Towards the Integration of Electric Vehicles into the Smart Grid

Ghanim Putrus, Gill Lacey and Edward Bentley

Abstract Electric Vehicles (EVs) have high energy capacity and their anticipated mass deployment can significantly increase the electrical demand on the grid during charging. Simulation results suggest that for every 10 % increase in households operating 3 kW EV chargers in an uncontrolled way, there is a potential increase of peak demand by up to 18 %. Given the limited spare capacity of most existing distribution networks, it is expected that large-scale charging of EVs will lead to potential problems with regard to network capacity and control. This paper presents analysis of these problems and investigates potential means by which the particular features of EV batteries may be used to enable large-scale introduction of EVs without the need for wholesale upgrading of power grids. Smart charging, using a combination of controlled EV charging (G2V) and Vehicle to Grid (V2G), can significantly help. The results presented demonstrate the benefits of smart charging for the grid and consider the impact of grid support on the EV battery lifetime. Various factors that affect capacity degradation of Lithium ion battery (used to power EVs) are analysed and the impacts of G2V and V2G operation on battery capacity loss and lifetime are evaluated. Laboratory test results are provided to quantify the effects of the various degradation factors, and it is shown how these may be ameliorated to allow economic network support using EV batteries without incurring excessive battery degradation in the process.

Keywords Electric vehicle · Smart grid · Li ion battery · Grid constraints · Grid to vehicle · Vehicle to grid · Smart charging

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1 Introduction

Increasing concern over the effects of climate change resulting from increasing global demand for energy and the persistent reliance on fossil fuels has led world leaders to set a target of a 50 % reduction of greenhouse gas emission by 2050 (the UK has an even more ambitious target of 80 %). In the UK, the contribution to CO_2 emissions from the surface transport sector is some 21 % of the total, leading to recognition of the need to electrify the transport sector to allow the UK to meet its 2050 emission targets. To encourage the uptake of EV and to allow for the expected increase in EV numbers, several countries have put ambitious plans to build the charging infrastructure for EVs (Office for Low Emission Vehicles 2011).

A range of EV is already on the market, chiefly comprising Plug-in Hybrid Electric Vehicles (PHEV) and battery powered EVs; the latter are usually powered by Lithium ion batteries with a capacity of a few tens of kWh (Kampmann et al. 2010). At present the market for EVs is limited, in view of their high price and limited range, but the market is expected to grow with anticipated rises in the price of petrol and advances in battery technology which will result in EV absolute and relative total cost of ownership reduction that will make the EV option more attractive.

Research suggests that uncontrolled charging of EVs can cause problems for the electric power grid due to the associated heavy electrical demand during charging (Putrus et al. 2009). As to whether a national power system is able to support large numbers of EVs, Taylor et al. (2009) found that if 90 % of Australia's peak annual generating capacity is available during off-peak periods, there would be enough energy available within the system to provide charging for EVs to make all existing urban passenger vehicle trips. The impact of the energy requirements of an increased number of EVs on the UK national power grid has been evaluated by a study which concluded that the grid capacity should be adequate for up to 10 % market penetration of EVs (Harris 2009). However, while the supply–demand matching for a region as a whole might be adequate to allow the use of sufficient numbers of charging points to support the EVs, there may be an impact on specific parts of the distribution system, particularly at the Low Voltage (LV) level. Local distribution substations and feeders for different areas may not have enough capacity to handle the increased load created by EV charging.

The impact of EV charging on the grid can be minimised by controlled charging and EVs can even be used to support the grid if their charging schedule is managed appropriately in a concept known as "Grid to Vehicle" (G2V) (Putrus et al. 2009; Jiang et al. 2014). Further, once the transport sector becomes largely electrified, it will be possible to use the energy storage capability of the EVs to mitigate problems arising or anticipated within the national power grid, as well as to provide storage to optimise the use of renewable energy sources (RES). EV batteries have considerable energy storage capacity and controlled charging can allow a schedule whereby they can be charged at a time when the grid has surplus capacity and discharged when the grid has a shortfall in capacity in order to meet peak demands and provide a storage facility for supply/demand matching. In addition, EV batteries can also be used to effectively balance the network frequency, 'shave' peak demand and provide emergency power in case of generation failure (V2G). Examination of this potential forms the subject of this paper.

As to when EVs would be connected to the grid (and thus available for charging and/or V2G), Babrowski et al. (2014) found that vehicle availability at charging facilities in Europe during the day for all countries is at least 24 %. With the additional possibility to charge at work, at least 45 % are constantly available. Results from EV trials (Bates and Leibling 2012) show that vehicles are parked for over 95 % of the time (23 h each day), so there is ample opportunity for them to be plugged in, charged and/or used to support the grid.

The study described in this paper is divided into three parts. The first (Sect. 2) presents the potential impact of EVs on the grid, using simulation results to support the analysis. The second part (Sects. 3–5) describes the means of alleviating the problems arising and presents potential opportunities for using the EV to support the grid supply. The third part (Sect. 6) describes the implication of the latter (EV to support the grid) on the EV battery capacity and lifetime, and is based in part on experimental tests on batteries. Section 6 defines the factors affecting battery degradation and introduces the various degradation mechanisms affecting EV batteries, so that these may be guarded against, allowing the minimum level of degradation to occur whilst the batteries are used to support the grid. Minimising battery degradation will maximise EV battery useful life, allowing the economics of EV operation to be made as favourable as possible. The knowledge of how to minimise battery degradation will allow maximum use to be made of the techniques suggested to maximise EV adoption given the constraints set by the grid. The economic benefits accruing from EV operation in accordance with the findings of this work are also discussed. In this way two of the most important factors militating against large-scale EV introduction, battery degradation and grid capacity, are addressed.

2 Impact of EVs on Existing Power Grid

EVs form a concentrated heavy load on the grid when compared to normal domestic power demands. EVs have high energy capacity and their anticipated mass deployment may lead to uncontrolled loading and a potential increase in peak electrical demand. Serious problems may be created for network operators from heavy charging demand to be met in certain times during the day, uncontrolled 'mobile' loads and seasonal 'migrations' of demand for EV charging.

