

Integration of Electric Vehicle Charging into an International and Environment-Friendly Context

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ABSTRACT

The market for plug-in electric vehicles (PEV) is gaining rapidly. Several original equipment manufacturers (OEM) have announced the start of new PEV model production. Hence charging a growing number of PEVs will have a major impact on the power grid, especially on the distribution grid. Effectively utilizing renewable energy for charging the PEV's battery is a major objective for reducing the OEM's CO₂ fleet emissions due to increased efficiency of the energy consumption. Uncoordinated charging will lead to an additional load on the power grid and an inefficient utilization of renewable energy.

As the charge of a PEV may double an average household consumption and usual plug-in times overlay the household consumption peak in the evening the ability of PEVs to shift their electric charging is considered grid-friendly.

Furthermore, adapting PEV charging to the availability of renewable energy would reduce CO₂ emissions and contribute to the adherence to national and international regulations. The volatile nature of renewables and unpredictability of the PEV fleet's total load, plug-in time and location, causes high challenges for the distribution grid operator.

It is the aim of this contribution to show results from research and applications of distribution grid integrations of PEVs with respect to technical limitations. Therefore, a methodology for Managed Charging of PEVs is introduced, the impact of charging multiple PEVs on the distribution grid is evaluated and a comparison between the European and the North American distribution grid is conducted.

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INTRODUCTION

Experts expect about 270,000 electric vehicles registered by the end of 2013 world-wide [1]. Several manufacturers assume the plug-in electrical vehicle (PEV) market increasing and have already announced the start of production (SOP) for their PEVs. The method of charging the PEV's battery with the goal of reducing the original equipment manufacturers' (OEM) CO₂ fleet emissions remains a common goal.

Charge power from 1 to 80 kW is usually provided by a service connection to the distribution grid [2], [3], [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. 3,000 kWh, which drastically increases the load on the distribution grid. In addition, the electricity is not used continuously over 24 hours but rather in 2 to 8 hours increments, simultaneously to the existing household peak load times in the evening [5], [6], [7]. The ability of PEVs to shift their electric charging to times between 12 p.m. and 7 a.m. is considered being grid-friendly due to the low household consumption at those times. This needs to balance customer's

desire to have the PEV charged in a timely manner and be capable of travelling longer distances or have the PEV available quickly or at dedicated low-price tariffs (e.g. Time-of-Use (TOU)).

Furthermore, it is optimal to adapt the PEV charging to the availability of renewable energy in order to act as a prosumer (a customer which consumes electric power and also provides/produces electric power to the grid) in future Smart Grids and provide system services. The renewable energy-oriented charging process and the behavior as prosumer have one thing in common - the non-predictability of the fleet's total load related to plug-in time, power of charging and location [6], [8], [9]. This is critical from the distribution grid operator's point of view due to the lack of predictable time for charging, e.g. between 12 p.m. and 7 a.m. As a consequence, distribution grids have to be planned for the unlikely event of maximum load and existing grids have to be expanded for this worst case, which reduces grid and economic efficiency drastically [9].

Local and public load management estimate the distribution grid's individual regional and temporal capacity and forward this information to the load management for the purpose of avoiding given grid restrictions (like voltage boundaries, load of neutral conductor, thermal loading of conductors and transformers, etc.) [7].

It is the aim of this paper to show results from research and applications of distribution grid integrations of PEVs with respect to technical limitations. The special characteristics of tri-phase distribution grids in Germany will be explained and the consequences of the internationally preferred single-phase charging will be illustrated. Results from different research projects and field tests will be presented. Simulations are done with EPRI's OpenDSS distribution grid simulation system [10].

DISTRIBUTION GRID

The classical power system, as it is setup today, follows a hierarchal approach starting from generation to transmission, to distribution and finally consumption. Within this hierarchy the distribution grid mainly describes the power grid from the last transformer substation all the way to the houses, also known as the last mile. Here power is distributed at medium and low voltage. However there are international differences in setup and regional differences in voltage levels as described herein.

System Setup

In many European countries four wires are used in distribution grids. There are three phase-to-phase conductors and the protective earth neutral (PEN) conductor which are provided by the substation transformer. This is known as Terre Neutre (TN) system. At the house service connection the PEN conductor is provided as a single conductor (TN-C system) or split into the protective earth (PE) and neutral (N) conductor (TN-C-S system) as shown in Figure 1.

