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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.

These are discussed in the following.

Transmission and distribution networks/infrastructure are investment intensive and there is no benefit for society in building several parallel and competing networks. Hence, the concept of natural monopolies is commonly accepted in this domain, resulting in one transmission system and several distribution systems, each of the latter serving a limited area. Fig. 1 illustrates the organizational structure of typical power systems in the ENTSO-E area of continental Europe and displays the roles and actors within it. One actor might incorporate several roles. Deviations from this structure can occur.

The regulator avoids unfair exploitation of the natural monopoly possibly resulting in unjustified high prices for network usage. It monitors and approves prices for transmission and distribution of energy but allowing network owners to achieve profit. Furthermore, the regulator implements incentives for an economic operation of the system as well as transparent and fair access to the network for all market players. However, the entity does not directly determine electricity prices.

The Transmission System Operator (TSO), Independent System Operator (ISO) and distribution system companies (DISCOs) operate the respective systems under rules approved by the regulator. Contrary to the ISO, the TSO not only operates but also owns the transmission assets in his are of supervision, which is called control zone. The control zone does not necessarily have to relate to country borders but usually it does. The operation responsibility of the TSO/ISO is not limited to the transmission network, but rather the entire power system. The TSO controls the voltages and ensures system security through contracting ancillary services for its control zone. These are used to balance differences between generation and consumption in real time, which stabilizes the frequency.

Ancillary services are contracted by the TSO via a separate market (Verhaegen et al., 2006) usually with relatively high prices (Rebours et al., 2007b). The services are provided by the contracted primary-, secondary- and tertiary reserves (UCTE, 2004). The costs incurred by the TSO for maintaining and operating the network and for keeping the network secure by using ancillary services are passed to the consumers through network usage fees and through the concept of Balance Groups (BG), respectively. The concept of BG is explained later.

Primary and secondary frequency controls are constantly active in order to keep the frequency stable within a small band around nominal frequency (50 Hz in the ENTSO-E). Primary reserves are activated locally at the contracted generators in the

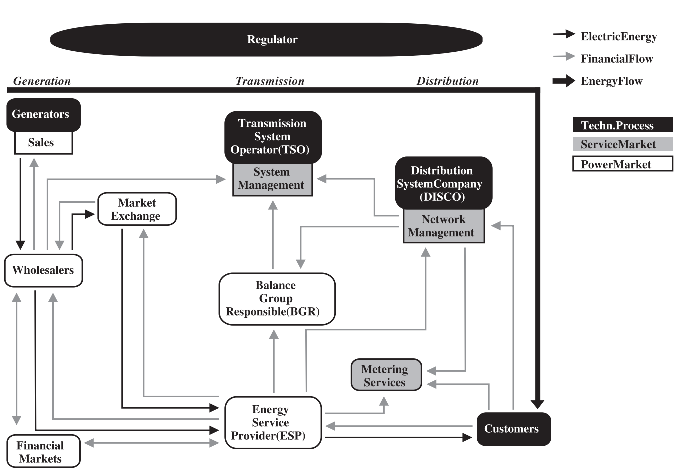

Fig. 1. Electricity roles and actors in liberalized electricity markets (Crastan, 2004).

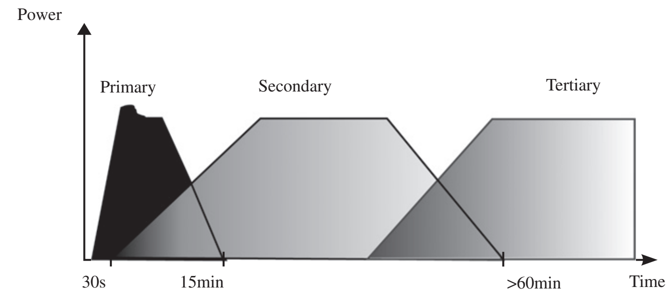

Fig. 2. Timescales of frequency regulation control in most European countries (Rebours et al., 2007a).

area of ENTSO-E. The activation is based on a frequency measurement and a control loop. The reserves balance small and counteract large errors. In the latter case, primary reserves are only able to stabilize the frequency at another value than nominal frequency. Secondary reserves are employed only by the TSO of the control zone in which the imbalance occured. The reserves recover the frequency to the set value, releasing primary reserves. They are activated via an Automatic Generation Control (AGC) signal sent by the TSO (Galus et al., submitted; Ulbig et al., 2010). Secondary reserves typically balance larger errors (e.g. errors from ramping, load forecasts, renewable energy infeed forecasts) and reestablish the planned cross border power flows. Tertiary reserves are activated manually, rather rarely and are used during unforeseen, large, long lasting disturbances. Fig. 2 gives an overview of different control reserves and their activation times in most ENTSO-E systems (Rebours et al., 2007a).

Generators and consumers participate in a power market, competing to sell and acquire power economically. Only large consumers act directly on electricity markets. The majority of consumers receive power from their suppliers, also called Energy Service Providers (ESPs) which aggregate consumer load. This aggregation leads to the minimization of fluctuating load behavior, a flattening of the load curve shapes and increased load prediction reliability (Bunn, 2000). ESPs, and other wholesalers, frequently do not posses any generation assets. ESPs acquire electrical energy either directly from the market or from wholesalers. The latter ones can also be active on financial markets, not necessarily focusing on energy.