As explained in Sect. 1, it is likely that the available national generation and grid capacity will be enough to meet the energy requirements of EVs for modest EVs penetration levels. Also, while the national aggregate capacity might be adequate, there are likely to be problems on specific parts of the grid, where local distribution substations and feeders may become overloaded by the increased load created by

EV charging. The following concerns regarding EV charging have been identified (Putrus et al. 2009).

- Uncontrolled loading due to increased deployment of EVs and potential increase in peak demand and overload of substations and feeders.
- Change in voltage profiles and violation of statutory limits.
- Phase imbalance (specific to single phase chargers).
- Reverse power flow (if V2G is adopted).

At the same time, mass deployment of EVs will create a very large energy storage capacity, which when considered as part of a smart grid can provide a valuable support to the grid. In a smart grid, the user will have the opportunity to plug in and charge the battery at will or when the price is right (to allow the possibility of arbitrage, buying power when it is cheap, such as in the middle of the night and reselling at times of peak demand), thus providing energy storage for supply/demand matching. In addition, there will be the need to allow EV operators to earn money by providing ancillary services and network support, e.g. voltage and frequency control using the energy stored in the EV batteries. It will often be possible to charge EVs from available micro-generation such as domestic Photovoltaic (PV) and Combined Heat and Power (CHP), thus charging from renewable energy and leading to efficiency savings due to reduced transmission losses. As a result there will be a need for smart grid interface controllers.

This paper presents the means by which the particular features of EV batteries may be used to overcome the difficulties inherent in the mass deployment of EVs, to enable large-scale introduction of EVs without the need for wholesale upgrading of power distribution systems.

2.1 Simulation Results

A typical LV distribution system is simulated using an Excel-based modelling tool that allows evaluation of the network performance for different operational scenarios in the presence of low carbon technologies, such as EVs and micro-generation (Lacey et al. 2013). The layout of the system is shown in Fig. 1. Typical daily load profiles, shown in Fig. 2, for the UK consumers for both summer and winter seasons were used (Barbier et al. 2007).

As mentioned earlier, EV charging represents a heavy load on the grid and therefore tends to cause overloading of the transformer and feeders as well as high voltage (HV) drops across the distribution system. To analyse this, the distribution system shown in Fig. 1 is considered with maximum (winter) loading conditions and domestic 3 kW EV charging for ~8 h (assuming 24 kWh battery capacity).

The problem facing distribution network operators with the introduction of EVs is that uncontrolled charging will tend to result in people plugging in their EVs when they return home from work at about 6.00 pm, when there is already a peak in demand for power. The problem will become worse as the uptake of EVs increases,

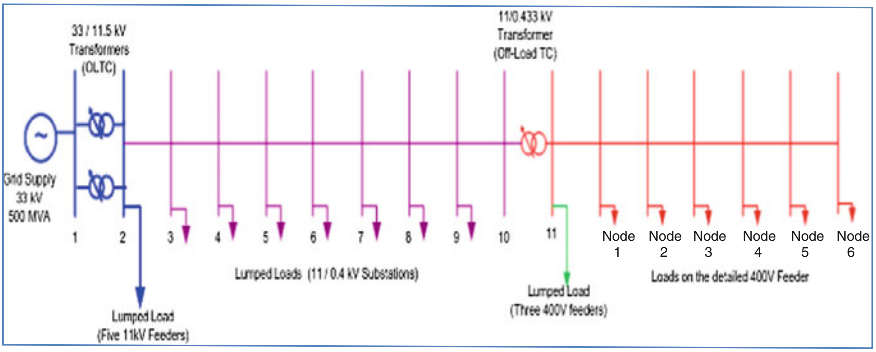


Fig. 1 Distribution network model

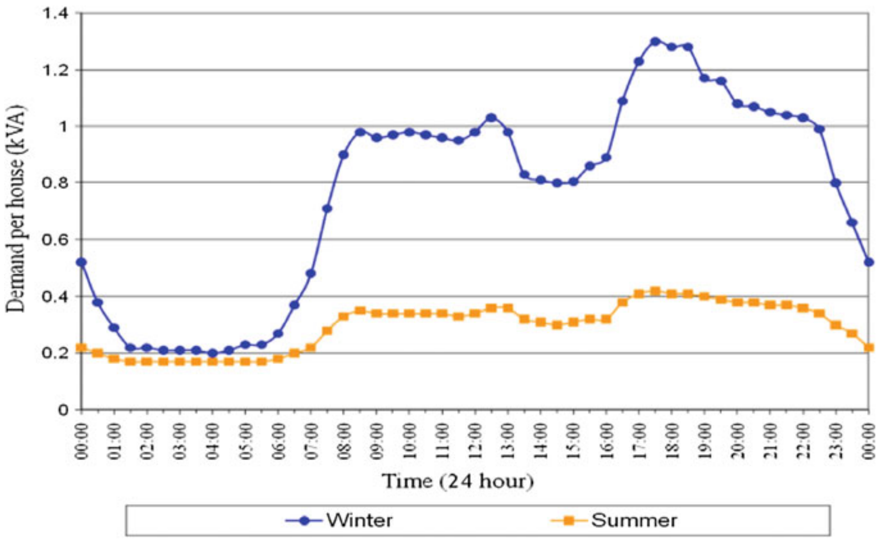


Fig. 2 Typical daily load profile for a domestic load based on ADMD referenced to a nominal 100 consumers and measured at a distribution substation on an outgoing feeder

as shown in Fig. 3 (zero to 30 % of houses having an EV). Peak demand rises by some 18 % for every 10 % increase in houses with an EV. Low voltage substations and feeders do not have a very large degree of spare capacity due to economic constraints, and a problem will be seen to arise at some degree of EV adoption.

The increased loading may also cause the voltage supplied to customers, particularly at the far end of the LV feeder, to fall below the statutory limit. Figure 4 shows the voltage at the far end of the LV feeder (Node 6 in Fig. 1) with different levels of households having a 3 kW EV charger.

