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Probabilistic quantification of voltage unbalance and neutral current in secondary distribution systems due to plug-in battery electric vehicles charging

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ABSTRACT

The work of this paper investigates the expected impact of level 1 plug-in battery electric vehicle charging on increasing voltage unbalance, undervoltage violations, and neutral current within secondary distribution systems. Plug-in battery electric vehicles charging have been probabilistically modeled using a Monte Carlo simulation, which determines the expected impact on a secondary system extending from the IEEE 34 bus test distribution system. The impact of electric vehicle charging is compared for different penetration levels, different charging methods, and different proportions of electric vehicles charging on either split phase in the secondary system. Results of the Monte Carlo simulation show voltage unbalance and neutral currents are greater when electric vehicle charging is biased to one split phase as opposed to equally distributed amongst both split phases. Furthermore, voltage unbalance is found to increase the number of undervoltage violations experienced in the secondary system.

1. Introduction

In response to the perpetually increasing gas prices, and as a means of reducing greenhouse gas (GHG) emissions; significant interest pertaining to plug-in battery electric vehicles (PBEVs) has developed. In Canada, the Government of Ontario offers incentive programs which provide financial rebates to consumers who purchase or lease a new PBEV [1]. Despite such environmental and economic benefits, the increased penetration of PBEVs may impose significant power quality (PQ) issues on the electric power distribution system (EPDS) due to PBEV charging demand [2].

1.1. Problem statement and motivation

North American residential homes are usually supplied from center-tapped distribution transformers providing 120 V/240 V through a single split-phase, 3-wire secondary circuit [3]. This 3-wire connection allows PBEVs to charge at homes using level 2 (240 V) or at level 1 (120 V) connections. The authors in [4] have studied the impact of PBEVs considering both charging levels and the results have shown that level 2 charging causes more overload to distribution transformers compared to level 1; hence reducing their lifetime [5]. Moreover, the results of [4] have also shown that level 2 charging causes more undervoltage (UV) violations at secondary nodes compared to level 1; however, the resultant unbalance on the system due to level 1 vehicle charging has not been fully investigated.

Since PBEVs are usually connected to either phase A or phase B of the split-phase secondary as shown in Fig. 1, PBEVs charging from level 1 may have several implications on PQ due to load unbalance which has not been fully investigated in split-phase secondary circuits. The resulting unbalance from level 1 charging may cause secondary nodes to experience voltage phase deviation (PVD) with increased potential to incur UV violations at the consumers' service entrance. Moreover, given level 1 charging currents may reach 12–16 A [6], unbalance may result in increased neutral current (NC), bringing attention to the risk of neutral overload.

1.2. Previous work

While the majority of published literature [7–26] focus on imbalance in three-phase systems, such systems may not respond to unbalanced loading in the same manner as the split-phase secondary system, in which 120 V loads are distributed between two split phases of a full phase as seen in the primary. Furthermore, literature considering level 1 charging in split-phase secondary systems either does not consider unbalance problematic [27], or

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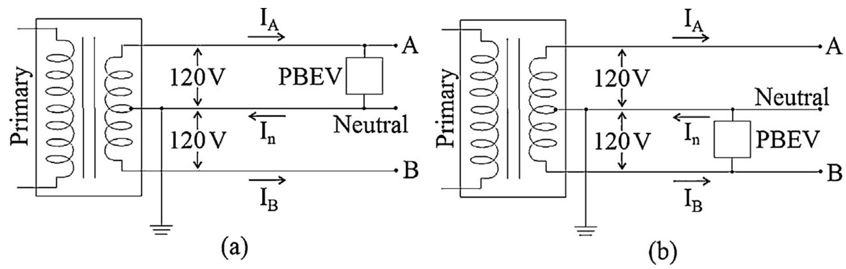

Fig. 1. Possible level 1 (120 V) PBEV charging connections. (a) Phase A and (b) phase B.

quantifies unbalance directly and does not investigate the resultant effects on unbalance on the system [28]. While previous works define voltage imbalance (VI) corresponding to the unbalance conditions on three-phase nodes; the usage of the term voltage unbalance however, is used by the authors' in this paper in order to specifically refer to split-phase unbalance.

1.3. Contribution

Given that unbalance causes both voltage deviations and NC which may pose severe PQ problems, there is a need for a detailed unbalance analysis to quantify split-phase VU, node UV violations and NC in North American secondary distribution system (SDS) due to PBEV vehicle charging. In response to this issue, the work presented in this paper looks to provide a comprehensive probabilistic quantification of the impact incurred by PBEV charging demand in terms of VU, UV violations, and NC on SDS using Monte Carlo. Furthermore, a detailed comparison of UV violations resulting from different PBEV-phase charging configurations is performed using different household-PBEV penetration levels ranging from 50% to 200%.

