Smart EV Charging Schedules: Supporting the Grid and Protecting Battery Life

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Abstract: Uncontrolled charging of electric vehicles (EVs) is expected to cause problems for power distribution networks as existing vehicles are continually being replaced by electric. Therefore, smart charging algorithms that prevent such problems will become necessary as uptake of EVs increases and they become more popular. Smart EV charging is not only useful to provide the necessary charge (energy) required by the user but may also be used to support the grid and protect battery health, which is investigated in this paper. Factors that affect battery life are quantified and their impact on battery degradation and ability (of EV) to support the grid are analysed. Charging regimes that can meet the driver needs, provide grid support and protect the state of health of the battery are proposed in this paper. The analysis presented demonstrates that smart charging that involves charging before departure, less frequent charging and limited vehicle-to-grid can prolong battery life compared with providing the same EV charge in an uncontrolled way. Thus, grid power is supported and battery life protected by the proposed smart charging regimes.

1. Introduction

Domestic transport emissions account for around a quarter of UK greenhouse gas emissions [1]. Electric vehicles (EVs) are promoted as they not only emit less carbon dioxide than conventionally fuelled cars, but also do not emit gases within towns and cities where pollution and deaths due to poor air quality are a problem. However, charging of EVs increases the demand on the power distribution network. Effectively, an EV is a large mobile load and there are significant challenges in providing sufficient charging capacity for mass deployment of EVs. Moreover, the battery capacity of an EV is expected to increase as manufacturers try to increase the EV range. Studies have shown that if only 10% of the cars on the road are electric, the network may have difficulty in avoiding system overload and ensuring power quality at the low voltage (LV) level, as EV charging is expected to be at times of peak demand [2, 3].

The UK national grid is meeting its low carbon targets by closing coal-fired power stations and increasing renewable generation, especially wind. For instance, 19 GW of existing generating capacity is expected to close by 2020 [4] and wind installed capacity could reach 32 GW (over 25% of UK capacity) with up to 5 million domestic PV installations generating 10-15 GW of power on sunny days [5]. Further, the generation capacity margin may fall to just 2% by 2020 [6]. In fact, problems of capacity may arise before 2020. The national regulatory authority Ofgem (Office of Gas and Electricity Markets), treat loss of load expectation (LOLE); as the key metric when assessing security of electricity supply. This is the average number of hours in a year when it is expected that there will be insufficient supply available in the market, and National Grid may need to take measures going beyond normal market operations to balance the system. In their July 2015 report [7], Ofgem considers that there is a wider range of uncertainty over the outlook for winter 2016/17; the LOLE could range between 2 and 15 hours (compared with 0-3 hours per year projected in their Capacity Assessment 2014). Given that the system is already stretched, extra demand from EVs will most certainly put extreme demand on the electricity infrastructure [8].

The increase in wind power from installations given planning permission in the UK represents an opportunity for renewables to replace coal fired power as baseload. This is only possible if grid storage is used to optimise the wind power by storing the wind power at times of low demand and releasing it when demand is high. There are many types of storage possible, and battery energy storage systems (BESS) are a significant contribution [9]. Identifying the expected lifetime of a BESS is a vital part of the business case and the method described here can be adapted for BESS.

The integration of EV charging with renewable storage can be done at the single home, business or wind farm level, and with or without stationary storage. These systems are becoming ubiquitous as part of the electricity network. The conclusions raised here may be used to develop a control algorithm that can optimise renewables whilst protecting battery life, or simply predict battery life from historic cycling schedules

EVs present both a challenge to the grid and also an opportunity to utilise the battery as a controlled load or storage to support the grid. Modern PWM based battery chargers can operate at unity power factor; unlike traditional rectifier based designs, which absorb reactive power and introduce serious harmonic current distortion. At unity power factor a PWM based charger will act as a constant power load (e.g. 3 kW or 7 kW) for the bulk of the charging time. In fact a PWM converter can operate at either a leading or lagging power factor as well as at unity, allowing for reactive power compensation to be provided for the grid. In addition, depending upon the switching frequency employed, the level of harmonic distortion introduced by a sinusoidal PWM converter can be reduced to any desired level. Power quality issues requiring grid support through voltage regulation and frequency regulation can be supported by battery storage , either from EV or BESS [10]. Controlling the time of charge, as is already available with some charge points [11] may relieve the burden on the grid. A more radical solution is to use the EV battery as a storage system; i.e. charge the EV when demand is low and discharge back to the grid (V2G) at times of high demand [12]. This can involve complex control to determine when the EV batteries need to discharge, or it can be a simple timer, predicting the need to discharge during the evening peak. In this way, the EV can help in matching demand to supply, support renewable energy and provide ancillary services for network support, such as voltage and frequency control on the balancing services market [13]. There are four electricity markets relevant to V2G [14]. The first is baseload (Kempton asserts that if just one quarter of the US light vehicle fleet were converted to electric, the load would be comparable to the entire electrical utility system). The second is peak power (avoiding charging during peak power and using V2G to ‘shave’ that peak). Thirdly is spinning reserves (up to 10% of a conventional power station output may be on standby to allow it to ramp up to provide a fast response – V2G can provide this more efficiently, and more quickly). Lastly is regulation (voltage and frequency control, required up to 400 times a day, for just a few minutes to balance the grid). Due to their fast response times and low capital costs, EVs are considered a better match for spinning reserve and regulation.

