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On integration of plug-in hybrid electric vehicles into existing power system structures

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ABSTRACT

Plug-in hybrid electric vehicles (PHEVs) represent one option for the electrification of private mobility. In order to efficiently integrate PHEVs into power systems, existing organizational structures need to be considered. Based on procedures of power systems planning and operation, actors are identified whose operational activities will be affected by PHEV integration. Potential changes and challenges in the actors' long- and short term planning activities are discussed.

Further, a PHEV operation state description is developed which defines vehicle operation states from the power system point of view integrating uncontrolled, controlled recharging and vehicle to grid (V2G) utilization in one single framework. Future PHEV managing entities, such as aggregators, can use this framework for planning and operation activities including load management and V2G. This operational state description could provide a solution for future short term planning challenges of PHEVs and an aegis for various routes of current research, which to date have been weakly linked to each other.

1. Introduction

The green economy, inspired by environmental concerns and energy security considerations, comprises various technology sectors. Recently, due to the strive for increased efficiency in private mobility, one of these sectors is the electrification of the car fleet through electric and plug-in hybrid electric vehicles (PHEV). The PHEVs equipped with a battery and an auxiliary internal combustion engine (ICE), can replace a substantial fraction of gasoline by partly using grid charged electricity instead (Bradley and Frank, 2009). Hence, the vehicle's environmental impact is strongly dependent on the energy generation source utilized for recharging. Advantages of this technology compared with conventional cars with respect to greenhouse gas emissions and other pollutants have been shown in Samaras and Meisterling (2008), and Voelcker (2009). In any case, PHEVs will add new load to the power system while potentially also offering storage capabilities through vehicle to grid (V2G) services.

1.1. Integration of PHEVs into power systems—topics addressed in literature

Currently, due to lack of experience, temporal PHEV behavior is hard to anticipate. It can be claimed that the vehicles' primary use is transport and, because they are mobile, an additional element of uncertainty is introduced by the spatial distribution of connection patterns. A large number of PHEVs connecting in one area might cause transformer or line overloading and voltage stability problems, especially at lower voltage levels (Pecas Lopes et al., 2009b). Hence, investigations considering time and location of PHEV load and its possible impacts are performed for different countries, areas and voltages levels. Specifically, generation profiles (Schneider et al., 2008), effects in high and medium voltage grids (Hadley, 2007) as well as feeder loadings and lifetimes (Yu, 2008; Roe et al., 2009) are studied. Further, active management schemes have been developed implementing load mitigation into off-peak times (Parks et al., 2007) and distributing scarce power efficiently under connected PHEVs (Galus and Andersson, 2008), thus relieving the network (Galus and Andersson, 2009a).

Electric vehicle batteries could also be used for power system services as Kempton and Tomic (2005) suggests. In the light of recent initiatives aimed at increasing fluctuating renewable energy generation (European Renewable Energy Council (EREC), 2007; Department of Energy (DOE), 2008), the potentially distributed PHEV storage could be used for balancing the fluctuating infeed. Balancing algorithms are developed in e.g. Takagi et al. (2008), Galus et al. (2010), and Pecas Lopes et al. (2009a). Studies indentified substantial revenues for such V2G services in different countries and power markets (US (Kempton and Tomic, 2005; Quinn et al., in press), SE & DE (Andersson et al., 2010)). However, investigations of V2G are performed, to a large

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extent, independently of the network considerations mentioned above and organizational structures of power system operation.

Recently, Guille and Gross (2009) provides a conceptual framework integrating V2G services into current organizational structures for ancillary reserves. However, V2G is not necessarily independent from other operation modi, such as controlled or uncontrolled recharging, since the vehicles need to be recharged to a degree individually chosen before departure.

1.2. Focus and objective of this paper

References mentioned in the previous subsection focus mostly on individual technological challenges. Except for Guille and Gross (2009), almost no attention has been paid to PHEV integration into existing organizational structures of power system planning and operation. However, technological concepts should preferably be related to these structures for easier implementation.

