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On the impact of single-phase plug-in electric vehicles charging and rooftop solar photovoltaic on distribution transformer aging

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ABSTRACT

This study investigates the impact of single-phase plug-in electric vehicles charging on increasing the rate at which center-tapped distribution transformers experience aging. Distribution transformer aging is investigated considering varying rooftop solar photovoltaic generation penetration rates. Monte Carlo methods are used to probabilistically estimate the transformer's loss of life considering the effect of time-of-use (TOU) pricing. The results of applying the proposed method have revealed that plug-in battery electric vehicle charging impact on both transformer aging and neutral current is largest in the case that vehicles charge based on time-of-use pricing methods. Further application has shown that while rooftop solar photovoltaic generation reduces transformer aging, no significant reduction in neutral current is observed.

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1. Introduction

1.1. Background

In 2009, the Government of Ontario launched the micro feed-in-tariff (microFIT) program [1], allowing homeowners to generate power from rooftop solar photovoltaic systems (PV) up to 10 kW, and get paid for the energy they produce over a 20-year term. Through adding such financial incentives for residential homeowners, the MicroFIT program aims to increase renewable energy generation in the province of Ontario. The Government of Ontario also launched the Ontario's Electric Vehicles (OEV) incentive program and Green License Plates [2] in 2013, through which Ontario residents receive up to $8500 in rebates for the purchase or lease of new plug-in battery electric vehicles (PBEVs).

1.2. Problem statement

While both microFIT and OEV incentives look to increase the penetration of Green technologies to reduce greenhouse gas (GHG) emissions in Ontario, the authors' previous work [3] has shown that charging the battery of electric vehicles using Level 2 (240 V) charging may significantly increase distribution transformer loading for several hours, resulting in reduced transformer lifetimes. Studies [4,5] have shown increased rooftop solar PV penetration may reduce loading on distribution transformers feeding the secondary system, and hence extending their lifetime; however these studies have not considered the split-phase nature of North American secondary systems, and therefore have not investigated the effects of rooftop solar generation considering Level 1 (120 V) plug-in electric vehicle charging.

The unbalanced loading caused by electric vehicle charging at Level 1 (120 V) in residential homes has been investigated in Refs. [3,6]. The results of these studies have outlined increased neutral current and reduced distribution transformer's lifetime as significant factors in considering split-phase electric vehicle charging impact. As the transformers lifetime is given as the split-phase winding which degrades the fastest, unbalanced loading due to PBEV charging reduces transformer lifetime faster than if the loading was balanced. In this respect, there is a need to quantify the effect of single-phase PBEV charging demand on the aging of distribution transformer's life whilst considering rooftop solar PV generation.

1.3. Work to date

While many works investigate the impact of electric vehicle charging on distribution transformer lifetime, a large number of studies [7–15] do not consider the effects of Level 1 electric vehicle charging; which charges using less power than Level 2 charging, for a longer duration of time. Studies considering Level 1 electric vehicle charging either do not consider the North American split-phase distribution transformer [16,17], or do not consider the

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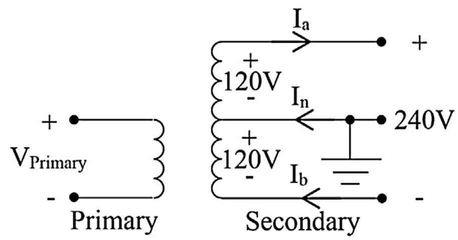

Fig. 1. Center-tapped transformer connections to secondary system.

effects of rooftop PV generation [3,6,18,19]. In this regard, no studies have investigated the mitigation potential of rooftop PV generation on reducing the impact caused by Level 1 electric vehicle charging.

1.4. Contribution

This paper presents a probabilistic approach using Monte Carlo to estimate the loss of life and neutral current impact on distribution transformers due to PBEV charging in an active distribution system. The power generation from rooftop solar photovoltaic is probabilistically estimated after modeling the secondary circuit components (e.g. transformer, service lines and service drops) feeding residential homes at which PBEVs charging is taking place. The approach presented in this study investigates the effect of time of use prices applied to electric vehicle charging as quantified in terms of distribution transformer aging and neutral current. Furthermore, the results of this study consider the impact reduction potential of rooftop solar PV penetration to reduce the impact of PBEV charging.