Distribution system companies (DISCOs) plan, operate and maintain the distribution networks. The DISCOs are responsible for a good power quality and security of supply in their region. Furthermore, they are legally bound to procure all information and data necessary for energy accounting tasks of ESPs and within BGs. The information procurement also includes the data in the case when consumers change their suppliers. Furthermore, the DISCOs determine costs for distribution network usage which are included in the network usage fees and passed to the ESPs which further distribute them to their consumers.

Customers are charged for the consumed electricity which is measured through metering services (see Fig. 1). The costs include the price of electrical energy, the network usage fee, the metering costs and balancing energy costs. The network usage fee covers investment and maintenance costs for electricity networks and the costs for ancillary service power procurement.

The balancing energy and the cost for it are derived from the BG. Consumers (also ESP), producers as well as traders of electricity may group themselves in BG which are not necessarily affiliated to a specific geographical area or DISCO within the control zone. A BG is managed by an entity, often called "Balance Group Responsible" (BGR), who takes over the administrative tasks of collecting information from loads, generators and traders. This information includes consumption and generation forecasts

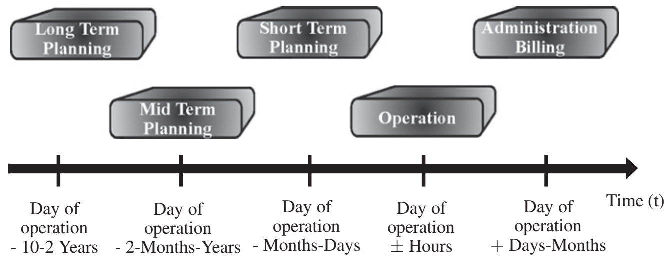

Fig. 3. Power system planning and operation timescales.

as well as scheduled imports and exports from trades for the next time interval (e.g. one day). Network information is not considered. The daily BG schedules are submitted to the TSO, which then assesses them in order to ensure balance of generation and consumption within the control zone. The approved schedules are subsequently used by the TSO to determine balancing energy charges for deviations from these schedules. The charges are derived from the costs of the energy provided by the ancillary services and are transferred to the consumers in the particular BG.

The aggregation taking place in BG provides the advantage for the TSO of avoiding the direct communication with a massive amount of actors. Furthermore, natural, uncontrollable load fluctuations can compensate each other leading to more reliable forecasts (Walker and Pokoski, 1985). Hence, the communication costs and operational efforts are minimized while contributing to simpler accounting related to balancing energy. Typically, there are tens to hundreds of BG in one power system.

2.3. Brief overview of planning activities in power systems

Several planning activities which the actors and market players need to perform can be delineated from each other depending on their particular time frame. They are introduced in Fig. 3.

Long-term planning typically considers a time span between one and 10 years. Network operators (TSO/ISO, DISCOs) expand the network where required, addressing long-term trends in energy consumption and transportation. Power producers make and implement decisions about the structure of their production portfolio. Typically, this planning takes into account long-term forecasts of primary energy sources, policy making and major, foreseen technological changes.

Mid-term planning is usually carried out from one month up to one year. The objective is to account for seasonal phenomena. In this time scope, network operators coordinate and carry out maintenance planning so that network security is not jeopardized. Power producers plan maintenance and optimal use of their assets. Mid-term forecasts include economic developments, weather- and load behavior.

Short term planning is performed from day-ahead, i.e. day before operation, up to one week. Forecasts at this stage tend to be quite accurate. BGRs plan their schedules while the TSO/ISO assesses system security based on network topology, generation and BG schedules. DISCOs use similar information to evaluate security of supply in their area.

During operation of the power system, i.e. the actual day of the operation, when the electricity is produced and delivered, the TSO/ISO monitors and ensures system security. Administration and billing takes place days after the energy delivery to the consumers.

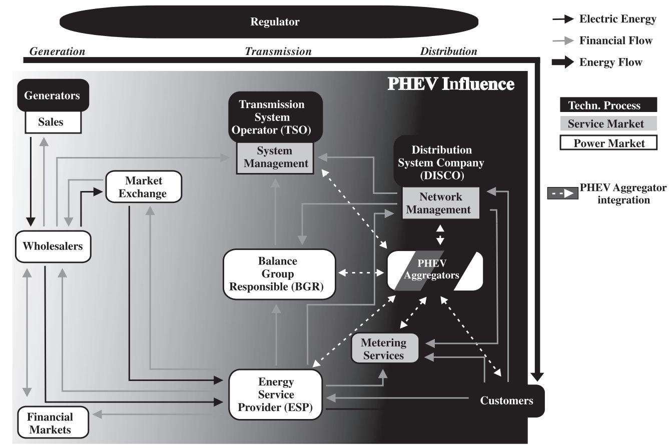

Fig. 4. PHEV influence on electricity roles and actors in liberalized electricity markets.

3. PHEVs in the context of power system operation and planning

A widespread adoption of electric vehicles will need to be considered in all activities within power systems. However, some activities will likely be subject to more rigorous modifications, in technical as well as in operational terms, than others. This is visualized through the colored area in Fig. 4. Here, the darker part indicates anticipated actors, which will most likely face more changes than those in the lighter coloured area. This can easily be understood when considering that the vehicles will connect to lower network levels and hence entities active on these levels will be affected more.

