Electric Power Systems Research 81 (2011) 185–192

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

# The impact of vehicle-to-grid on the distribution grid

Kristien Clement-Nyns*, Edwin Haesen, Johan Driesen

*K.U.Leuven, Electrical Engineering Department ESAT-ELECTA, Kasteelpark Arenberg 10 box 2445, B-3001 Heverlee, Belgium*

A R T I C L E   I N F O

*Article history:*
Received 9 November 2009
Received in revised form 18 January 2010
Accepted 20 August 2010
Available online 28 September 2010

*Keywords:*
Charging strategy optimization
Distribution grid
Plug-in hybrid electric vehicles
Renewable energy
Vehicle-to-grid

A B S T R A C T

Plug-in hybrid electric vehicles (PHEVs) can be connected to the power grid. The power flow of this connection can be bidirectional, so vehicles can charge and discharge. This vehicle-to-grid option can aid to improve grid efficiency and reliability. A simulation covering an entire day is essential to obtain an accurate assessment of the impact of PHEVs. It is important to know when, statistically, vehicles are available for charging or discharging. In this work is shown that uncoordinated charging of PHEVs in distribution grid can lead to local grid problems. Therefore, coordinated charging and discharging is investigated and a voltage constraint is implemented. These vehicles can support the grid in terms of voltage control and congestion management. In that way, the distribution grid can handle more PHEVs without reinforcements. Distributed generation units are more common nowadays in the distribution grid with some of these generation units based on intermittent renewable resources. This paper shows that there could be a good combination with PHEVs as they can provide storage to take care of the excess of produced energy and use it for driving or release it into the grid at a later time. In that way, consumption and generation are more efficiently matched.



## 1. Introduction

Plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs) have an advantage compared to hybrid electric vehicles (HEVs), i.e. a connection to the electric power grid allowing more opportunities. The vehicle can not only charge, but also discharge and thus inject energy into the grid. In that way, PHEVs can support the grid. This is indicated as vehicle-to-grid (V2G) operation. The electrical consumption for charging PHEVs amount to 5% of the total electrical consumption in Belgium by 2030 [1].

Currently, there is little storage available in the power grid so demand and generation must be perfectly matched and continuously managed to avoid frequency instabilities. PHEVs have an energy storage capacity which is rather small for each individual vehicle, but the number of vehicles will be large, yielding a significant energy storage capacity. At any given time, at least 90% of the vehicles are theoretically available for V2G [2,3]. These vehicles must be connected to the grid when idle. There must be enough vehicles plugged in during the day to provide grid services therefore it could be beneficial to give incentives to vehicle owners to stay plugged in. Most of the weekdays, vehicles follow a schedule which does not vary much from week to week [4]. The electrical storage of PHEVs could provide grid services via V2G concept and add a surplus value to the vehicle owner [5]. The vehicle owners need energy for driving at more or less predictable times and the grid operator needs power to match demand and consumption [2]. PHEVs can handle large and frequent power fluctuations because they are designed that way for driving needs [6].

When uncoordinated charging of PHEVs is applied, the vehicles will immediately start to charge at full power, e.g. 4 kW, when they are plugged in until they are fully charged or leave earlier. Uncoordinated charging will cause local grid problems in terms of extra power losses, which can be regarded as an economic concern, and voltage deviations, affecting power quality. This decreases the efficiency of the distribution grid. Therefore, coordinated charging is introduced in this article, where the objective function is to minimize the power losses. In previous work [7,8], vehicles were only able to charge and could not discharge and therefore supporting the grid was not possible.

The idea of this research is to support the grid by using a bidirectional power flow. A voltage control is implemented as a constraint in the optimization problem to increase the power quality of the grid by using coordinated charging and discharging. A smart meter or an embedded controller is therefore essential [9]. A full day simulation is also considered to achieve a more global overview of the impact of charging PHEVs on the distribution grid. The research fits in a more global context where also other new technologies, such as combined heat and power systems and photovoltaic cells, are implemented in the distribution grid in combination with PHEVs. The proposed methodology can help evaluating planned grid reinforcements versus PHEV ancillary services to achieve the most efficient grid operation. It allows to determine a maximum hosting capacity of the grid for PHEVs. The coordination of the charging

* Corresponding author.
*E-mail address:* Kristien.Clement@esat.kuleuven.be (K. Clement-Nyns).

0378-7796/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.epsr.2010.08.007

and the implementing of voltage control can postpone the reinforcements of the grid.

## 2. Vehicle-to-grid concept

### 2.1. Connection to the grid

The connection to the electric power grid offers opportunities for PHEVs for charging the vehicle but also for discharging and thus injecting energy into the grid. In the ideal case, the electricity consumption should match perfectly with wind and solar energy and the generation of conventional power plants. Because of forecasting errors and the intermittent behavior of renewable resources, imbalances occur and generation and demand do not perfectly match. The vehicles can help to match consumption and generation by charging and discharging 'on the right moment'. The combustion engine can also deliver electricity during peak hours, though this is not realistic for several reasons. The emissions, emitted locally, in this case will rise because of the local generation and the efficiency will be lower compared to large power plants. There is also a cooling problem for vehicles which remain stationary while delivering significant amounts of power. Emptying their fuel tank will also reduce their driving range and increase the noise level.