This paper focuses on the integration of electric vehicles into existing power system structures. Other topics, such as transportation issues, regulatory policy frameworks, economics of PHEV operation etc. are not discussed. The view here is strictly limited to the question of how to enable fastest integration of PHEVs into power systems taking into account the complexity of existing power systems' technical and organizational structures. In order to consider the envisioned PHEV utilization modes and their interdependencies, a PHEV operation state description is developed which is similar to the well established power system state definitions (Kundur, 1994). The integrative structure of the PHEV state description considers uncontrolled-, controlled- and bidirectional PHEV modi. Hence, the description could be useful for future PHEV planning activities. The objective of the paper is summarized as:

1. to explain the relevant, practical aspects of power system organization, planning and operation as well as the related challenges of PHEV integration into these structures,
2. to structure and integrate existing research on PHEV integration via the PHEV state description to provide a realistic conceptual view for electric mobility integration into power systems and future research.

The paper starts with a conceptual overview of current power systems. It incorporates a brief description of technical and organizational structures as well as planning activities of various actors. The subsequent section elaborates on which areas and actors of power systems planning and operation are affected by the introduction of PHEVs. The fourth section develops the operational state description for PHEVs when connected to the power system. The fifth section provides an example illustrating the usability of the framework. Finally, some concluding remarks are given.

2. Conceptual overview of electric power systems

Power systems have developed over several decades, resulting in different architectural designs and operation schemes in different countries. Due to political decisions, many electricity systems are nowadays liberalized. Therefore, the design and operation of liberalized systems will be taken as the basis for this paper. Three different structures of power systems are of interest in this paper, i.e:

- Technical structure,
- Organizational structure,
- System planning structure.

These are described in the following sections.

2.1. Technical structure of power systems

The purpose of power systems is the generation, transportation and distribution of electricity to end consumers and from the technical point of view, the structure of power systems can be defined to incorporate the following hierarchical layers:

- Generation,
- Transmission,
- Distribution,
- Consumption.

Traditionally, large generation blocks, like nuclear or fossil fueled, and hydro power plants, inject power into the transmission system. The system must be dimensioned to accommodate these large amounts of power and transport them over long distances. The transmission system can be said to act as the backbone of a power system. Interconnections between power systems of different countries are done dominantly on this level. In order to minimize resistive losses, the voltage (U) levels are usually higher than 110 kV, in Europe most commonly 220 and 400 kV $((P_{loss}/P_{transmitted}) \sim (P_{transmitted}/U^2))$.

On a regional level, power delivery is carried out by distribution systems. These systems are connected to both high voltage transmission systems as well as lower voltage end consumers. The usual flow of power is from transmission systems via distribution systems towards consumers. However, this principle is changing in many systems as increased numbers of distributed generation (DG) units, such as wind turbines or photovoltaic systems, are connected at the distribution level. In some conditions, e.g. strong wind and low load, this can result in a reversed flow, where the power flows from the distribution system towards the transmission system. The voltage levels in distribution systems range from 110 kV down to 400 V (commonly known as 230 V phase-to-ground, country dependent).

Consumers can be connected to any voltage level. However, at the lower voltage level less power can be transported. Hence, the level on which the consumers are connected is dependent on the amount of consumed power. Large industries with a significant consumption may draw their power directly from the transmission network. Household consumers are almost exclusively connected to the lowest voltage level.

The equipment used for power delivery is generally split into two types:

- Primary equipment,
- Secondary equipment.

Primary equipment refers to system components which carry high currents or are subject to high voltages. Their purpose is the transport of large amounts of energy (Kosakada et al., 2002). Typical examples are overhead lines, transformers, switches, etc. Secondary equipment represents auxiliary devices and systems for metering, monitoring, supervision, protection and control (Bower et al., 2001).

2.2. Organizational structure of actors in power systems

There are three issues that are of particular importance for the organizational structure of power systems:

- Natural monopoly,
- Regulation,
- Competitive power markets.