Figure 5 shows the voltage profile across the length of the LV feeder (Nodes 1–6 in Fig. 1) for three cases: ‘no EV charging’ situation and then 20 and 30 % of

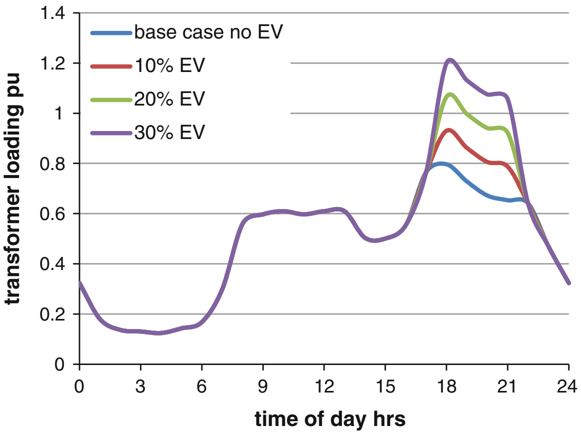


Fig. 3 Transformer loading for EVs with unscheduled 3 kW (uncontrolled) charging

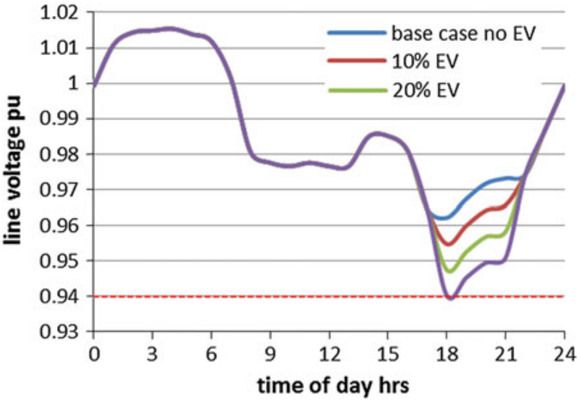


Fig. 4 End of feeder voltage with varying uptake of 3 kW EV chargers

households operating a 3 kW charger at the same time. As can be noted, charging of EVs creates extra loading on the feeders and therefore extra voltage drop. At 20 % level, the system is able to maintain the load voltage within the statutory minimum limit of −6 %, by the operation of the on-load tap changer (OLTC). However, with a 30 % level, the tap changer reaches its limit and the voltages at Node 6 approach the statutory limit.

3 Controlled EV Charging

3.1 Grid to Vehicle (G2V)

Controlled charging, e.g. by using incentives for customers, will reduce daily variations and improve load factor (match network capacity). If successful

Fig. 5 Voltage profiles for different EV 3 kW charger penetration Levels

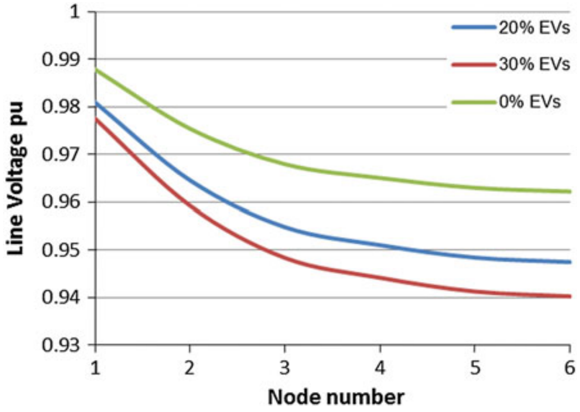
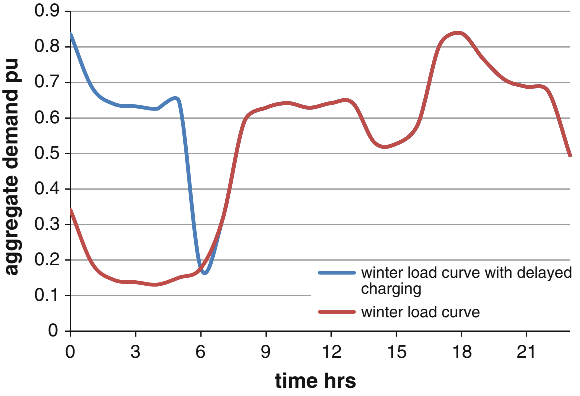


Fig. 6 Winter load curve, showing load levelling effect of delayed 3 kW EV chargers when 30 % of houses have EVs

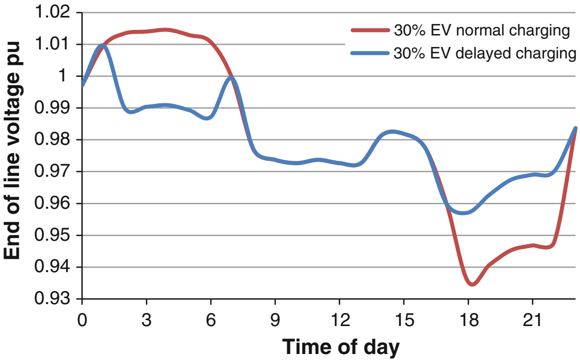


incentives are introduced, the attractive possibility of levelling the demand load curve over 24 h presents itself. In Fig. 6, it is assumed that 30 % of houses have EVs and these are charged at the optimum time for the grid (after midnight), by staggering/phasing EV charging times. EV charging will then occur at the times when the underlying demand for power is low; so the increase in demand does not exceed the peak level.

Figure 7 shows the effects on the voltage at the far end of the feeder (Node 6 in Fig. 1) caused by delaying charging. As can be seen, the under-voltage caused by uncontrolled charging is eliminated when controlled charging is deployed. This demonstrates the inability of existing distribution systems to support high levels of domestic EV charging whilst maintaining the legal minimum load voltage, unless some form of demand management is adopted.

Barbier et al. (2007) and Sulligoi and Chiandone (2012) reported that with significant renewable energy generation connected to the distribution network, the distribution system may experience a voltage rise, particularly during low demand. G2V may be designed to complement the generation profiles of renewable sources

Fig. 7 Showing end of line voltage for 30 % 3 kW EVs with and without delayed charging



and therefore is an ideal approach to charge EVs from renewable energy as well as relieve the grid from extra burden and losses.