Another way to support the grid is to use the EV battery as an uninterruptable power supply or ‘second life’ batteries to provide Grid storage when the EV batteries are no longer useful for driving [10]. In all these applications (using the battery to support the grid), consideration must be given to the effect of such operation on battery state of health (life). Based on international standards, (e.g. SAE J240 Life test for automotive storage batteries), an EV battery is considered to be at the end of its useful life when its capacity drops to 80% of that when it was new; if battery life is reduced due to the charging schedules required to support the grid, then the EV battery must be replaced more often, at great expense, which may be financially unviable.

To investigate the effect of grid support on battery life it has been necessary to model the degradation effect of the battery cycling schedules required for grid support and compare them to the corresponding uncontrolled charging schedules. Using a battery degradation model [15], it is possible to compare the degradation of a battery providing grid support with one that doesn’t (conventional use). The methodology adopted in this investigation is:

- Identify the factors that impact battery life from published results for lithium ion batteries.
- Run laboratory tests to measure the correlation between each impact factor and battery life.
- Identify EV charging schedules used at present from driver behaviour studies.
- Use a grid-modelling tool [16] to identify the charging schedules that would be beneficial to the grid.
- Map these schedules onto the battery degradation model using the impact factors as variables.
- Compare the results of the battery degradation for uncontrolled charging and smart charging that provide support to the grid (G2V and V2G).

In this paper, section 2 gives a summary of the potential impact of uncontrolled charging of EVs on the grid. Section 3 summarizes the methods available for EVs to support the grid (G2V and V2G) and introduces their potential impacts. Section 4 presents the factors that affect battery life and quantifies the impact of different conditions on battery degradation. Section 5 gives a comparison of three charge control regimes and section 6 explains how battery state of health (SOH) can be optimised using smart controlled charging. Conclusions are given in Section 7.

2. Uncontrolled Charging on and its impact on the Grid

Uncontrolled charging refers to charging determined by the EV driver, which may occur at any time. To show the effect of different types of charging on the low voltage (LV) network, the authors have developed a network modelling tool [16], which forms the basis of the figures in this section and section 3.

It calculates the effect of different loads on a LV feeder, using a typical winter and summer daily load profile for domestic customers in the UK (Fig. 1). The network model is described in more detail in the reference and briefly comprises one three phase 400 V feeder from the 11/0.4 kV transformer with typical fault infeeds and ratings. The feeder has 8 nodes and the voltage profiles are taken from the node indicated by the description on each figure; the 3-phase current is constant across the feeder. Standard power flow analysis has been used in the model to determine the power flow for each scenario. EV home charges are rated at 3 kW or 7 kW with a corresponding full charge duration in the order of 8 to 3 hours, respectively. At this low rate, the charging current is effectively constant, and care has been taken to use large changes in SOC so the results are not affected by EVs prematurely finishing charging.

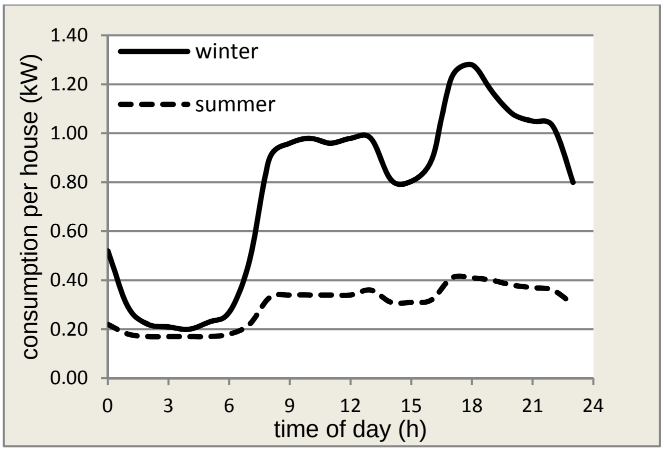
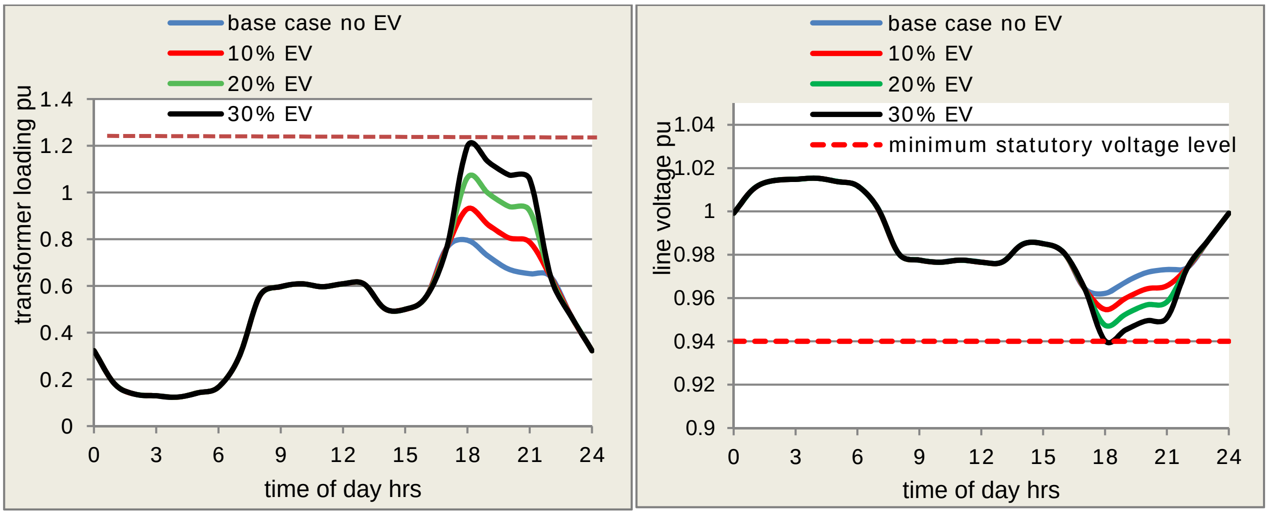