For instance, DISCOs could need to reinforce their local distribution grids to supply increased demand. ESPs will need to plan for meeting increased energy demand caused by PHEVs considering a yet unknown temporal distribution. Metering services and administrative systems will likely be more complex, as electric vehicles and PHEVs are mobile loads possibly connecting at various locations during the day while switching administrative areas, BGs and distribution networks. Organizing the information exchange between affected actors is crucial for proper accounting and operation in the balance group concept.

V2G services will raise the complexity of managing PHEVs even more, changing financial and energy flows while increasing stress on distribution equipment. TSOs, BGRs and ESPs then need to consider the PHEVs differently, as they will no longer be passive loads but possibly feeding energy into the lowest network level. This might even change the classical organization as new entities, managing PHEVs adequately, could evolve (Andersen et al., 2009). Such entities are indicated by the box *PHEV Aggregators* in Fig. 4. So far, it is not completely clear in which processes and markets these entities will be active. Hence, no arrows indicating commodity flows are linked to this entity, but it is located in the darker area of Fig. 4 and close to the power system actors with which it will most probably interact closely. Presumable interactions with actors are indicated by the white dotted arrows, whose rationale is further elaborated in the following two subsections.

Planning for PHEV introduction is obviously crucial. In each of the planning timescales introduced in Fig. 3, power system actors need to internalize the challenges imposed by PHEV integration and the envisioned PHEV utilization schemes. The following subsections will outline challenges in different planning stages and during operation for actors which are affected by PHEVs.

3.1. Long- and mid term planning

Long term planning is based on future energy consumption scenarios. Available studies, often including electric mobility development paths, show that generators, wholesalers and energy markets will likely experience an alteration of electricity consumption through widespread PHEV use. In fact, the International Energy Agency indicates in its 450 ppm scenario that a 21% share of global engine technology sales in 2030 will relate to PHEVs (International Energy Agency (IEA), 2009). This is confirmed by other studies, e.g. Turton and Moura (2008). Future market price levels due to PHEV adoption are investigated as well (Wehinger et al., 2010). Hence, some tentative knowledge on long term electric mobility development is available, which generators, wholesalers and others can use for the assessment of future price levels, investment- and production plans. These actors are arranged in the lighter area of Fig. 4.

Network operators rely on similar studies. Information on future PHEV adoption rates, on PHEV connection localities, -capacities and on transportation demand development, the latter a domain so far not of primary interest to network operators, would be of importance to them. However, especially from the viewpoint of DISCOs to which PHEVs physically directly connect, the focus needs to be shifted to lower network levels.

The PHEVs use a comparably high power rating when recharging and change locations. This could imperil grid stability at certain connection points and times (Ipakchi and Albuyeh, 2009). Asset overloading and voltage sags induced by locally increased active power consumption and insufficient infrastructure might deteriorate power quality and security of supply (Pecas Lopes et al., 2009b; Clement et al., 2009). This situation might vary even between different areas of one city. Hence, future network planning, typically performed in long term planning using local load forecasts, needs to assess potential private transport scenarios and possible PHEV fleet power demands. Thus, extensive fleet tests (Karner and Francfort, 2007) as well as integrated transport and network simulations (Galus and Andersson, 2009b) need to be performed to gain insights into temporal and spatial electric mobility demand evolution and resulting grid reinforcement needs. That is when considering the vehicles as an uncontrollable load.

Envisioned V2G services aggravate planning challenges since possible impacts are difficult to anticipate. The V2G services could impact generators and market prices in the case where vehicles provide peak power. DISCOs need to take into account network impacts of increased and fast switching bidirectional power flows possibly using advanced secondary equipment, able to manage PHEVs efficiently. This equipment, however, partly needs to be developed together with appropriate standards for metering and billing.

From the organizational point of view the concept of BG and load schedules might need to be revised to incorporate more flexibility because PHEVs, acting in V2G- or controllable load mode (i.e. load management), inherently behave differently than stationary, uncontrolled loads. BGR will need to take this aspect into account in the long run. One suggested solution for these services are PHEV aggregators (Quinn et al., in press) depicted in Fig. 4. Their integration within the BG concept and their interaction with BGR, TSO and metering providers remains to be investigated. The same is valid for a necessary reorganization of ancillary services in order to allow PHEV contributions. Currently, large generators are usually contracted for these services due to restrictions on bids which are limited to comparably large powers and long contract times. From the PHEV point of view this is unfavorable (Andersson et al., 2010). A legal extension of the BG framework, as well as ancillary service procurement providing standards and dividing responsibilities, is needed.

Mid term planning could include areal and seasonal variations of specific traveling patterns (e.g. during holidays). However, this is not further discussed here.

3.2. Short term planning and load forecasting

Future short term planning of DISCOs, BGRs and ESPs will most probably be significantly affected by the different envisioned utilization schemes of electric vehicles. Short term planning is used to assess system security and energy consumption. Hence, it is crucial for actors such as BGRs, DISCOs and ESPs to investigate temporal PHEV transport behavior and its energy demand since these will change the well known load curves. Not considering PHEV energy demand appropriately in the day ahead load schedule will introduce massive planning errors in BG schedules and will lead to substantial financial penalties.