The management, i.e. dispatching, of the PHEVs is crucial. Communication is needed between the vehicles and the utility grid, by sending signals to request energy from the PHEVs [2]. For the vehicle-to-grid concept, three elements are required. First, a power connection to the grid must be available, second, a control connection is essential for communication with the grid operator and third, there must be an on-board precision metering for knowing the battery content [4]. The vehicles can be represented in three ways. First, the signal can be sent to each vehicle separately or to a central controller supervising the PHEVs in a single facility, e.g. a parking lot. The third possibility is a third-party aggregator who is responsible for separately located vehicles.

### 2.2. Ancillary services

PHEVs are for the moment more expensive compared to conventional vehicles. In [2], it is concluded that selling energy could be beneficial for these vehicles. The batteries can act as a source of stored energy to provide a number of grid services. The most promising market for these vehicles is probably that of the ancillary services [3]. Possible services for V2G are: supply of peak power, supply of primary, secondary and tertiary control (for frequency regulation and balancing), load leveling, and voltage regulation. PHEVs are able to respond quickly and thus serving for high value electrical services. It is unlikely that each vehicle will be contracted separately because the maximum power output of each vehicle is too low. But a fleet manager or aggregator could conclude a contract for a fleet of PHEVs. The advantage of dealing with an aggregator or fleet manager is that a single party represents a more significant amount of power, that is the accumulated power of the vehicles in the fleet. Moreover, the availability profile of a larger group of vehicles is much smoother. A single vehicle owner could conclude a contract with the aggregator without being concerned about the interface with the electricity markets.

#### 2.2.1. Frequency regulation

One aspect of grid management is to provide power reserves to maintain frequency and voltage and facilitate the efficient handling of imbalances or congestion. So it is essential to keep the frequency at appropriate levels, i.e. between 49.99 and 50.01 Hz according to the ENTSO-E, the former UCTE [10]. Frequency regulation has several levels of control: primary, secondary and tertiary control.

The primary reserves regulate the frequency and stabilize the European grid to avoid blackouts. The frequency control is activated automatically and continually. Primary control can only be activated if primary reserves are available. The primary reserves are about 100 MW for Belgium. The response time is smaller than 1 s.

Secondary reserves are allocated a day ahead to balance the grid and are adjusted automatically and continually, both upward and downward on a 15 min time base. If the frequency is lower than 50 Hz, the batteries could be discharged (regulation up) and if the frequency is above 50 Hz, the batteries could be charged (regulation down). On average, the regulation up and down are equal. The impact on the battery is a small discharge due to charge and discharge efficiency. The reaction time is a few seconds. These reserves are used for imbalances between nominated and measured power injections and to restore the frequency.

There are two types of tertiary reserves: tertiary production and tertiary offtake reserves. These reserves are used for major imbalances and congestions. In contrast to primary and secondary reserves, these are activated manually and only a few times per year. These reserves must deliver their power within 15 min [11].

It is not clear which types of ancillary services are economically profitable for PHEVs. According to [6], secondary and tertiary control are assumed to be competitive and primary control is supposed to be highly competitive. In [12] primary control is expected to have the highest value for V2G. According to [13], peak power control could be the most economical solution in Japan. The power that must be delivered by tertiary reserves would be too high and the duration too long for the vehicles [14]. Thus only primary and secondary control could be interesting from a technological point of view.

#### 2.2.2. Voltage regulation

In a low-voltage grid, cables are common and the resistance $R$ is large compared to reactance $X$. Adjusting the flow of active power in this grid will influence the voltage amplitude. The voltage regulation maintains the voltage between the limits defined by the mandatory standard EN50160 [15]. This voltage control can be embedded in the charger. The charging of the vehicles will stop when the voltage at the grid connection becomes too low. In a further step, discharging of an unit of active power can also be taken into account to increase the grid voltage.

#### 2.2.3. Load leveling and peak power

For load leveling, the demand is shifted from peak hours to off-peak hours. Therefore, dispatching is necessary. PHEVs could discharge during the daily peak loads, replacing the peak capacity generators that are only used during peak demand hours. If these vehicles want to discharge during the peak hours, they will have to charge during the off-peak hours. In the case the energy which is stored during off-peak hours, is released during peak hours to relieve congestion in the grid infrastructure, supplying peak power and load leveling are the same. Supplying peak power is possibly difficult for PHEVs because of the relatively long duration and the storage limitations. Thus, supplying peak power is generally not profitable as the largest cost is the wear of the batteries [14]. Load leveling is more likely because the vehicle does not necessary need to discharge during peak hours. The total consumption of electricity will not be lowered but shifted to the hours of low electricity consumption which are the off-peak hours to minimize the power losses and to increase grid efficiency. The implementation of smart meters or real-time pricing and coordinated charging is essential.

### 2.3. Opportunities for PHEVs

PHEVs have the potential to support a residential distribution grid but are technically and economically unsuitable for all kind of