3.2 Vehicle to Grid (V2G)

EV batteries have considerable energy storage capacity and controlled charging can allow a schedule whereby they can be charged at a time when the grid has surplus capacity (e.g. surplus renewable energy) and discharged when the grid has a shortfall in capacity (or renewable energy). In addition, EV batteries can also be used to provide supply/demand matching and effectively balance the network frequency and provide emergency power in case of generation failure. In V2G operation, where large numbers of EVs are aggregated and the composite energy stored is able to be used for grid support, the system allows provision of a potentially large-scale power reserve.

The V2G process may be used intelligently to ameliorate EV charging problems. Figure 8 demonstrates how the overloading of transformer caused by the scenario of charging with 30 % of households having EVs at 3 kW may be removed by arranging for the EVs to discharge their stored energy when the system is highly loaded at 6.00 pm, and recharging at a convenient time.

Another problem experienced with LV distribution systems when significant distributed generation (DG) is connected to the system is the potential for overvoltage, particularly when the DG is connected at the end from the supply point (Sulligoi and Chiandone 2012). Figure 9 shows the voltage profile at the far end of the LV feeder in Fig. 1, in the presence of renewable energy generation at a level based on the targets for 2050 (DECC 2010). As can be seen, without the use of controlled charging, the voltage will rise well above the statutory limit of 10 % above the nominal line voltage. This problem may be dealt with by using a suitably timed charging and V2G, as shown in Fig. 9, assuming 40 % of the households have 3 kW EV chargers.

Fig. 8 Transformer overload caused by EV charging, and its mitigation using V2G

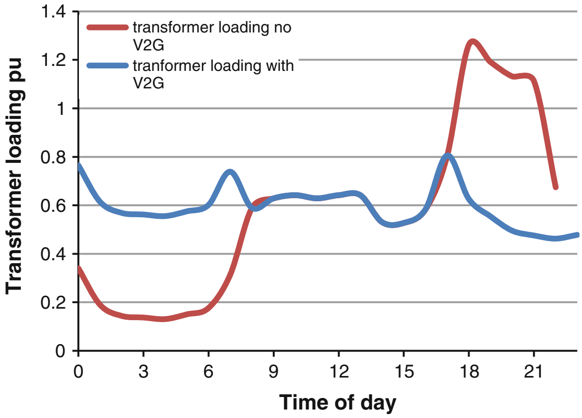
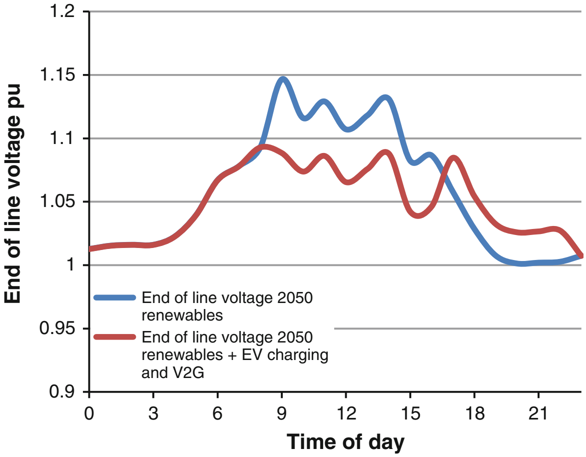


Fig. 9 End of line overvoltage caused by renewables, and its removal using EV charging and V2G



3.3 *Smart Charging*

Traditional battery chargers operate at nearly constant power for most of the charging time; input power tapering off as the battery is being charged. High-power EV chargers initially charge at constant current and this is then changed to constant voltage before reaching full charge. These chargers do not provide the optimum conditions for protecting the battery and maximising its life span. As will be described in Sect. 6, high charging current may damage EV battery, particularly at low (below 0 °C) and high (above 40 °C) temperatures, and that batteries have their remaining life prolonged by gentle low current charging regimes (Peterson et al. 2010). This shows the need for 'smart chargers' where the charger output (charging rate and time) varies with battery conditions, grid state (available power) and EV user requirements, as shown in Fig. 10.

A smart charger is required to determine the optimal charging current rate by considering the network condition, the battery's state of health (SOH) and state of

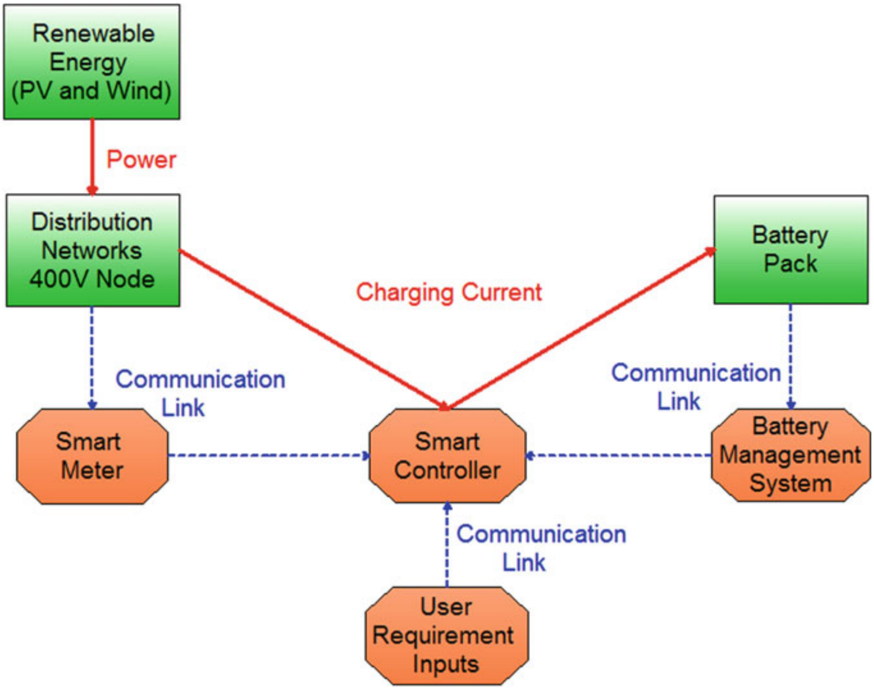


Fig. 10 The concept of EV smart charge controller (Jiang et al. 2014)

charge (SOC) (based on information from the battery management system), and EV user requirements (journey length and charging waiting time) (Jiang et al. 2014). The controller may also respond to direct signals from renewable energy generation or indirect signals (e.g. weather conditions). In this way, smart charging will meet user requirements, maintain battery SOH, support the grid and optimise the use of renewable energy. The rules for optimum smart charging may include the following, given by Jiang et al. (2014):

i. Charge the battery to user specifications (to ensure EV is charged and available for next journey), as long as there are no restrictions from the grid or the battery SOH.
ii. Monitor the grid condition (voltage and thermal limits) and adjust the battery charging current (if needed), in proportion to the deviation from the nominal (rated) limits.
iii. Monitor the battery SOH and adjust the battery charging current (if needed) in order to avoid negative impacts on the battery cycle life.
iv. The priority of each input can be adjusted, depending on the design requirements.