Fig. 1. *The load profile is based on After Diversity Maximum Demand (ADMD) referenced to a nominal 100 consumers and measured at the LV substation [17].*

A 24 h domestic profile with no EVs is modelled and then overlaid with the results when a stepped percentage of households having an EV charger are added. The EV charger is modelled as a constant power load as the data used is half hourly based and any changes in power drawn by the charger are considered negligible over this time scale. Uncontrolled charging can be at any time, but the effect of charging at the end of the working day (6 pm) is demonstrated which corresponds to the domestic evening peak in demand. The effect is shown in Fig. 2a where the load exceeds the rated transformer power when 20% or more of the houses have EVs. The load is shown to increase by ~14% with every 10% increase in EVs.

Uncontrolled charging may also affect the voltage profile, as shown in Fig. 2b. As can be seen, 30% EVs bring the network voltage below the statutory minimum at 18:00 h. Other results obtained by the authors [16] show that if 7 kW chargers are used, then 10% EVs will cause this effect.



a *b*

Fig. 2. *The effect of increasing EVs on LV network [16]*
a Transformer loading in p.u.
b The p.u. voltage showing statutory minimum as the dotted line

3. Using EVs to support the Grid

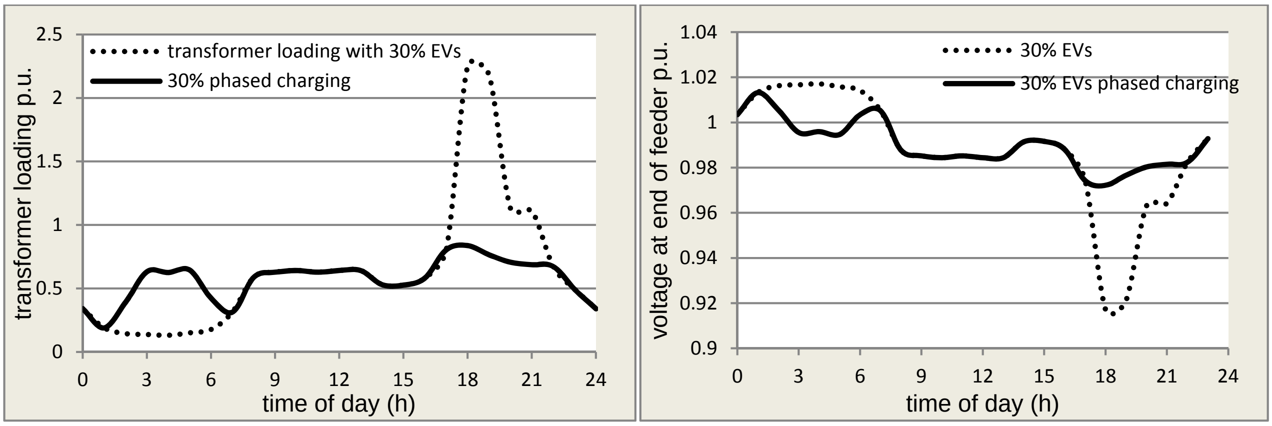
EVs can offer grid support by:

1. Charging only when the grid has sufficient capacity
2. Discharging the EV battery to the grid at times of high demand (V2G)

Both controlled charging and V2G can have the effect of levelling of power demand over a 24 hour period, if the EV is kept plugged in. Surveys have shown that an EV is parked for 95% of the time [18], so there is ample opportunity for it to be plugged in and available for grid support. This pattern allows greater penetration of EVs before assets are overloaded, better use of renewable energy resources (as surplus generation may be stored) and delaying asset upgrade which would have been due to increasing peak demand.