Further, assessment of possible location changes is also essential for these actors and particularly for DISCOs. PHEVs might possibly switch between different distribution systems when driving, making it hard to appraise the system loading and ensuring security of supply. In the near term, recharging at home after returning from work, i.e. during low load periods of the system, can be considered as a valid assumption in order to assess grid stability (Hadley, 2007; Roe et al., 2009). With higher availability of recharging spots, consumer preferences considering working, shopping and leisure times, traffic dependencies, etc. will alter uncontrolled recharging behavior and exacerbate the temporal and spatial short term planning complexity for all actors. Currently performed field tests (Karner and Francfort, 2007) and agent based transport simulations will lead to a deeper understanding of PHEV behavior and enable better forecasts (Galus et al., 2009; Waraich et al., 2009).

However, uncontrolled recharging is almost exclusively discussed without relation to the other envisioned schemes (controlled charging, V2G). These latter services could likely modify the uncontrolled recharging substantially, e.g. shift PHEV energy demands to different times and locations. Suggested controlled recharging schemes, i.e. smart charging, are often based on real time energy pricing (Kessels and van den Bosch, 2008) and presume complete PHEV participation. While the schemes often neglect the individual energy demand for specific trips, the schemes can also increase the peak load of the grid in case the prices are low during unplanned renewable energy generation infeed. So far it remains unclear how controlled recharging can be integrated in the BG planning and accounting concepts while considering energy demands of individual cars and overall network security.

In addition to controlled recharging, V2G services have been suggested. Investigations of V2G often focus on economic cases illustrating potential profits (Quinn et al., in press). They rarely consider PHEV energy demands in order to travel to the next destination. However, these energy demands are crucial, especially when actually allowing for PHEV discharging (e.g. for peak shaving, load following, balancing energy provision). In such a case, V2G needs to offer the possibility to recharge the vehicles in order to ensure that they will be able to reach their next destination using electric energy. Hence, the vehicles should be able to quit V2G services in order to recharge sufficiently before departure. Such transfers to other operation modes could strongly influence planned schedules, similar to the case of controlled recharging. Furthermore, widespread V2G services can lead to critical states of the distribution network (e.g. islanding), which need to be analyzed by DISCOs in order to assure security of supply.

It remains to be investigated how transfers from V2G service to a controlled recharging- or an uncontrolled recharging scheme could be implemented technically. However, with insufficient knowledge on V2G provision in the DISCO's grid and without an integral planning and operational framework, integration of V2G schemes into naturally grown power system structures will be a difficult task.

3.3. Operational structure for PHEVs

Independent of which entity actually manages the cars, a general operational framework for connected PHEVs, which offers an integral view on the different envisioned PHEV operation modes, is beneficial. The framework needs to integrate PHEVs in uncontrolled as well as controlled mode and V2G services. It should also consider that PHEVs need a certain energy amount to be driven. Hence, transfers between modi or the possibility to completely quit the particular service in order to recharge sufficiently should be integrated. Section 4 will suggest such an operational framework for both dispatchable- and nondispatchable PHEVs.

3.4. Administration and regulatory issues of PHEVs

Regulatory issues like administration, metering and billing of PHEVs are of great interest as well. However, it is yet unclear which actor (e.g. BGR, DISCO, or Aggregator) that will actually employ control schemes and whether the schemes will consider network states as suggested in Galus et al. (2010). Presumingly, vehicles could be integrated into the organizational structure of power systems via existing actors or roles although their planning schemes and legal authorization would need to be modified. Important information for PHEV management is often not available for particular actors. For example, the BGR does not know in which operation state the distribution system is currently. This lack of information could prevent necessary control actions which could avoid stressing the grid.

New actors', such as PHEV-Aggregators (see Fig. 4), eligibilities and responsibilities are also yet to be defined (Guille and Gross, 2009; Andersen et al., 2009).

The actor controlling the PHEVs will need to employ smart metering and communication technology, which is already available (Guinard et al., 2009). However, it remains to be studied how a billing and control scheme can be implemented, especially since the vehicles are not a stationary load. Information exchange between the PHEVs, their managing entity and the established actors in power systems is crucial and could be based on state-of-the-art mobile phone communication, e.g. GSM. It can be envisioned that necessary standards would need to be at least nationwide as vehicles might easily leave one and enter another billing area/country.

4. Operational framework definition for PHEVs in power systems

A framework embracing the different utilization schemes is developed in the following. It has to incorporate the power system point of view while the PHEVs are connected to it. Hence, the framework is similar to the well known power system state description found in Kundur (1994). This description defines the states *Normal*, *Alert*, *Emergency*, *In extremis* and *Restoration* as well as transfers between them.

While already (Galus and Andersson, 2009b) suggested several possible states from the vehicle point of view, Fig. 5 defines a state description of PHEVs from the power system point of view.