A smart charger which can allow two-way power flow will be needed to provide for V2G and V2H services. Smart charging involves incentivising the EV users to adopt a charge regime which optimises battery health and avoids charging during times of high grid demand whilst still allowing freedom of use for driving.

4 Smart Distribution Grid

A possible configuration of a future smart distribution system is shown in Fig. 11, in which bidirectional communication links and the flow of information are essential. All EV chargers are connected to the household-level smart charge/V2G controller, which is linked to the household smart metre. The metre calculates the net household power supply (e.g. from PV) and demand and sends data continuously to the Medium Voltage (MV) aggregator. The data bit rate can be very low, as it represents a single number sampled perhaps once a minute. In turn, the data received by the local smart metre from the MV aggregator will consist of a signal to control EV charging power demands. If the area served by the MV aggregator is as a whole able to supply all demands, but one particular line is reaching its limits, EV charging on that line alone will be curtailed. If the whole area controlled by the MV aggregator is short of power, all lines will experience a curtailment. The system can be developed to bring on stream V2G power from particular areas of the MV aggregator's control zone where it is needed.

This system allows EV users to charge at differing rates depending for instance on the SOH of the battery and ambient temperature, to maximise EV battery life. In the event that there is a sudden problem with the power availability in the MV system, the control signal can effectively shut down demand for EV charging power.

The MV aggregator under this approach would send data to the HV aggregator, again perhaps minute by minute, advising of the total net power requirement of the MV area. Signals from the HV aggregator will allow the MV aggregator to adjust

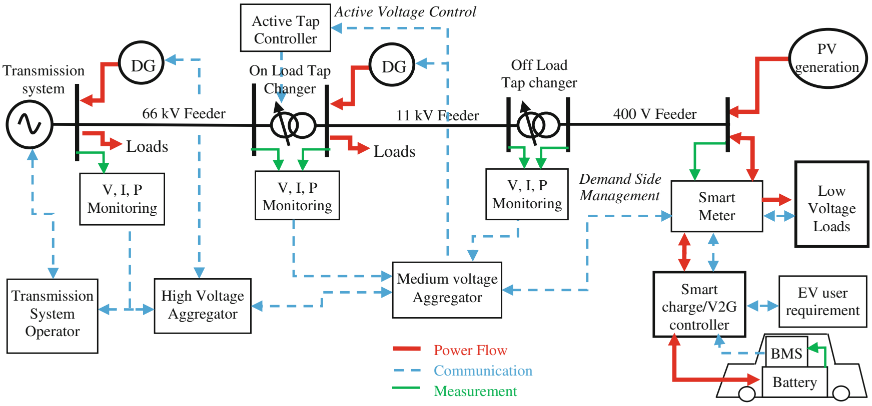


Fig. 11 A smart grid showing medium and low voltage elements of a distribution system incorporating smart charging (adapted from Putrus et al. 2013) (BMS: Battery Management System; DG: Distributed Generation)

supply and demand in their own area, so that overall system balance is achieved. Load flow analysis would be carried out continuously by both HV and MV aggregators to ensure that the areas for which they are responsible operate within the relevant network limits such as transformer and cable loading, and voltage limits.

5 Vehicle to Home (V2H)

Vehicle to Home (V2H) is a small-scale operation of V2G, in which a single EV battery is used to supply power for a single household. The use of V2H is intended to provide power to the home at times of supply failure or during peak demand. This energy may be stored in the EV from the grid or from a local micro-generation during a different time of day. Appliance usage by a single household is not subject to averaging, so the power demand from the single household might resemble that shown in Fig. 12. The average power demand portrayed is moderate, but peaks of 10 kW appear in the load profile.

Potentially, an EV bidirectional charger rated at 7 kW could supply about 70 % of the peak demand, averaging out the load profile so that it would be more readily supplied by, for instance, a PV installation owned by the household. The EV battery is designed to produce peak power outputs greater than 7 kW for short periods, and will not suffer undue damage by being used in this way. On this basis, the grid would merely have to supply the average domestic load rather than the instantaneous demand, rendering the job of the distribution network operator easier. In addition the transmission and distribution losses would disappear, making this option the most efficient as well as the most ‘green’.

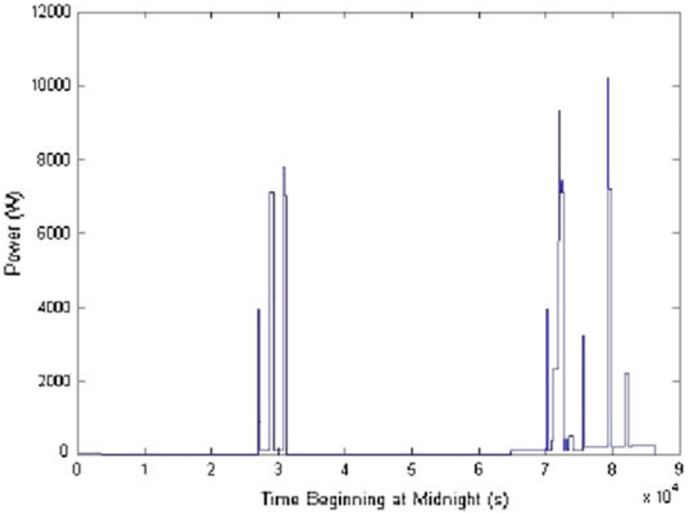


Fig. 12 Instantaneous power demand for a single house (Haines et al. 2009)

The total energy supplied by the battery in V2H will need to be replenished by the grid or by micro-generation to ensure the battery is still charged for driving. The total daily energy demand of a typical house in the UK on average is around 7 kWh in summer and 18 kWh in winter. In the UK, the output of a 3 kW PV installation can provide up to 20 kWh in summer and only about 2 kWh in winter, rendering the household potentially grid independent in the summer.