3.1. Effect of controlled charging on the LV network

Fig. 3 shows the effect of 30% of households charging EVs at 7 kW on the LV network voltage and transformer rating Fig. 3a shows that controlled charging can actually level the loading of the transformer by utilising extra capacity at night, thus delaying the need for network upgrade. Fig. 3b shows the same effect on the voltage profile at the far end of the LV feeder. The minimum voltage is ~0.97 p.u. with controlled charging rather than an impermissible ~0.915 p.u. without control. Smart charging, e.g. by using incentives for customers to modify their behaviour, will help prevent overloads, keep voltage levels within statutory limits and improve load factor (match network capacity).



a *b*

Fig. 3. *30% EVs added to ADMD profile with and without controlled charging[16]*
a Transformer loading
b Voltage at the end of the feeder

3.2. Effect of V2G on the LV network

If EV chargers are designed to allow bidirectional power flow, even more support can be provided to the network as shown in Fig 4. Fig. 4a gives an indication of the effect on the load profile for the transformer loading given in Fig. 2 (30% of houses having EVs with 3 kW chargers) when V2G is used. As can be seen from this likely scenario, V2G will reduce the peak demand in the evening (peak shaving) and allow better utilization of the available assets [19].

The promotion of domestic renewable energy and PV generation is predicted to create a network load profile in the summer like that shown in Fig. 4b, for the UK based on the targets for 2050 (DECC 2010). This figure shows the voltage profile without and with V2G. As can be seen, without V2G, the voltage could rise by up to 15% on a sunny day at the end of a LV feeder. Without V2G, this generation would be wasted as the grid cannot allow such a voltage rise. These results demonstrate the ability of V2G to absorb the surplus PV generation during the day and keep the voltage within statutory limits.

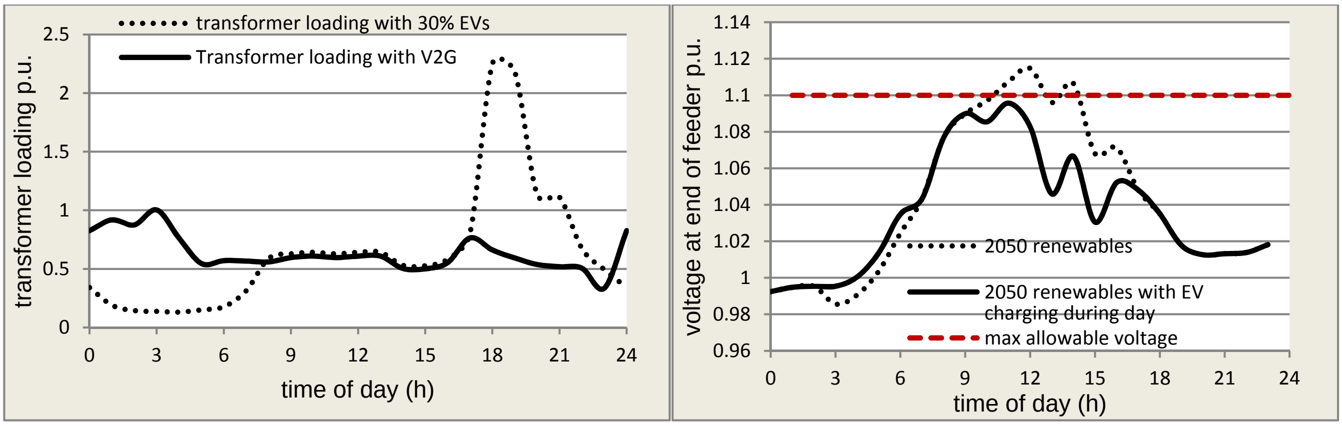


Fig. 4. *Effect of V2G on LV network [16]*
a.11kV/400V transformer loading with and without V2G
b. Effect of V2G on voltage profile when PV is present

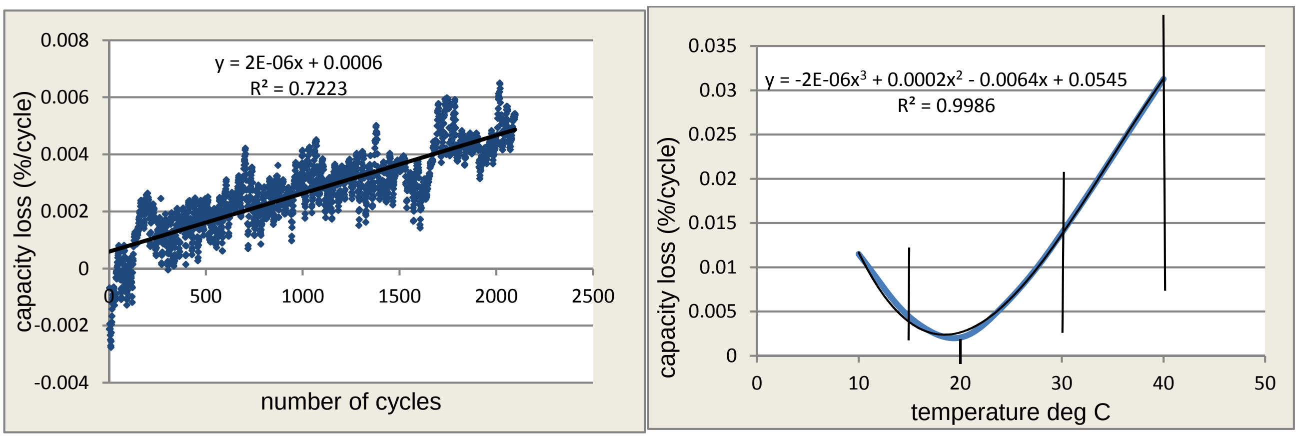
3.3. Effect of grid support on battery life