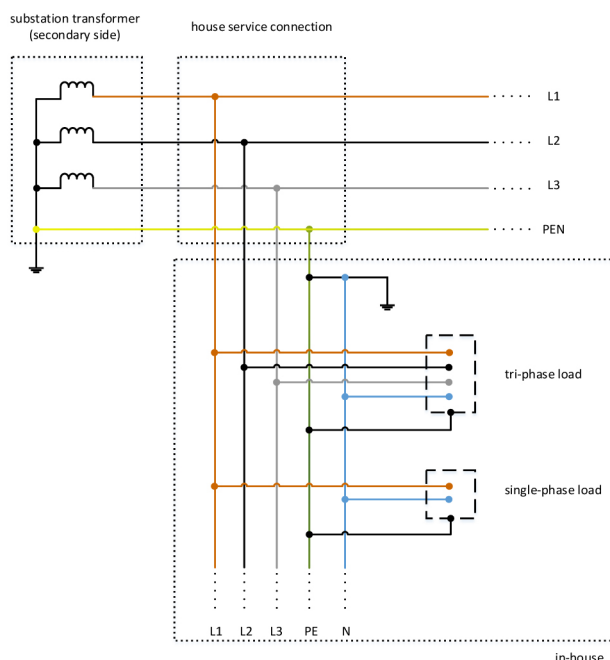


Figure 1. TN-C-S System

For all modeling and calculation in this contribution the TN-C-S system is assumed, as recommended by RWE [11].

Typical Considerations

Connecting several loads to a given system setup (TN-C-S system herein) might not be as easy as it appears. Especially not in the case of PEVs, as each PEV may double the average household consumption. Some considerations and restrictions have to be taken into account.

Such considerations are based on the connection to the distribution grid and the effect they may have to it. One aspect refers to the number of phases a load is connected to and if this load affects the symmetry of the three phases. Within a symmetric tri-phase system each phase is 120° apart from the others, has the same voltage and carries nearly the same current on each phase. Affecting the symmetry leads to an inefficient utilization of the distribution grid and can lead to violations of given grid requirements, like the voltage band [12].

The voltage band is a defined area, in which the voltage may vary. Based on EN 50160 [12] the voltage in the European grid may vary $\pm 10\%$ of its nominal value. Due to the resistive character of each conductor the voltage varies on the conductor based on the load of each conductor. Leaving the voltage band violates grid requirements and the grid has to be expanded.

Another consideration is the total loading of grid resources like conductors and transformers which are not allowed to be exceeded. In a symmetric tri-phase system grid resources can be loaded up to their maximal (thermal) loading. However, in an un-symmetrized tri-phase system additional effects may be considered such as the loading of the neutral conductor. As a result, an un-symmetrized tri-phase system may reach its limits much faster than a symmetrized system. For a tri-phase system the maximum asymmetry in particular the ratio of negative to positive sequence components must not exceed 2% [12] as required in Europe.

In addition, the type of load has to be considered, especially for PEVs where electronically switching components are used for charging. Any switching load in the grid will generate more or less harmonics. These harmonics sum up and preload the neutral conductor. Currents of up to 80 A are already measured. Any additional loading of the neutral conductor, either by single-phase loads or asymmetric tri-phase loads will further stress or even overload the neutral conductor.

Besides these natural restrictions there are restrictions defined by each distribution grid operator (DSO). These restrictions are defined in various technical connection conditions (TCC) such as the TAB Nord in Germany [13]. These TCCs define further restrictions. Following the TAB Nord that means, among others, that each house service connection is limited to a maximum of 64 A per phase (at 230 V) and the neutral conductor must not

exceed 20 A at each house service connection, for a single-family home. Higher connection powers must be requested and approved by the DSO [13].

All these restrictions and considerations have to be taken into account when simulating or evaluating the integration of PEVs into the grid.

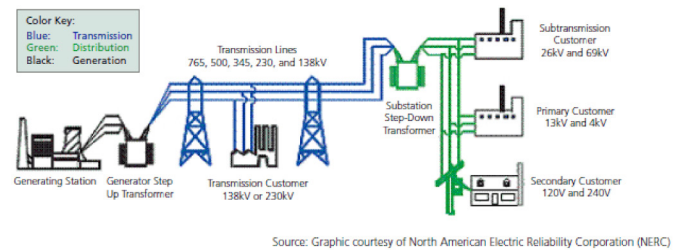
Comparison to the North American Distribution Grid

Some differences exist between the European and North American power system. These differences mainly apply to the distribution grid while the transmission grid equals the European transmission grid.