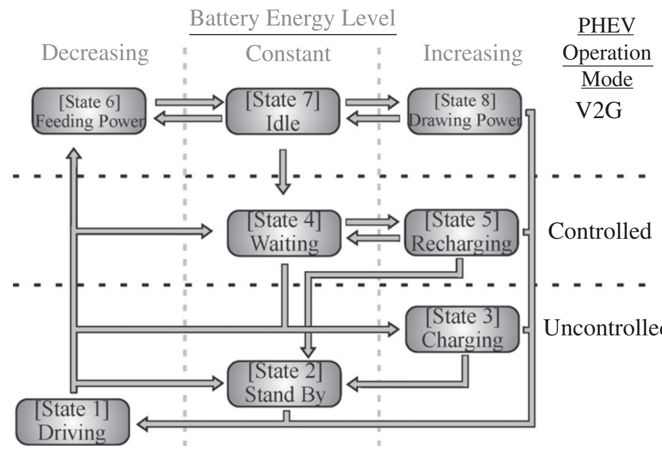

Fig. 5. Operation states of connected PHEVs from the power system point of view.

The states are defined depending on different battery energy level conditions and particular PHEV operation modes. As for the battery, the energy level of the connected PHEV/EV battery can either be constant, decreasing or increasing. These battery energy level conditions are denoted at the top of the figure. Further, several PHEV operation modes can be envisaged and have been mentioned earlier. They are introduced on the right hand side of the figure and are defined to be uncontrolled-, controlled charging and V2G services. Hence, a matrix can be formed, visualized by the dashed lines, through which different PHEV states can be distinguished from each other. Possible transitions between states are indicated by arrows in Fig. 5. The functionality of the framework is described in the following based on the PHEV operation modes.

4.1. Uncontrolled charging

The main purpose of PHEVs is individual transport, during which the battery energy level is decreasing to an extent defined by the characteristics of the particular trip. This situation is represented by the *Driving* state in Fig. 5. It can be considered as the interface between the power and the transport system. This state is completely decoupled from the network view.

A transition from *Driving* into the uncontrolled *Stand By* state can be envisaged. The *Stand By* state embodies the situation of a grid connected vehicle with a full battery. In the *Stand By* state no influence can be exerted from the PHEV managing entity. The PHEV can leave this state by disconnecting and going back into the *Driving* state.

The second possible state in the uncontrolled PHEV operation mode is the uncontrolled *Charging* state. Here, the vehicle is connected to the grid at arrival and the battery is not completely full. The battery is then recharged but no external control actions are undertaken. Charging lasts until the battery is full. When fully recharged, the vehicle transfers from the uncontrolled *Charging* state into the *Stand By* state until it is disconnected and departs. Obviously, a transition from uncontrolled *Charging* to the *Driving* state is possible, because the owner might simply disconnect his vehicle when leaving, even if the vehicle is not completely recharged. In summary, this scheme does not presume any coordinative control actions at all. Thus, the influence on the power system is solely driven by the stochastic behavior of PHEV users.

4.2. Controlled charging

A transition from the *Driving* state into the controlled charging mode can be envisioned as well. In order to be inserted into this mode the vehicle needs to be connected to the grid, be equipped with an adequately intelligent connection module and somehow be legally bound (e.g. contracted) for controlled charging. Two states, similar to the uncontrolled charging scheme, can be defined here. The difference is that both states can be accessed and controlled.

The *Waiting* state is similar to *Stand By* since the battery energy level is stable in both cases. However, the states differ from each other because in *Waiting* the car is not yet completely recharged and the controller has decided that the vehicle is not recharged.

The *Recharging* state is analogous to *Charging* in the uncontrolled scheme as the energy level of the battery is increasing. However, frequent transitions between controlled *Recharging* and *Waiting* as well as variations of the charging power are possible and are decided by the particular controller. This is not the case in the uncontrolled mode.

Once completely recharged to the desired state of charge (SOC), the vehicle performs a transition to the *Stand By* state. Here, it is not accessed by the controller until departure. Transitions from *Recharging* or *Waiting* directly to *Driving* are possible by simply disconnecting the PHEV from the grid and leaving. This is illustrated by the transition path from *Waiting* over controlled *Recharging* to *Driving*.

The framework establishes a possible transition from the controlled to the uncontrolled charging scheme for PHEVs in the *Waiting* state. This transition represents a case where the car owner requires energy immediately. It offers the possibility to exit from the controlled charging mode in order to simply recharge the vehicle in an uncontrolled manner. Clearly, such a possibility needs to be included in the contracting rules of the managing entity and would need to be considered in its planning activities. In any case, the energy flow in this scheme is unidirectional—from the power grid to the PHEV.

4.3. V2G services

V2G services constitute the third PHEV operation mode to which the vehicles can transfer from the *Driving* state. This mode also requires intelligent connections to the power grid and is dependent on V2G controls. V2G services incorporate three different states, one state more than for controlled charging because here the battery energy level can be decreasing. The V2G operation mode comprises the states *Feeding Power*, *Idle* and *Drawing Power* as shown in Fig. 5. The cars can be assumed to be in the *Idle* state when connecting. The next state is chosen dependent on V2G management algorithms and state transitions are performed. The transitions and PHEVs states in the V2G mode are presumed to take the network states (e.g. line capacities, voltage constraints, etc.) fully into account, similar to controlled charging.