The results presented in the previous sections demonstrate the ability of controlled charging to allow seamless increased penetration of EV charging without having a negative impact on the grid by only charging when there is sufficient grid capacity. In fact, controlled charging may also be used to support the grid by increasing the charging rate when there is a surplus of generation, e.g. from renewable energy. In this way, EVs can play an important role in future power networks (smart grids) by providing flexible demand side management support. V2G adds another dimension by allowing the stored energy in the battery to be used to support the grid in periods when demand is higher than available generation, e.g. during evening peaks (peak shaving). This will avoid overload of existing assets (e.g. distribution feeders and transformers) and facilitate operation within voltage statutory limits. V2G requires the use of converters (chargers) which allows bidirectional power flow, but this is easily achieved in practice and the extra cost incurred may be justified by the benefits provided from grid support. However, one important issue that need to be addressed before such grid support becomes commercially and practically viable is their impact on the battery state of health (i.e. life), given that the battery is the most expensive part of the EV [20]. 2012 costs for a pure EV of ~$800/kWh at pack level translates into a pack cost of $21,000 for a 2012 medium sized BEV with a range of 150 km. In 2030, under a baseline scenario, this is predicted to drop to $6,400 for a BEV with a range of 250 km [21]. As will be shown in the following section (4), increased charge transfer and average state of charge created by smart grid operation can affect battery life. This aspect has not been adequately addressed in the literature, and therefore is analysed in the following sections together with appropriate measures to reduce these effects.

4. Factors affecting battery degradation

Published results in the literature for lithium ion batteries have identified four impact factors involved in the degradation of lithium ion cells [22-25]. Further tests conducted by the authors allowed each factor to be investigated in turn, whilst controlling the others. The results were found by measuring the capacity of the cell under standard conditions before and after each cycle test. The cycling was performed on an Arbin battery tester [26], with temperature controlled by using an environmental chamber. The equipment is shown in Fig 5. The Arbin battery charger is PC controlled and includes 16 channel, each has a voltage range 0-20 V and current range 0.001-10 A. Each cell was cycled at least 50 times with the controlled schedule between capacity tests. Each test was repeated on several cells for reliability, and the percentage capacity loss per equivalent full cycle averaged for each factor. These results obtained from testing similar cells have led to verifiable results on the impact of four factors on battery health as shown in Fig. 6.

Figure 5: *Lab arrangement: showing Arbin battery charger (left) and environment chamber (right)*



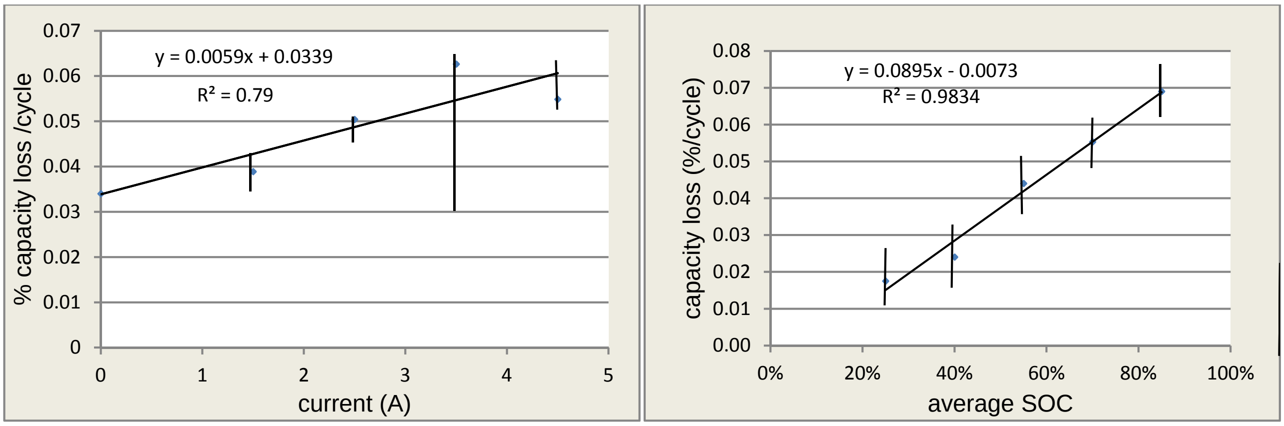


Fig. 6. *Experimental results of lab tests showing how each factor affects degradation*
a. Capacity whilst cycling over 2000 cycles showing linear increase (uncontrolled temperature)
b. Capacity loss whilst cycling at temperatures ranging from 10°C to 40°C
c. Capacity loss varies linearly with charge rate
d. Capacity loss as a function of average SOC, based on experimental results

4.1. Charge throughput

The more charge transferred during cycling, the greater the degradation [23]. This requires the cycling to take into account the depth of discharge or the change in state of charge (SOC) during each cycle to normalize for equivalent full charge cycles. Testing verified that the capacity loss is linear with the amount of charge throughput after the first few cycles. The loss rises quite steeply initially and then appears to level off. Extensive tests have shown that for the cells tested, the measured average capacity loss was $C_T = 4.525 \times e^{0.041 \times T}$ where T is the temperature of the cell. This baseline value is used to calculate the overall percentage degradation when V2G schedules are being compared.