2. Distribution transformer impact metrics

2.1. Distribution transformer neutral current

Fig. 1 shows the equivalent circuit diagram of the center-tapped distribution transformer windings used to feed secondary circuits. When the currents drawn by split-phases A and B are not equal the presence of a neutral current I_N may be observed. Kirchhoff's Current Law (KCL) expresses this resultant transformer neutral current as the vector sum of the transformer split-phase currents in (1).

$$I_n = I_a - \mathbf{I}_b \tag{1}$$

where $\boldsymbol{I}_n$, $\boldsymbol{I}_a$, and $\boldsymbol{I}_b$ represent vectors of the neutral, split-phase A, and split-phase B currents measured at the transformer.

2.2. Distribution transformer aging

The IEEE Standard C57.91-2011 [20] details the standardized methodology used to calculate the percentage loss-of-life (LoL) of a given transformer based on the transformers hot-spot temperature.

$$LoL(\%) = \frac{F_{EQA} \times t \times 100}{\text{Normal Insulation Life}} \tag{2}$$

where the normal insulation life of a transformer is typically 180,000 h [20], t is the total number of hours in a day, and F_{EQA} is the average aging factor.

$$F_{EQA} = \left(\sum_{n=1}^{N} F_{AA,n} \Delta_{t_n}\right) / \left(\sum_{n=1}^{N} \Delta_{t_n}\right) \tag{3}$$

Given time step size Δ_{tn}, the aging acceleration factor $F_{AA,n}$ determines the increase in transformer lifetime degradation based on the winding hottest-spot temperature θ_H.

$$F_{AA} = e^{\left[\frac{15000}{383} - \frac{15000}{\theta_H + 273}\right]} \tag{4}$$

Table 1
Transformer loss of life parameters.

Parameter	Value
θ_A	30 °C
$\Delta\theta_{H,R}$	27 °C
$\Delta\theta_{TO,R}$	53 °C
τ_{TO}	6.86 h
τ_W	0.08 h
m	0.8
n	0.8
R	4.87

Where θ_A is the ambient temperature, $\Delta\theta_{H,R}$ is the hottest-spot conductor rise above the top-oil temperature under rated load, $\Delta\theta_{TO,R}$ is the top-oil rise above the ambient temperature under rated load, τ_{TO} and τ_W represent the top-oil and winding thermal time constants respectively, n and m are empirical top-oil rise and winding constants, and R is the ratio of load loss at the rated load to the no-load losses.

Table 2
Secondary distribution system extension nodes.

Node	Original load rating	Transformer rating	Number of residential homes
822 Phase A	50.69 kVA	50 kVA	10
846′ Phase B	17.00 kVA	25 kVA	6
862′ Phase B	20.87 kVA	25 kVA	6

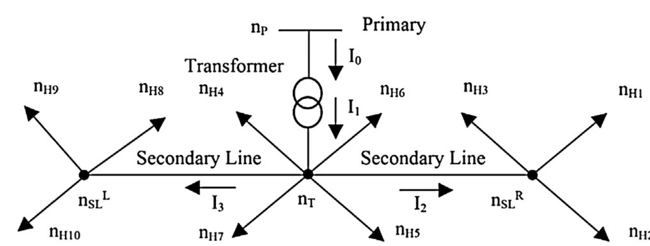

Fig. 2. Ten house secondary system.

Transformer lifetime aging depends on the hottest-spot temperature, denoting the point of insulation on the transformer which deteriorates the fastest. Table 1 lists the thermal parameters needed for LoL calculations on a distribution transformer with 50 kVA nameplate rating [3].

3. Probabilistic simulation methodology

3.1. Modified IEEE 34 Bus Test Distribution System

Typically, distribution systems in North America consist of a primary system which extends secondary circuits used to feed residential customers. The primary system modeled in this work is taken as the IEEE 34 Bus Test Distribution System [21] using the exact lumped load model detailed in Ref. [22]. In order to accommodate secondary circuits, the load at each node listed in Table 2 (with apostrophes denoting intermediate node extension based on the lumped load model) was extended with a corresponding secondary circuit as follows. Single phase loads listed in Table 2 were removed and replaced with corresponding center-tapped transformers as rated in Table 2. Each transformer was further extended with a secondary circuit used to feed homes, with circuit model based on the archetype design in Ref. [23].

An example layout of the 10-house secondary distribution system (SDS) fed from a 50 kVA distribution transformer is depicted in Fig. 2 with residential house nodes labeled n_{H1} to n_{H10}. As detailed in Ref. [23], secondary lines (SL) and service drops (SD) are assumed 4/0 AA and 1/0 AA triplex cables respectively.

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