The V2G management is different than the controlled charging scheme because it follows different objectives, so far not fully defined in literature. For instance, the management could serve any kind of ancillary services (primary-, secondary- or tertiary control) or it could perform valley filling and peak shaving.

Transitions between the controlled charging and the V2G scheme can be envisaged but are not imperative. The cars could possibly leave the V2G scheme in order to be sufficiently recharged when departing. Further, the vehicle might also be allowed to completely leave the V2G scheme and charge in uncontrolled mode until the demanded SOC is reached. These transitions offer the important possibility to quit the V2G services if they intervene with individual energy and transport demands. The availability of the exit option could depend on special contracting of the V2G managing entity. Obviously here as well,

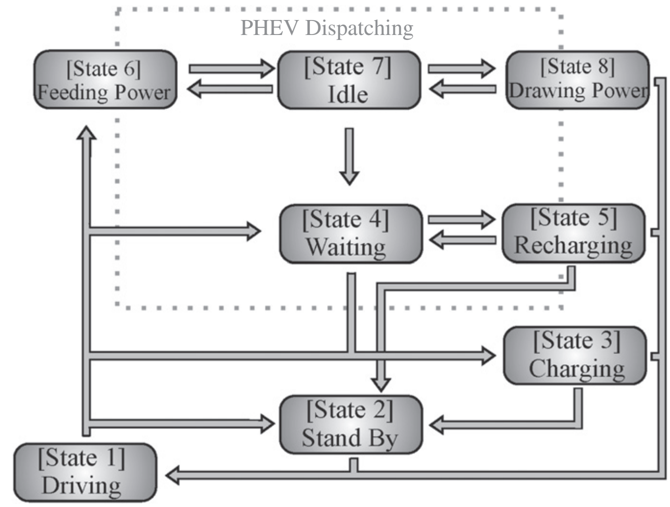

Fig. 6. Dispatchable PHEV vehicle operation states in the power system. The dispatch is dependent on the objectives of the PHEV managing entity.

transitions between the states of the V2G- and controlled charging scheme have to be considered during planning stages of the managing entity.

The two modi of controlled charging and V2G services can be seen as the part of the framework where PHEVs are actively dispatched between operational states. The dispatch would be based on individual PHEV states, the particular mode, the utilized algorithms and the objectives of the managing entity. Fig. 6 shows the area of active dispatch, e.g. grid controlled states (*State 4*–*State 8*) through the dotted area. The states within the area can be actively used for advantageous system integration of individual transportation into power system operation and planning.

5. Framework application

In order to illustrate the activities described in Section 3 and the usefulness of the framework developed in Sections 4.1–4.3, two simple cases, which apply the operational state description for PHEVs, are investigated and compared.

5.1. Example

In the example considered there are PHEV Managers, which allow to perform PHEV demand management considering grid constraints and daily price curves. The method which is used by the PHEV Managers assigns utility functions to each vehicle. The utility functions are dependent on the vehicle's actual SOC, their desired SOC at departure, their individual parking time, and the actual energy price. The maximization of the total utility at each network node leads to an optimal energy distribution among connected PHEVs while ensuring network security and favoring low price periods for recharging. The method is elaborated in Galus and Andersson (2008, 2009a) where it is illustrated to perform the herein defined controlled charging mode, only.

The system which is simulated in this example comprises a simple network of four nodes including a PHEV Manager device at each node and a fleet of in total 30,000 PHEVs. For simplicity, controlled recharging is set to be price independent. Hence, all cars which connect in controlled recharging mode try to recharge immediately. If the network should face congestion due to PHEV demand, available power is optimally allocated to connected cars according to the decisions of PHEV Managers (Galus and Andersson, 2008, 2009a). In this case, only parts of the fleet are recharged.

The vehicles in the simulation incorporate an individual SOC at arrival, a desired SOC at departure, an anticipated departure time, a 3.5 kW power connection and a 30 kWh battery. Their temporal behavior has been simulated through a transport micro-simulation (Waraich et al., 2009) of a typical work day in a transportation network including 28,000 streets. The temporal behavior assumes that all PHEVs are connected at the beginning (e.g. 0.00) of the day and the end (e.g. 24.00) of the simulated day. Individual SOCs and desired SOCs are set randomly. The individual SOC always lies between 20% and 100%.

Two cases are studied according to the framework of Fig. 6 to demonstrate its applicability and are defined as:

Case 1: V2G services are performed without PHEV state transfer to other modi (e.g. recharging),

Case 2: V2G services are performed but PHEV state transfers to controlled charging are allowed.

Fig. 7 shows the two above cases and the difference between them using the operational state description. In case 1, illustrated in Fig. 7(a), controlled *Recharging* and V2G services are completely decoupled. The vehicles leaving V2G services do not transfer to controlled charging in order to achieve their desired SOC at departure and are hence not controlled by the PHEV Managers. The cars simply depart, partly without having a sufficient SOC. Therefore, these vehicles do not impose load on the system.