A further great advantage of V2H is that it can display a smoothing property as far as the grid is concerned. Vehicles are usually parked, and hence available for V2G for around 96 % of the time (Kempton and Tomic 2005). Therefore, the EV battery can provide a good service to the grid or home as well as being able to maintain the requisite average SOC to enable use as a vehicle.

6 EV Battery Degradation Caused by Smart Grid Support

Using EV batteries to balance supply and demand through V2G will result in extra charge transfer through the battery (cycling) and therefore the impact of this on the battery SOH needs to be evaluated to ensure that the effects on the battery (the most expensive part of the EV) are minimal, or even zero. To do this, it is important to define the main parameters that affect battery degradation and then use these factors to model the impact of V2G. As described in Sect. 3.3, by using smart charging of EVs, the battery SOH can be taken into consideration whilst providing support to the grid. In this way, the charger ensures that there will be minimum or no impact on the net charge transfer and therefore the battery SOH. However, there are several factors that affect battery SOH which need be considered, and these are described in detail in this section.

In the following, the process of EV battery degradation and the main factors that contribute to this are presented. The aim is to evaluate whether the use of EV battery to provide grid support (which it is capable of as shown above) will have any impact on the battery SOH; that is, whether the cycling patterns required for V2G or V2H will degrade the battery more quickly than standard (uncontrolled) charging only.

6.1 Methodology for Defining Battery Degradation

The degradation factors are identified and their weights are determined from available literature and from experimental tests conducted by the authors. Test results and research have enabled the life of a lithium ion battery to be predicted with reasonable accuracy using mathematical modelling techniques based on derived coefficients for each of the parameters that affect battery degradation. It should be noted that the results only apply for the type of battery being tested, as the model is derived from experimental tests on a specific battery type. Different batteries, even with the same chemistry, will follow the same trends but the value of each modelling coefficient may be different.

For EV applications, a battery is considered to be at ‘end of life’ when the fully charged capacity is 80 % of the new value. This is normally described in terms of a reduction in the battery SOH. The SOH at any time represents the percentage of a capacity possessed by a battery at that time when fully charged to the fully charged capacity when the battery is new. So, in this case the SOH will have fallen to 80 %.

6.2 Battery Capacity Loss (Lifetime)

Battery life time is defined by the permanent capacity loss of energy storing capacity, which may be divided into two types: calendar loss and cycle loss. The former is the capacity loss due to the passage of time, whether or not the battery has been in use (charged and discharged). For Li ion batteries, the calendar loss is dependent on temperature and SOC. Degradation tends to slow down when the battery is not in use and results show that a battery maintains its energy storage capacity if stored in a temperature around 5 °C and the SOC is kept low. The battery SOC affects the electrical stress between the electrodes and consequently the battery calendar life (Spotnitz 2003; Lunz et al. 2011a, b).

The use of EV battery to support the grid will result in more cycling (charge/discharge) of the battery. Consequently, concerns have been raised regarding the damage caused to the battery due to this operation and whether the gains for supporting the grid justify the loss in battery life.

The cycle life of a Li ion battery is defined in terms of the capacity loss per cycle due to charge entering and leaving the cell during cycling. The capacity loss is caused by the charge transfer between the electrodes and therefore is dependent on the way the battery is being used during the charging and discharging cycles. Four impact factors affecting battery ageing in terms of SOH have been identified. These factors are the operating temperature of the battery, the average SOC, the Depth of Discharge (DOD) in each cycle and the charging/discharging current flowing into and out of the battery. It is worth mentioning that these factors are interlinked and are determined by the chemistry of the battery as well as the reaction (both chemical and physical) during the charging and discharging process.

6.3 Factors Affecting Battery Degradation

There are four variables at play here; the temperature, the charging rate, the average SOC and the DOD. An attempt is made to analyse them and then to identify the ‘sweet spot’ where optimum battery SOH allows maximum support for the grid.

i. *Operating Temperature*

Research shows that cycling Li ion batteries at differing temperatures causes varying levels of irreversible battery capacity loss (Kaneko et al. 2013). The effect of temperature on cycle life of Li ion cells is shown in Fig. 13. As shown, the cycle life progressively reduces below 0 °C and above 50 °C. Cycling cells outside a specified range accelerate the capacity loss in the cells and when the temperature approaches 70 °C, a thermal runaway becomes likely. The battery thermal management system must be designed to keep the cell operating within the specified range (usually around room temperature) at all times to avoid premature wear out of the cells. It is worth noting that the cycle life quoted in manufacturers' data sheets is usually based on operation at room temperature (~20 °C), which may not be realistic for EV applications.

ii. *Charging Rate*

Dubarry et al. (2011) and Ning (2004) showed that battery cycle loss accelerates with charging current rate. Using experimental data and modelling based on electrochemical behaviour, Dubarry et al. (2011) showed that for the first 500 cycles or so the capacity fade is linear. This result is backed up by the results presented in Ning (2004) which also shows an experimentally linear rate with current density, as shown in Fig. 14.

