

MC-based Risk Analysis on the Capacity of Distribution Grids to Charge PEVs on 3-ph 0.4-kV Distribution Grids Considering Time and Location Uncertainties

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ABSTRACT

The increasing number of Plug-in Electric Vehicles (PEVs) impacts the power grid due to their high demand in power and energy, and uncertainties in the charging behavior. Typical PEVs are charged single-phase up to 32 A (7.2-kVA) or tri-phase up to 32 A (22.0-kVA). Both charging technologies have to be discussed in order to determine their impact on planning and operating of low-voltage distribution grids to assure a reliable and stable PEV charging.

Traditional grid planning and analysis methods, which average and evenly distribute PEV loads on the distribution grid, fail in providing a realistic answer about the grid capacity to charge PEVs. The question; How many PEVs can be charged simultaneously on a distribution grid remains unanswered.

Therefore, this paper describes a novel methodology to realistically evaluate the grid capacity for PEV charging on 3-phase 0.4-kV distribution grids. The proposed methodology is a modified Monte Carlo (MC) simulation technique, which analyzes grid capacity with respect to charging location, technical distribution grid limitations, and PEV charging techniques. The MC technique is numerically optimized to analyze large distribution grids and scaled up PEV charging. Results will be compared to traditional analysis techniques.

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INTRODUCTION

The increasing number of electric vehicles (EVs) is discussed several times. About 270,000 EVs were registered by the end of 2013 world-wide [1] and several new models entered the US market in 2014 [2]. Plug-in electric vehicles (PEVs) started as niche market with two vehicles in 2010 and reached 14 models from nine different automakers (OEMs) in 2014 [3].

On the one hand, an increasing number of PEVs has a positive environmental impact due to the reduction of fossil fuel, CO₂ reduction while driving and the possibility to use renewable energy for charging the PEV's battery. On the other hand it has a substantial impact to the power grid which cannot be omitted [4]. Individual electricity consumption of PEVs, with a total annual mileage of 15,000 km/9,000 mi, matches the average German household consumption of approx. 3,500 kWh [5]. Charge power ranges from 1 to 80 kW, and is usually provided by a service connection to the low-voltage distribution grid [6],[7],[8]. In addition to that, the electricity is not consumed continuously over 24 hours but rather 2 to

8 hours, simultaneously to the existing household peak load times from 6 p.m. to 12 p.m. [9],[10]. Hence, an increasing PEV penetration will impact the distribution grid massively [4],[11].

One important question to OEM remains; "How many PEVs can be (simultaneously) charged?" Analyses are obtained by some utilities and conclude that many PEVs could be charged electrically. On the other hand, experimental sites and own research shows a different result. Already a few charging PEVs can exceedingly violate grid requirements and, therefore, can black-out the actual grid. This discrepancy occurs from applying traditional planning and analysis methods, neglecting technical aspects of the tri-phase low-voltage distribution grid. Traditional planning and analysis methods overestimate the existing grid capacity. These methods originate from experience from the past and might be true for traditional household loads. However, these methods and used assumptions fail for new non-deterministic and heavy loads such as PEVs.

In this paper a novel method for planning, analysis and evaluation of the grid's capacity for PEV charging will be introduced. Unlike traditional planning and analysis methods, this method considers grid conditions, considers the PEV connection pattern and accounts

for grid restrictions and requirements (like system voltage, asymmetry, loading, etc.) with focus on the tri-phase 0.4-kV distribution grid. As a result the exact number of PEVs charging simultaneously will be determined. Providing the exact number of simultaneously chargeable PEVs on a distribution grid will eliminate the OEM's uncertainties and supports the communication between OEM and distribution grid operator (DSO). The introduced method is implemented in a modelling prototype [12] which is based on EPRI's OpenDSS distribution grid simulation system [13] and applied in field tests in cooperation with BMW Active-E.

PEV CHARGING AND THE POWER GRID

PEVs are electric vehicles with a battery and the ability to charge the battery on an external power source [14], the power grid. Usually, PEVs are connected to the low-voltage (LV) distribution grid at Level 1 (120V) or Level 2 (230V/240V). Differences apply among different power grid infrastructures on different continents, particularly between the North American and the European distribution grid [15].