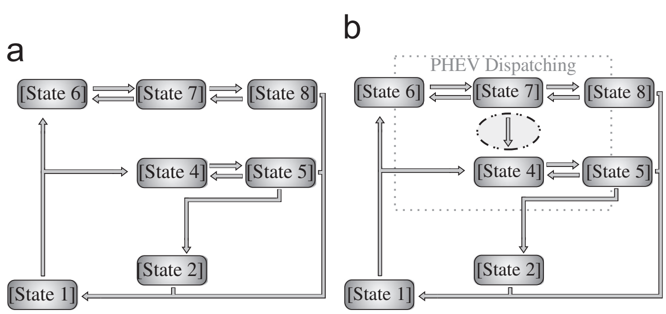

Fig. 7. Operational state descriptions of the two cases used for the example. (a) Case 1: PHEV operational state description *without* enabled V2G-controlled charging transfers, (b) Case 2: PHEV operational state description *with* enabled V2G-controlled charging transfers.

Case 2 introduces a transition path between V2G services and the controlled charging mode illustrated in Fig. 7(b) through the grey circle. Now, PHEVs are actually able to quit V2G services in order to be sufficiently recharged through the PHEV Managers' decisions. The transfer back to the V2G mode could be possible, but is not included here.

Both cases allow for immediate departure. Furthermore, the transfer from the controlled *Recharging* state to the *Stand By* state is also included in the simulation to incorporate the possibility that PHEVs have been fully recharged within the controlled mode but have not yet departed. For simplicity, transfer from the *Driving* state to uncontrolled charging has not been taken into account here.

In order to include both cases in the concept of PHEV Managers, it has been extended for the following simulations to include V2G services. Two types of PHEVs are then considered within the fleet, where one is in controlled charging mode, only. It covers 30% of the cars and it is managed according to the concept of utility functions introduced in Galus and Andersson (2008, 2009a). The other 70% of the vehicles are assumed here to provide load frequency control.

A control signal, depicted in Fig. 8, which is transmitted by the TSO, was used as an input signal for the PHEVs. The per unit value of the signal determines the actual power to be delivered to or drawn from the system assuming a contracted power (here 4 MW) for the complete PHEV fleet. Positive signal values mean that PHEVs need to be discharged, negative that they need to charge. Hence, according to Fig. 5, they switch between the states 6–8 of the V2G mode. Zero net energy usage for system services is not assumed. It can be seen in Fig. 8 that the utilized signal is negatively biased. This bias poses an advantageous situation for the PHEVs in V2G mode as it implies that the vehicles are recharged on average throughout the day. However, with connection intervals shorter than 24 h, it is possible that the net energy called for system services is positive during the specific connection interval. Then, on average, the PHEVs would need to supply more energy to the grid than they would get.

The PHEV Manager assesses every time interval (here 15 min) whether the individual PHEV in V2G mode needs to recharge immediately in order to achieve the desired SOC before the anticipated departure time. Should this be the case, the vehicle quits V2G services and transfers into the controlled charging

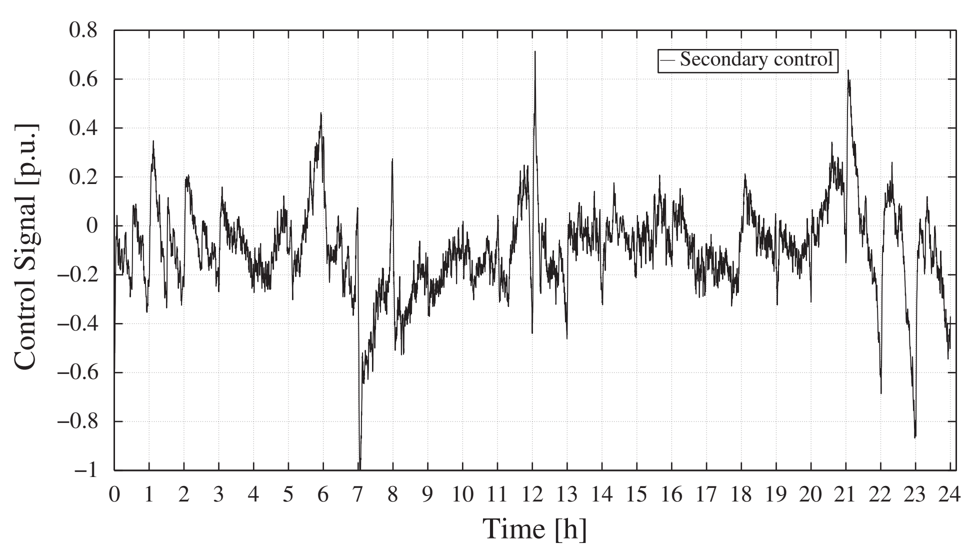

Fig. 8. TSO secondary control signal in 5 s intervals for 24 h.