1.4. Work organization

This work is organized as follows: Section 2 briefly discusses VU and NC in SDS, Section 3 details the modeling of SDS and PBEV charging demand and Section 4 outlines Monte Carlo method. Section 5 presents the results, and Section 6 concludes the papers findings.

2. Voltage unbalance and neutral current in SDS

Typically, SDS starts at the distribution transformers and ends at the consumers' meters. In North America, the distribution transformers feeding the secondary circuit in residential subdivisions are center-tapped to provide residential consumers with 120 V/240 V. As part of the ANSI C84.1 standard [29], voltage deviation is measured with respect to the root mean square voltage (V_{rms}). As SDS voltage magnitudes of nodes A and B shown in Fig. 1 are assumed to be identical with 180° phase difference, this may not be the case with PBEVs charging single-phase resulting in VU. In this paper, the authors define VU in SDS in analogy to the three-phase voltage imbalance definition in ANSI C84.1 [29] using maximum voltage deviations in phases R, S, and T with average voltage V^{P}_{avg} in the primary system.

$$\mathrm{VI}(\%) = \frac{\max\{V_R - V^{P}_{avg}, V_S - V^{P}_{avg}, V_T - V^{P}_{avg}\}}{V^{P}_{avg}} \times 100 \quad (1)$$

In SDS, the VU can be defined in the secondary system using the maximum split-phase voltage deviation in phases A and B from the average voltage V^{S}_{avg} (2). The VU formula can be reduced by substituting in (2) with the value of V^{S}_{avg} defined in (3) to obtain percentage VU in (4) in reduced form.

$$\mathrm{VU}(\%) = \frac{\max\{V_A - V^{S}_{avg}, V_B - V^{S}_{avg}\}}{V^{S}_{avg}} \times 100 \quad (2)$$

$$V^{S}_{avg} = \frac{V_A + V_B}{2} \quad (3)$$

$$\mathrm{VU}(\%) = \frac{\max\{V_A - ((V_A + V_B)/2), V_B - ((V_A + V_B)/2)\}}{(V_A + V_B)/2} \times 100 = \frac{|V_A - V_B|}{V_A + V_B} \times 100 \quad (4)$$

The unbalanced loading caused by PBEV's charging using level 1 120 V may result in VU due to different voltage drop between split-phases which may lead to one or more of secondary nodes to experience UV violations. In order to quantify the effect of PBEV charging in causing UV violation in SDS nodes, the minimum normal operating voltage of 114 V recommended by ANSI C84.1 [29] is used.

As depicted in Fig. 1, the NC is zero only if phases A and B are equally loaded; otherwise NC becomes non-zero and may exceed allowable limits causing neutral conductor/cable overload in SDS. Usually, neutral current $\boldsymbol{I}_n$, where a bold letter indicates vectors, is a measure of the current unbalance in the secondary circuit and can be computed from (5):

$$\boldsymbol{I}_n = \boldsymbol{I}_A + \boldsymbol{I}_B \quad (5)$$

3. SDS modeling including PBEV charging demand

The original IEEE 34-bus primary distribution test system [30] includes spot loads and distributed loads. Distributed loads are modeled as lumped loads by adding intermediate nodes at one quarter of the feeder length (l) taking two thirds of the load, while the remaining one third is placed at the end of the feeder as illustrated in Fig. 2. Table 1 lists the distributed loads as lumped load representations according to the model in [31]. A complete model of SDS components (e.g., distribution transformer, SLs and SDs) is developed in this study. The spot loads at three primary nodes (nodes 822, 846′, and 862′) are replaced by three center-tapped distribution transformers (one 50 kVA at node 822 and one 25 kVA for

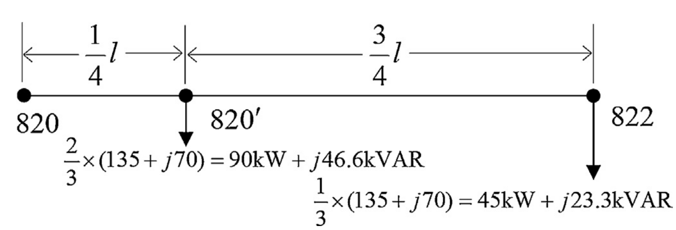

Fig. 2. Exact lumped load model representation of distributed load in primary.