4.2. Temperature

Test results show that the best battery temperature for charging and driving is around 20°C. This is verified in literature [24, 27]. Temperatures above this value have been found to increase battery degradation due to unwanted side reactions damaging the cell [28], which occur faster at higher temperatures. Low temperatures cause a higher internal cell resistance, which reduces performance [29]. Fig. 6b shows lab results verifying that capacity loss is at a minimum when cycling occurs around 20°C.

4.3. Charge rate and driving style

Experimental tests showed that increasing charge rate accelerates degradation, as shown in Fig. 6c. Tests conducted by the authors and available in the literature both indicates that the factor is linear at rates under 1C [25] so a linear trendline is assumed in the following analysis. Domestic chargers, which are those under consideration here, provide power at either 3 kW or 7 kW (i.e. under 1C for passenger EVs).

Faster discharge due to high driving speeds and/or hard acceleration has similar effects on degradation due to an increased battery discharge rate. However, the battery discharge rate does not affect charging so will not be analysed here.

4.4. Average state of charge

Average SOC can be calculated by integrating the SOC with respect to time over the 24 hour profile. In cases like the present study, where the SOC is known only at hourly intervals, a direct average SOC can be found by summing the 24 SOC hourly values and then dividing the result by 24. From this one may see that if an EV battery is intentionally discharged and then kept at a low SOC for a number of hours before recharging, the average SOC measured over the 24 hour period may be reduced compared to the case where the battery is left throughout the period at a high SOC. Tests show that the lower the average SOC, the lower the degradation, this is also verified by literature [22]. Lowering average SOC can be achieved in several ways; generally for calendar life, this is fixed (stored SOC), but average SOC changes with cycling schedule. If a certain amount of charge is to be applied to the battery within a 24 hour period, then the time and duration of charging can be altered to change the average SOC. For example, leaving the ev battery at a low SOC with subsequent delayed recharging can yield a lower average SOC over a 24 hour period than early charging with the battery then remaining at a high SOC for some hours. Fig. 7a shows how the SOC can be varied by controlling charging over one day. It shows the difference between the scenarios when the EV is charged immediately after arrival at charge point or immediately before driving. The example given is for a cell cycled with a charge rate of 3 kW, 10 hours disconnected time and 14 hours connected and available for charging, with a maximum SOC of 75% and a minimum of 25%. The average SOC can be calculated from these SOC and time values and the average SOC for early and late charging is 57% and 43%, respectively.

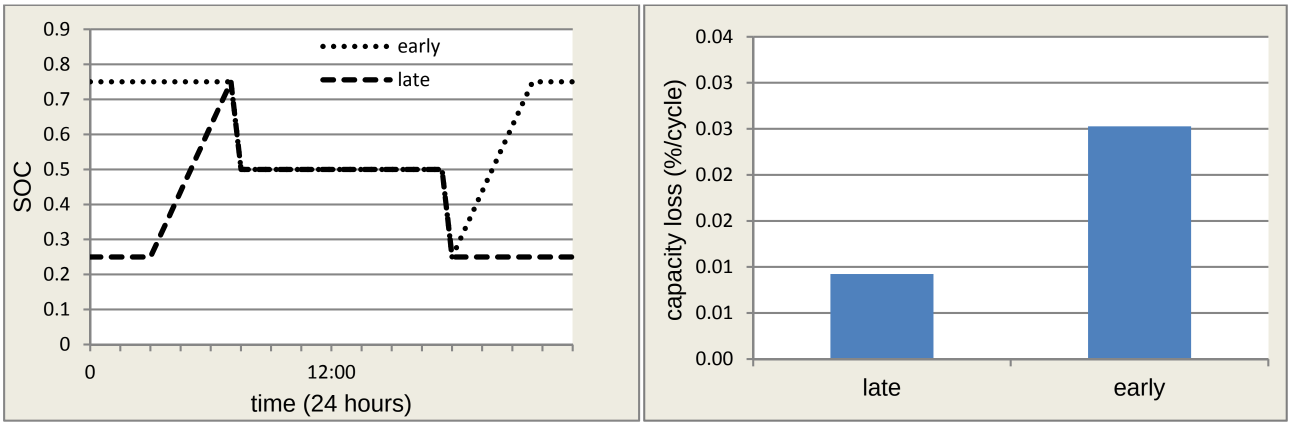


Fig. 7. *early and late schedules to demonstrate the effect of average SOC whilst cycling on battery degradation*

a. Profile of the SOC of an EV battery over one day, with early and late charging
b. Capacity loss in cells cycled for 5 months with early and late schedules

Real time tests over five months for cells cycled daily, keeping conditions the same and varying the start time for charging show that indeed the capacity loss is lower for late charging, as shown in Fig. 7b.

To quantify the correlation between SOC and capacity loss, tests were set up which varied the time spent at full charge, whilst keeping all other factors the same. The results are shown in Fig. 6d, which demonstrate the linear variation of average SOC with percentage capacity loss, with a high degree of agreement. These results allow the correlation between capacity loss and average SOC to be approximated using the equation of the trend line.