PEVs are new and non-deterministic loads from a power grid perspective. They consume power that exceeds the power consumption of traditional household appliances. They also consume as much energy as an average household does. Hence, PEVs impact the power grid massively particularly with an increasing penetration [15]. This impact is recognized by utilities (DSOs) and OEMs, as poor power quality may impact the charging process. On the other hand a smooth PEV charging supports the customers' acceptance of PEVs.

Statistically the majority of PEVs is connected to the power grid during the evening and night hours (6-12 pm) [16]. The actual behavior of an individual PEV, which may affect the distribution grid negatively, remains non-deterministic due to an unmanaged charging process. The interface between PEV and power grid remains on the immediate power demand when plugged in. Hence, uncertainties regarding time, location, power/energy demand, and connection pattern remain.

Uncertainties of PEV Charging

The unmanaged charging process starts as soon as the PEV is plugged in and ends when the battery is fully charged or the PEV is plugged off. Uncertainties remain in terms of:

1. Time
Uncertainties in regards to the charging time lead to the question of; how many PEVs will be charged simultaneously and does the charging event(s) interfere with other power demands, e.g. the household peak load?
2. Location
For an individual PEV it cannot be foreseen where the PEV gets plugged-in. Answers need to be derived for individual distribution grids (urban, suburban, rural) and actual connection locations.
3. Power demand
Depending on the make and model of the PEV the distribution grid may be affected more or less by the charging process depended on the power throughput of the actual vehicle.

4. Connection pattern

Depending on the make and model of the PEV and/or charging infrastructure the vehicle may be connected single-phase or tri-phase to the distribution grid. In case of single-phase charging, until today, it remains undetermined to which phase the PEV is connected to. Hence, different combinations of connection patterns appear.

Power Grid Requirements

In order to provide a secure and reliable power supply, utilities and customers are required to fulfill certain requirements and standards. Utilities need to supply power meeting the standards and customers (e.g. PEVs charging on the power grid) must not violate these requirements while consuming power.

Grid requirements are defined in standards (e.g. DIN/EN 50160 [17]) and technical connection requirements [18]. These requirements define for instance a voltage band, limits for tri-phase asymmetries, neutral wire loading, etc. If these requirements are violated the charging process may be interrupted and/or local black-outs may occur. In any case the customer's experience will be impacted negatively.

In the modelling introduced below the following criteria are respected in order to satisfy the standards and requirements for a successful charging process:

1. Voltage limitations
DIN/EN 50160 [17] defines a voltage band of $\pm 10\%$ of the nominal voltage which must not be exceeded. Any violation may stop the charging process or result in an unexpected behavior. Tighter restriction may be required by some utilities (e.g. $\pm 8\%$) to cover the voltage drop behind the service connection.
2. Asymmetry
Any unbalanced load in a tri-phase system causes an asymmetry, which is the ratio between negative to positive sequence component [19]. This asymmetry must not exceed 2% [17].
3. Neutral wire loading
Any unbalanced or single-phase load in a tri-phase system also loads the neutral wire. As defined by the technical connection requirements [18] the neutral wire loading must not exceed 20 A at each service connection.
4. Loading of wires and transformers
Each power demand causes a loading of wires and transformers in the distribution grid. These loadings must not exceed technical limitations (dependent on the used components) and utility requirements for operation (e.g. max. permanent loading of 60%¹).

1. Most utilities define a maximum permanent loading of wires and transformers of e.g. 60% of its capacity in order to maintain a safety margin. PEV charging is considered being a permanent load as it consumes high power for 4-8 h on a regular basis, e.g. daily. If this 60% loading is exceeded permanently the utility is required to plan charging

PEV Connection Pattern

There are several possible ways to connect a PEV to a tri-phase LV distribution grid. Tri-phase and single-phase charging is available. OEMs agreed on single-phase charging due to their international market. Hence, single-phase charging is the preferred method that is expected for the (near) future.

Today's charging infrastructure has a non-deterministic setup. As devices for charging (e.g. wall-box, charge pol, etc.) are connected tri-phase to the distribution grid, PEVs are connected single-phase to these devices. There is currently no method or standard that determines the connection by phase. Hence, several connection patterns are possible, as shown in [Figure 1](#).