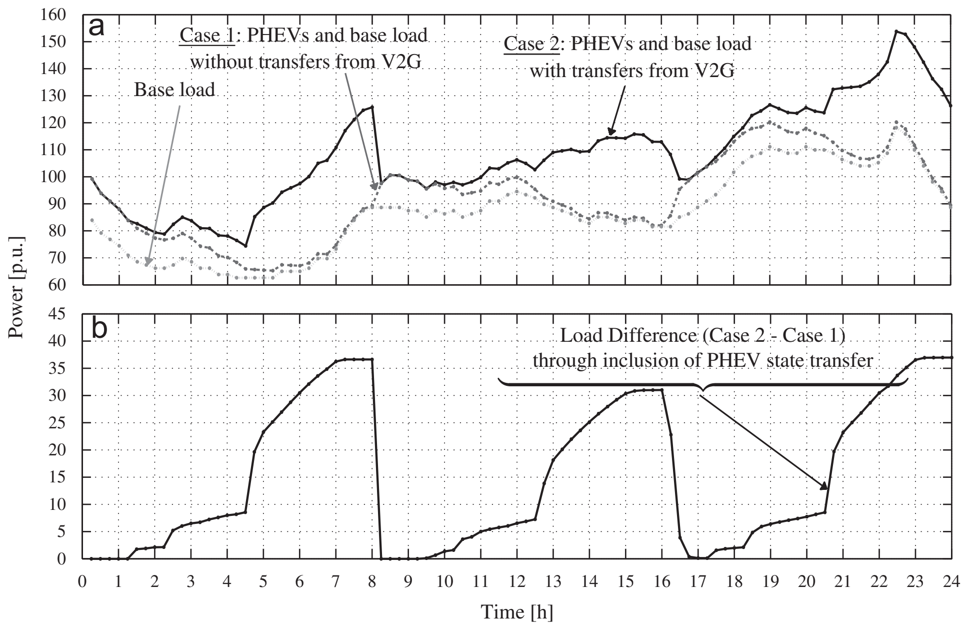

Fig. 9. Effect of PHEV transfers from V2G to controlled charging state: (a) Load curves for system base load (bright grey), total load including PHEVs without V2G transfers (dark grey) and with V2G transfers (black), (b) difference between the loads with- and without V2G transfer.

mode of the PHEV Manager, in which it is recharged to the desired level before departure.

5.2. Simulation results

Note that the following simulations are not supposed to deliver quantitative results about possible load curve mutations. The goal is rather to show that there is a difference between planning of PHEV demand including operation mode transitions, which take into account individual transport demands, and not considering them. The simulations will demonstrate why the various PHEV modes should be included into a holistic planning and operation of pertinent entities, e.g. BGRs, DISCOs, and PHEV Aggregators.

The implications of not having an integral view on the different utilization schemes and not considering possible changes of PHEV operation modes are illustrated in Fig. 9. Fig. 9(a) shows the base load of the network through the dotted, light grey graph. The load curve, measured by an utility, is assumed to be predominantly residential. Hence, the shape shows low load during the night and high load in the evening hours. The peak between 10 and 11 p.m. is due to time of use pricing and to the ripple control of household water boilers being switched on. It is representative for ca. 130,000 households.

The black, dashed line illustrates case 1 of the example. The load includes controlled charging of PHEVs without considering transfers from V2G to the recharging mode. The cars contracted for V2G services (70% of the fleet) supply the secondary control demand until they leave, no matter if they attain the desired SOC before departure or not. Here, the feature of using the internal combustion engine if the battery should be depleted is crucial.

Clearly, the overall load level is higher than the base load. The shape of the load curve is also altered. It can be seen that vehicles predominantly recharge during the night before leaving to work. At work they connect immediately and recharge again in order to attain a SOC that is sufficient to reach their home. It was assumed that the energy to be recharged should be 10% more than was used on the way to the working place. This behavior results in a peak around 8 a.m. Some PHEVs then leave again, traveling somewhere else, before driving back to the home location. At home they start to recharge again, increasing the level of the system load.

The black graph in Fig. 9(a) shows the load curve of case 2 enabling the state transfer from the V2G- to the controlled charging mode. The transitions defined by Fig. 7(b) are performed by the PHEVs in order to be recharged adequately before departure. Obviously, the load is different than in case 1. Load shape and level are altered. The difference between the two cases of the example is plotted in Fig. 9(b). It is substantial even for the low PHEV penetration simulated here (30,000 PHEVs for 130,000 households equals ca. 23% penetration rate). Hence in the case of V2G integration, considering energy demands for individual vehicle trips through the proposed framework leads to a different short term load forecast than neglecting them. If such transport demands are not taken into account at the planning stage, considerable balancing energy amounts need to be utilized to correct these shortcomings which might introduce costly planning errors.

Utilizing the proposed operational state description for PHEVs in a planning stage could allow PHEV managing entities to incorporate the PHEV mode transitions into their short term planning. This will minimize planning errors and avoid substantial financial penalties while offering a distributed storage for the system.

6. Concluding remarks

In this paper, a brief overview of power systems planning and operation is given. It is used to delineate tasks and actors, whose existing organizational and operational structures could be altered when integrating PHEVs into electricity systems. Impacts of PHEV integration on roles and actors in planning stages are discussed and possible effects on their long- term and future short term planning are elaborated.

Concentrating on future short term planning and operation including V2G as well as charging services, a PHEV operation state description is developed. The PHEV states are defined from a power system point of view. They are derived from utilization schemes that have been suggested for electric vehicles. Transitions between vehicle operation states are deduced for system friendly operation considering potential, individual consumer transportation demands. The framework is able to integrate different research development paths while relating their different objectives to current and future power system operation and planning. New business models, once established, could use the framework for PHEV integration into system operation.

The usefulness of the framework has been demonstrated through a simple case study considering V2G services for secondary control. The example illustrates that different PHEV operation states cannot be regarded independently from each other in short term planning.

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