5. A comparison of three smart charge control regimes

Smart charging allows the time that charging starts to change in response to signals from the grid. Controlled charging can support the network at times of high demand by delaying charging or even performing V2G power flow (discharging). The control signal could be generated centrally (e.g. dynamic pricing) or locally (e.g. local measurement of network voltage) in order to decide when power flow for charging can be allowed. The driver is required to specify the time by which the charging must be complete. Smart charging may also take into account ambient temperature, driving style, etc. but these factors are not considered in this paper.

A comparison of an uncontrolled charging scenario with one under smart control is presented in this section. The values used are those of realistic charging schedules to demonstrate the effect with real application. The results are from tests of lithium ion cells cycled with the schedules described in section 4. The controlled schedules have been compared on the network model to ensure they do support the grid [16]. The battery current is assumed to be the same for charging and V2G. The most significant differences are the three discussed in the following.

5.1. Charging before departure (delayed charging)

Cells subjected to the same conditions were kept together for 5 months and cycled with early and late schedules, illustrated in Fig.7a, were tested to measure the percentage capacity loss per cycle. The cells were cycled daily at a current corresponding to the equivalent C rate for 3 kW charging to give the results in Fig. 7b. The only difference was the time of charging – immediately on connection in the evening at 6pm (early), or starting so that full charge is achieved just before disconnection in the morning at 8am (late). The results show that the decrease in SOC resulting from delayed charging leads to reduced capacity loss and thus less degradation, which is verified by the literature on calendar life [30].

5.2. Charging when spare grid capacity is available

Delayed charging can be achieved with a simple timer, but a more sophisticated central or local control of the charge could be adopted.

Typical values of average SOC from early and late charging derived from Fig. 7a are shown in Table 1. Also included is a row showing the average SOC when the EV charging is allowed when there is spare capacity on the grid. In this case, some charging occurs during the day when domestic demand dips. The average SOC for cells cycled using this regime, based on a typical ADMD profile results in an average SOC of 58%. Using equation (1) that is found from the trend line of the test results in Fig. 6d, the percentage capacity loss per cycle (dC/dc) varies with average SOC (S) as shown in Table 1.

$$dC/dc = 0.0895S - 0.0073 \quad (1)$$

Table 1 Percentage capacity loss derived from equation (1), based on varying SOC values

Schedule	Average SOC (%) S	Capacity loss (% loss/cycle) dC/dc
Charging when arriving home	57	0.044
Charging when spare grid capacity is available	44	0.032
Charging before departure (delayed charging)	43	0.031

5.3. Charging with V2G providing storage during the evening peak demand

The evening peak will be increased with uncontrolled charging, which would allow charging on the ‘early’ schedule. Late charging leaves this peak unchanged, but V2G reduces the peak by allowing power to flow from the battery to the grid at this time. The three possible schedules are shown in Fig. 8a. V2G allows the minimum SOC to reduce to 10% in the evening, followed by charging after midnight. This reduces the average SOC (which increases battery life), whilst increasing charge throughput (which reduces it). The result of tests where cells were cycled using these schedules is shown in Fig 8b showing the predicted life for batteries performing V2G is better than when early charging is used, but worse than for late.

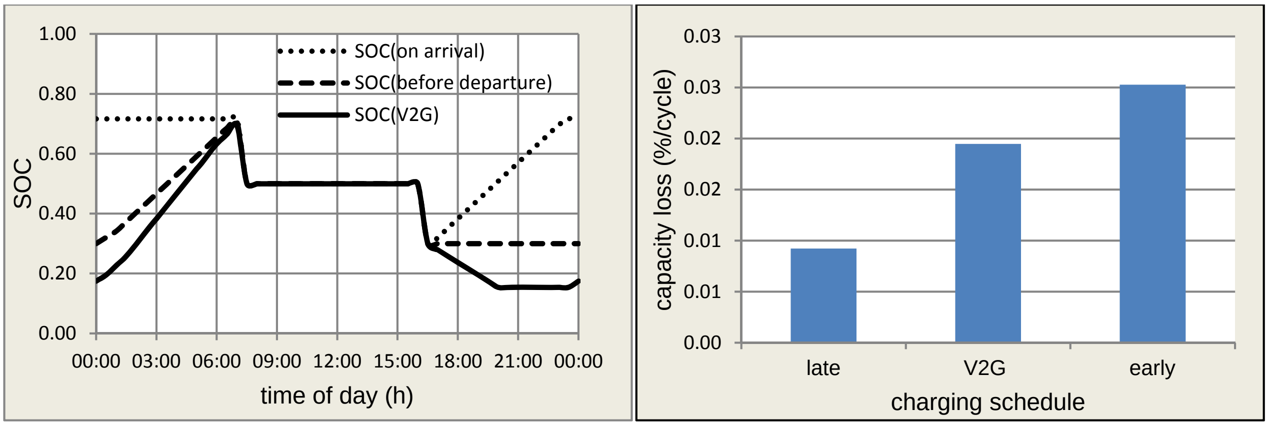


Fig. 8.Three smart control regimes

a. Cycling pattern of three schedules

b. Variation of battery life with charging schedule

6. Smart charging regimes and corresponding modelled battery capacity loss

Typical EV charging behaviours can be analysed and a prediction calculated as to the likely battery life for batteries similar to those tested and under the same conditions. A calculation can be made of the percentage capacity loss per cycle using the percentage capacity loss per unit charge transferred and that lost per cycle for different values of average SOC. This gives an indication of the battery SOH, which is a ratio of the fully charged capacity of a used and a new battery. Battery degradation is found to be most sensitive to charging regime [31]. With careful control V2G can act as energy storage for the Grid [32], or it can act to level domestic load using vehicle to home(V2H) scheduling [33, 34]