The values are empirical but a correlation can be found using a base of 20 % at 1C rate after 500 cycles; this gives a degradation rate for the 23 kW of 0.0004. Scaling from Fig. 14 gives the battery loss values in Table 1 for different charging rates based on commercial charging stations. To verify these results several more tests were undertaken at different charge rates and all the results obtained appear to show that the lower the charging rate the better the SOH.

iii. *State of Charge*

The SOC of an EV battery is the battery capacity at any time expressed as a percentage of maximum capacity. It is usually determined by integration of the

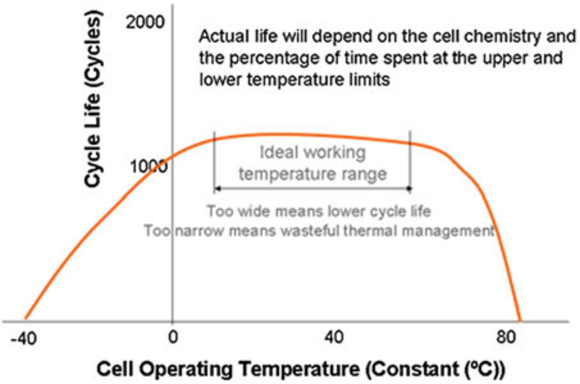


Fig. 13 Variation of battery cycle life (irreversible capacity loss) with temperature of cycling (Electropaedia et al. 2014)

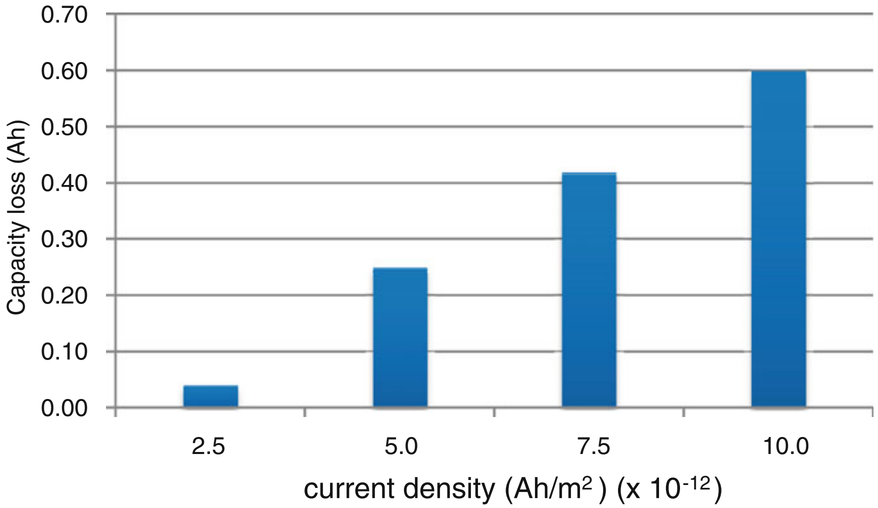


Fig. 14 Plot of capacity loss after 500 cycles with current density (i.e. charging rate) (adapted from Ning 2004)

Table 1 Derived capacity loss due to charging rate

Equivalent kW charge rate	Loss after 500 cycles	Loss per cycle	% loss per cycle
3	0.0125	0.000025	0.0025
7	0.03	0.00006	0.006
23	0.18	0.00036	0.036
50	0.43	0.00086	0.086

charging and discharging current. Charging at high SOC causes more damage to the battery than at lower values (Vetter et al. 2005). This is because the risk of stress cracking of the electrodes due to volume change and chemical breakdown of the battery's components is more likely at high SOC.

The average SOC for an EV battery depends on the SOC before and after charging and also before and after driving. It also depends on the time the battery spends in discharged state and that spent in charged state. In this research, the average SOC is calculated using the time of charging and the time when the car is charged ready for driving. The assumption is that the car is charged up ready for the next trip when it is connected, unless delayed charging or V2G is specified. The SOC whilst connected but not charging is then used to find the average SOC.

Figure 15 shows the results of testing $LiPF_6$ battery cells at different SOCs but at the same DOD, temperature and charge/discharge current rate. The results show that battery cycle number (capacity lifetime) reduces if the battery is cycled at high SOC. These results, and others obtained by the authors, demonstrate that battery life is prolonged by keeping the average SOC as low as possible. That is, using battery

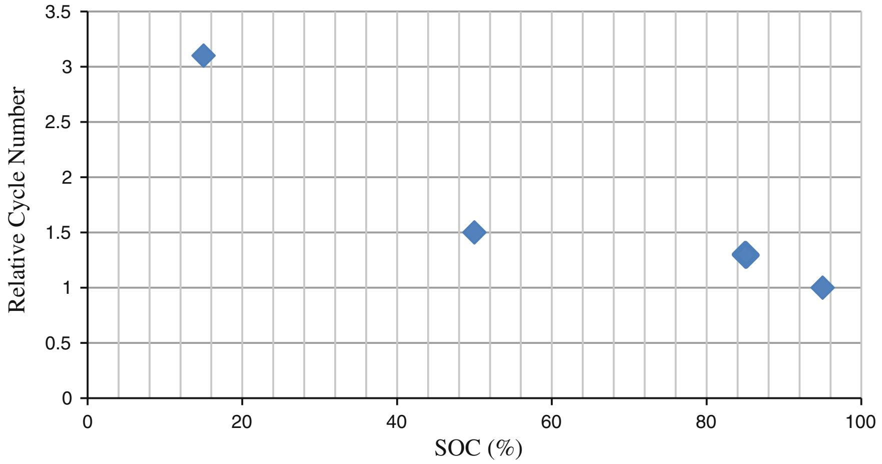


Fig. 15 Relative cycle number (capacity lifetime) for cells cycled at different SOC (adapted from Lunz et al. 2011a, b)

charging only when essential for the next trip, only charging what is required for the next trip and charging before driving, not immediately after.

iv. *Depth of Discharge*

Battery life is found by Peterson et al. (2010) and www.cars21.com (2010) to depend on the total charge throughput (Ah). Cyclic ageing is mainly due to mechanical stresses because of the volume change as the active material enters and leaves the electrode and is therefore dependent on the amount of charge transferred during charging and discharging. This can be isolated using the change in SOC, assuming a periodic charge/discharge cycle. Ignoring other ageing effects, the total energy throughput is fixed so that one cycle of 100 % change in SOC is roughly equivalent to 10 cycles at 10 % change in SOC and 100 cycles at 1 % change in SOC. The DOD is then the 100 % minus the minimum SOC in the cycle. Results of capacity loss with varying partial cycles, but grouped for average SOC, are shown in Fig. 16. The results back up what was stated earlier: that lower SOC means lower losses. The change in SOC (coloured bars) is not significant. Therefore, the DOD is not a factor, only the amount of charge transferred. If the DOD is defined as the change in SOC when the maximum is always 100 %, then the DOD is a factor insofar as it affects charge transfer.

