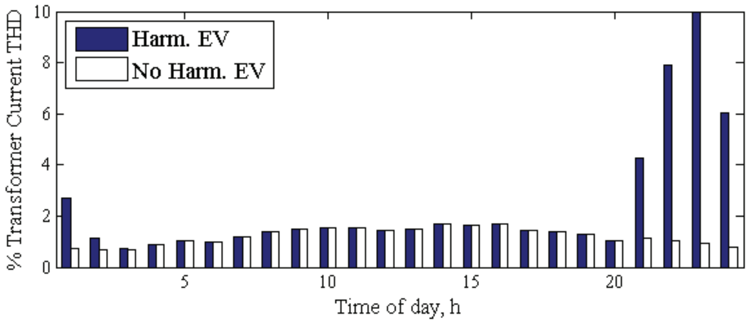

Fig. 9. Transformer current THD for TOU scenario

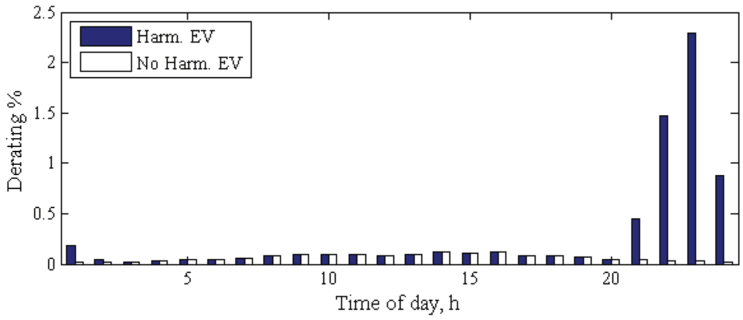

Fig. 10. Transformer recommended derating in percentage of the rated load capability, TOU scenario

Figures 11-13 demonstrate the fact that, deploying a real time rate for billing the battery charging could decrease the charging impact on the transformer to acceptable values. A current THD of less than 5% and K-factors near to one, ensure that there is no need to derate the transformer. Again the influence of charging start time distribution on $\mu(P)$ can be seen in the figures. In fact, in this scenario $\mu(P)$ has been spread over the day in a more even way, resulting in an acceptable transformer operation during the whole 24 hour time interval. The merits of this refinement will become more tangible when a higher penetration of plug-in electric vehicles exists.

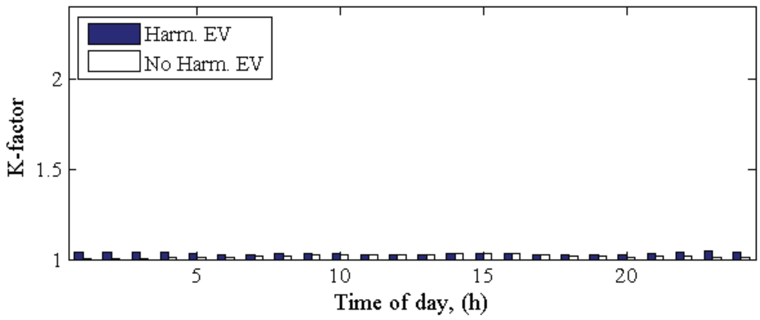

Fig. 11. Daily transformer K-factor, RTR scenario

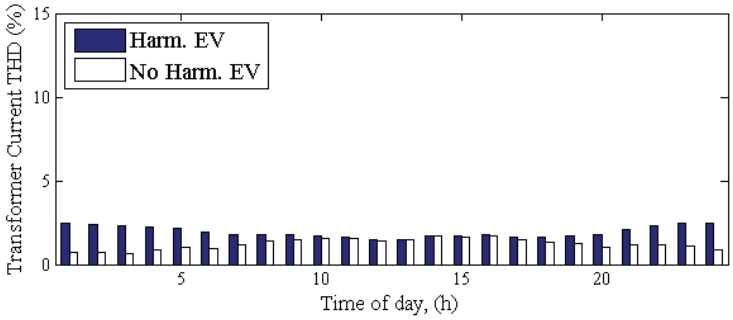

Fig. 12. Transformer current THD for RTR scenario

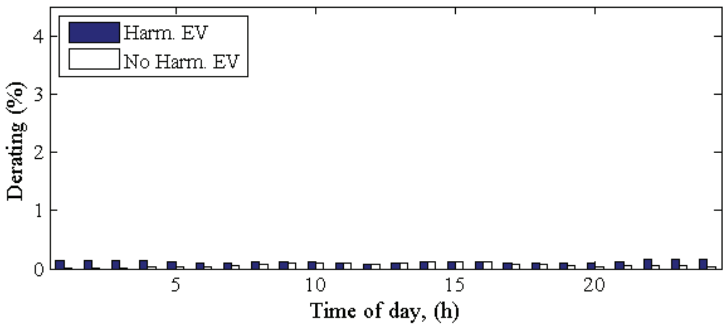

Fig. 13. Transformer recommended derating in percentage of the rated load capability, RTR scenario

8. Conclusion

The simulation developed in this study, investigates statistical modeling of plug-in electric vehicles charging load in order to assess its impact on transformer life, in a realistic way. Since the model includes battery charging start time variable, three corresponding charging rate scenarios were considered to evaluate how they might affect transformer current distortion and its k-factor derating. Results showed a maximum of 1.25, 13.25% and 4.34% rise in the K-factor, THD and derating, respectively, for the worst case scenario of fixed charging rate. Besides, simulations demonstrated that applying real time rate billing is the most promising scenario by which the distribution system operator could ensure operation with least stress on the supplying transformer due to spreading of the expected charging load during the day. Therefore, as we know that derating has some disadvantages (such as low efficiency, possible long-term maintenance problem (overload) and over-current protection false tripping), instead of derating or using expensive *k*-rated transformers (that are designed to handle the heat generated by harmonic currents while keeping the losses low), deploying real-time charging rate for vehicle charging stations can preferably prevent transformer failure even in case of high penetration of harmonic-rich EV charging loads.

This work focused on billing rate. In fact its discussion was from the distribution system operator point of view. With the development of smart programmable chargers researches on algorithms that take into account both EV owners and system operator points of view (including optimum charging cost and various network operating issues such as the explained transformer derating) are getting attention.

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