The hierarchy of the power grid is subdivided into different voltage levels from generation in big power plants down to the house service connections [14]. At each voltage level the tri-phase characteristic is maintained down to the medium-voltage (MV) level. At the MV level the distribution grid exists already and that is where the differentiation between the European and the North American grid appears. While the European distribution grid maintains the tri-phase characteristics down to the low-voltage (LV) level as well and all the way to the house and in-house (Figure 1), the North American distribution grid is differently set up and transforms from a tri-phase grid into a single-phase grid from the MV to the LV level.

In the European distribution grid the last transformer substation is placed somewhere in a neighborhood. The primary side is connected to the MV level at a voltage level of 10-30 kV. The secondary side provides a voltage of 400 V (tri-phase) and substation transformers are usually rated between 315 KVA and 1 MVA supplying an entire neighborhood with power.

The North American distribution grid follows a more decentralized transformer approach from the MV to the LV level. The last transformer substation is also placed somewhere in a neighborhood but is connected to the high voltage (HV) level (several hundred kV) on the primary side. The secondary side provides a MV at about 7.1 to 34.5 kV (tri-phase). This tri-phase MV supplies an entire neighborhood. Figure 2 shows the basic structure. From there the tri-phase characteristic changes to a single-phase characteristic¹. On the MV distribution grid there are several pole-mounted transformers which supply one or a few houses with power. The primary side of these pole-mounted transformers is connected to a single phase on the MV grid [15]. The secondary side provides 240 V with a center tap; hence 2×120 V which is provided to the house service connection(s). Figure 3 illustrates the system setup and the inner circuit of the pole-mounted transformer.



Source: Graphic courtesy of North American Electric Reliability Corporation (NERC)

Figure 2. North American Power System

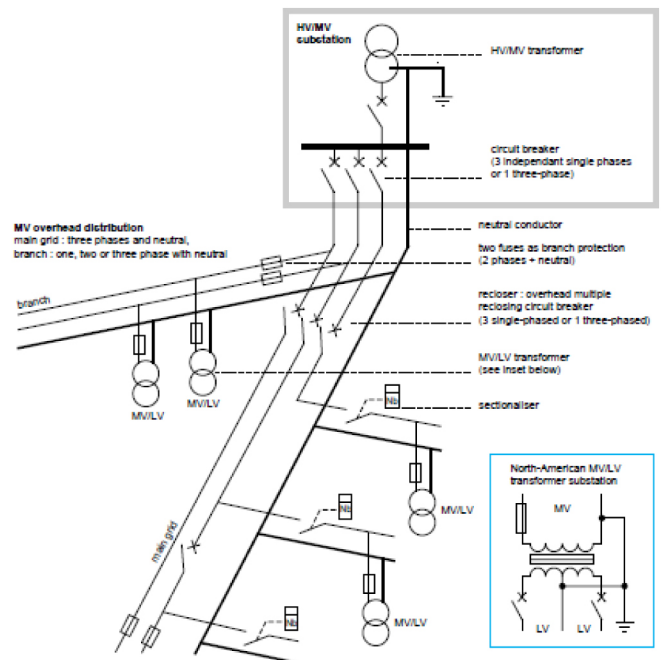


Figure 3. North American Distribution Grid [15]

PEV CHARGING

The PEV charging process is a topic that is discussed many times and not concluded commonly until today. Basically the charging of PEVs is driven by the users. The users want the PEV charged up when they need the vehicle. Every day's preference may change for a specific user but is somewhat predictable for a fleet of PEVs [9], [7]. Typical plug-in times range in the evening times, which overlay the household pick times from 6 p.m. to 12 p.m.

Typical Charging Modes

The PEV's charge coupler is described in IEC62196 [4]. Two AC-couplers are specified. While the Type 1 coupler, which supports single-phase charging, is dedicated for the US and Japanese market, the tri-phase charging is enabled by the Type 2 coupler. Besides the AC charging, several DC charging standards have been developed, e.g. CHAdeMO and the Combined Charging System [4], [3].

Typically at home the single phase charging will be the normal use case in Europe for vehicles of international operating OEMs, due to the leadership of the US market.

1. Some people refer the North American LV grid to a two-phase system because it has two-phases that are 180° apart which basically is a single-phase three-wire system.