In summary, experimental results show that the best temperature for battery cycling life is around 20 °C and that battery capacity loss increases with increasing current rate, SOC and number of charges transfer during charge and discharge. Thus the effect of each parameter in combination can be used to predict the battery degradation and useful life.

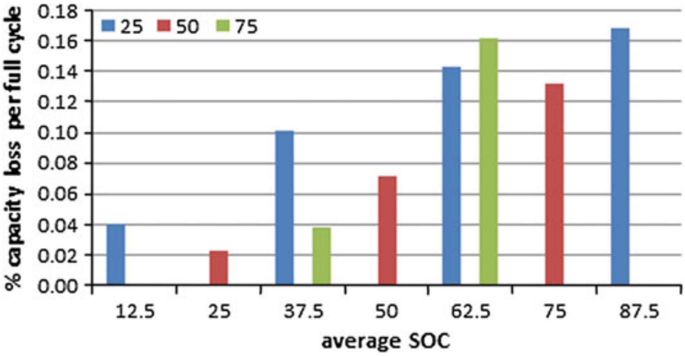


Fig. 16 Capacity loss for cells cycled at varying ΔSOC

6.4 The Effects of V2G and V2H Operation on Battery Lifetime

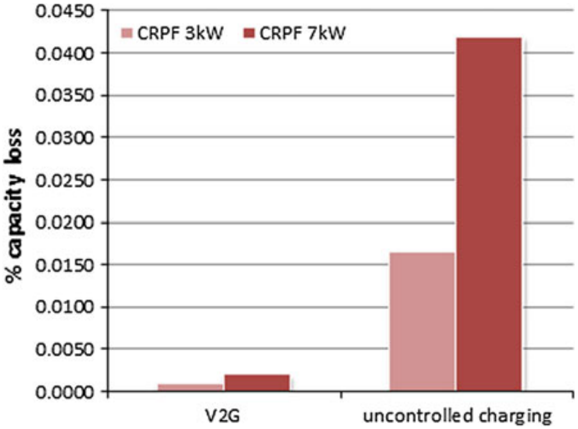
To evaluate the effects of cycling on the EV battery life time, experiments were conducted and results obtained in order to make a comparison between the effects of V2G and V2H (which would in themselves reduce battery life through the increased charge transferred) with the effects of uncontrolled charging (when the adverse effects of a higher average SOC would reduce battery life). The temperature and charge rate were kept constant.

Samples of Lithium Iron Phosphate ($LiFePO_4$) cells, which use similar chemistry to typical EVs currently on the market, were cycled at a rate equivalent to 3 and 7 kW, to represent the alternative rates for EV home charging. For each case, two cells were cycled with uncontrolled charging; where charging starts as soon as the EV would return home and is plugged in at the end of the day's work at 6.00 pm. Two other cells were controlled to charge later at night (to represent G2V) and two other cells were allowed to discharge to 10 % SOC during the evening (V2G) and then charged up at night.

Three possible scenarios were then analysed. The first in which the EV was charged (starting at 6.00 pm) to 70 % SOC and kept in this condition until it was required for driving at 8.00 am (uncontrolled charging). The second scenario is controlled (smart) charging, where the EV battery is kept at 30 % SOC until a later time when the charger brings the SOC to 70 % by 8.00 am (G2V). The other pathway involved carrying out V2G by discharging the EV battery down to 10 % SOC and then keeping the battery at this low SOC until the latest time during which the charger could bring the EV battery to 70 % SOC by 8.00 am. In all cases, the initial SOC at plug in is assumed to be 30 %.

The results obtained from these tests are shown in Fig. 17 (the results for G2V are not shown, as the capacity loss was negligible). As can be seen, under these conditions, the capacity loss is lower when using G2V and V2G, which is due to the

Fig. 17 Li ion cells subjected to different charging patterns



lower average SOC and hence less electric stress between the electrodes of the battery, as explained earlier. Further tests and analysis revealed that the effect on capacity loss for each pathway varies with the initial SOC upon connection of the EV. As the initial SOC at plug in increases, the battery lifetime seems to increase under conditions of uncontrolled charging. This is because of the effects of the extra degradation caused by the increased average SOC are offset to some degree by the reduced charge transfer experienced compared to that under the V2G regime. For the latter, as the initial SOC at plug in is increased, the percentage loss of capacity per cycle increases (leading to a shorter lifetime) due to increased degradation caused by the increase in charge transfer.

7 Conclusions

The work described in this paper shows that the most important feature of the EV, from the point of view of grid connection, is that the actual charging time and rate may be arranged to fit in with other demands upon the local distribution network. Controlled charging can help minimise the possibility of transformer overload and feeder voltage drop. In addition, the storage capacity of the EV battery may be used to intelligently reinforce the grid, by controlling the charging time and current rate to balance demand/supply and support the grid (G2V). Further, the battery may be used to supply power at times of scarcity, and absorbing it when in surplus, bringing supply and demand for power into equilibrium (V2G). However, concerns have been raised about the effects V2G may have on battery lifetime. Available literature shows that battery cycling reduces battery life due to increased charge transfer, as does faster charging.

The results of the research presented in this paper show that smart charging prolongs battery life as compared to what might be termed the ‘standard’ approach of uncontrolled charging at home. A combination of delayed controlled charging (G2V) and V2G results in comparable battery life, with the opportunity to earn revenue from carrying out grid support. This is an added value to the benefits smart charging brings to the grid by permitting a higher level of EV adoption and increased amounts of renewable energy penetration without the need for re-engineering the existing power grid.

The cost of the battery is the greatest single replacement cost associated with ownership of an EV. For example, in June 2014, the replacement cost of a Nissan Leaf battery is given at about $6500+tax (Ottaway 2014), compared to purchase prices for a new car ranging from $29,000–$35,000 (Car Ranking and Advice website 2014). Receiving payment from the grid operator for using the EV battery to provide balancing services to the grid (G2V or V2G) could be an attractive option for an EV owner concerned about the high capital outlay.

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