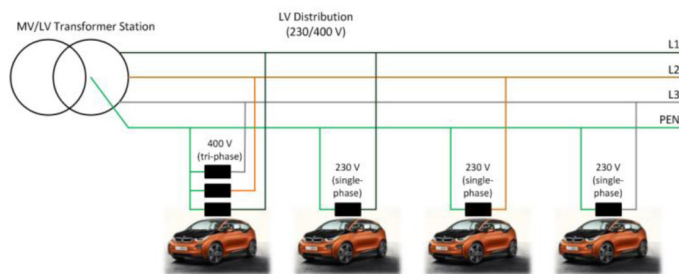


Figure 1. Grid connection patterns of a tri-phase LV distribution grid

Each connection pattern is non-deterministic in time and location from a power grid perspective.

Power Grid Planning and Analysis

The most common grid planning and analysis techniques currently in use are generally based around a number of factors and analysis methods that were learned through decades of experience. Those traditional methods tend to assume average and equal distributions of symmetric tri-phase loads in the power grid and usually evaluate the loading of wires and transformers only.

One commonly used factor is the concurrency factor. It is based on an estimation of how much power is drawn by an installed load (e.g. residential loads) on average during a defined peak interval and allows for an estimation of the total network impact of a number of similar loads during said interval. This approximation allows for a cost optimization by limiting the overrating of the grid's capacity. However, it only works if the type of load is numerous enough and has a relatively equal distribution throughout the grid. Due to the inaccurate nature of this process an additional safety margin is required. Another assumption of today's planning and analysis methods are the usage of tri-phase symmetric loads. Hence, asymmetries or impacts based on asymmetries are not part of the evaluation today. Also, as the exact location/service connection of PEVs cannot be determined in a common power grid analysis, PEV loads are averaged and evenly distributed throughout the grid. Hence, effects of clustering of PEVs, e.g. on a parking lot, are not evaluated.

Therefore, utilities usually overestimate the distribution grid's capacity for PEV charging which leads to a high risk for the mass roll-out of PEVs. Considering the lack of data and experience in regards to PEV charging behavior, the currently low PEV penetration, and necessity of

safety margin, it has to be concluded that this type of planning method is not suited for the analysis of PEV charging or to determine the grid capacity of tri-phase low-voltage distribution systems.

MONTE CARLO SIMULATION & ANALYSIS

The over-all goal of the research was to develop a new and more realistic method to determine the capacity of a distribution grid for PEV charging. The focus was to determine the exact number of PEVs or to provide a probability of PEVs able to charge simultaneously on a distribution grid. Therefore a novel method was developed. In opposite to traditional planning and analysis methods, which average and distribute the PEV's load evenly throughout the grid, this method respects the actual power consumption of the PEV, the location the PEV is connected to, the connection pattern, and asymmetrical grid loading.

Based on a modified Monte Carlo (MC) simulation, combined with an asymmetrical steady-state load flow calculation, realistic combinations of connection patterns in a distribution grid can be evaluated and compared against grid requirements and standards. As a result, combinations that do not violate grid restrictions can be determined without any assumptions or statistical distribution of the PEV's load.

Monte Carlo Simulation

The Monte Carlo (MC) simulation is used to solve problems numerically, which are hardly solvable or not solvable using deterministic algorithms. It is often described as an approximated solution for different problems in physical, mathematical and economical topics. The simulation is conducted by applying various so called Monte Carlo methods which differ in their scope of application. Basis of the method is a large dimensional space (random experiments or combinations) and, thus, an (almost) non-deterministic character of the problem. By altering the set of input parameters in a stochastic way and repeating the iterations as much as suitable, the simulation results in values that is indicative of the real system's behavior.

By this focus, the large dimensional space is represented by all possible PEV connection patterns of the distribution grid (called combinations herein). Hence, the input of the MC simulation is the modelled distribution grid with its entire set of possible connection patterns of PEVs.

Simulation Method

In a first step the MC simulation is initialized. The actual (real-world) distribution grid model, which is setup before, is used to create an empty lookup table (LUT) which is filled with possible connection patterns (combinations) in each step of the iteration. As the simulation is combined with a steady-state load flow calculation kernel (OpenDSS [13]) a load flow calculation is executed with each iteration. During the initialization process a first load flow calculation without PEV loads is executed in order to validate the grid model and MC simulation inputs.