6.1. Charging before departure

Delaying charging (i.e. charging before departure) lowers average SOC. For example, an EV that charges at a rate of 3 kW to 100% from a discharged level of 10% takes 8 hours. The EV may be plugged in at home for 14 hours. Thus the EV could remain at 10% SOC for 6 hours before charging, or charge to 100% and remain at this level for 6 hours until required. Late charging increases battery life. A decrease in 10% average SOC results in a predicted increase in battery life of 8.95%, assuming all other conditions remain unchanged.

6.2. Less frequent charging

Surveys [18] suggest that the average daily car journey is less than 40 miles and that the EV is charged every day giving an average charge of 86%. This means that the average driver needs only to charge every other day, or less frequently. Charging on alternate days will reduce the average SOC to 72% for the same conditions and thus increase battery life by 12.5%, for the same number of miles driven.

6.3. Charging with optimum V2G

V2G involves increasing charge throughput as well as decreasing average SOC. Greater charge throughput shortens battery life, but lowering the average SOC lengthens it. In addition, the capacity available for V2G depends on the SOC at connection, which is referred to as the minimum SOC. The capacity loss from V2G is always larger than that due to late charging alone, but there is a 'sweet spot' where early charging loss decreases with minimum SOC (and thus average SOC) and loss from V2G increases due to greater charge transfer. Comparison of the two factors using the modelling developed from tests is shown in Fig. 9. A comparison of the percentage capacity loss for V2G compared with uncontrolled charging shows that V2G causes less degradation than charging alone if the SOC after driving (min SOC) is less than 40%.

Financial incentives for V2G might encourage the EV owner to use the battery for this purpose, but the amount of V2G needs to be limited if the battery life is not to be noticeably affected.

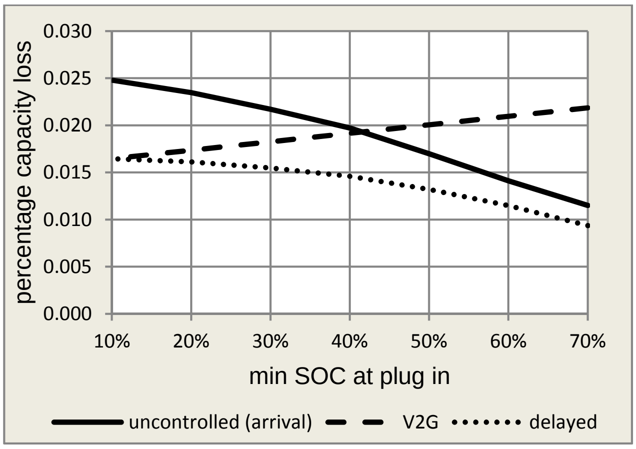


Fig.9. *Percentage capacity loss per cycle for V2G as it varies with SOC at connection*

6.4. Optimising battery health

The knowledge obtained from the tests can be used to inform the use of controlled charging. There are two principles to be considered when using smart charging to prolong battery life – keep average SOC to a minimum and keep charge throughput to a minimum. These principles can be easily followed by the knowledgeable EV owner and also form the basis of a control strategy for a smart charger.

- Charge just before using (delayed or late charging).
- Allow SOC to fall and only charge when there is insufficient capacity for next use.

- Use V2G only if the SOC of the battery is less than 40%.

7. Conclusions

The adverse effects of uncontrolled charging of EVs on the LV network has been demonstrated, where even 10% of domestic vehicles being electric may cause issues of system overload and/or poor power quality. Smart control of EV charging to avoid and even ameliorate these issues has been demonstrated. This can be achieved by delayed (controlled) charging (until after the evening peak when there is a spare grid capacity), charging from domestic renewables and allowing V2G to 'shave the peak' in times of high demand.

Delaying charging until required may not be possible in all instances. Of course a minimum charge must be kept in the vehicle for emergencies and the driver must be able to override the charging schedule to allow for unforeseen circumstances. But if the typical pattern of the EV plugged in at 18:00 hours and not required until 07:00 the next morning is used, it doesn't matter when during that 13 hour timespan that the charging occurs.

The effect of controlled charging on the EV battery life is analysed using modelling based on lab test results performed over two years. The model allows the capacity loss to be calculated and battery life to be predicted for different operating conditions, including uncontrolled and controlled charging. The two main factors that affect battery life and are involved in the charge control are identified as the average SOC and the amount of charge transfer. The results obtained show that lowering the average SOC and charge transfer have a significant effect on battery health and provide longer battery life. If all other conditions remain the same, a 10% decrease in average SOC results in a 9% improvement in battery life. Controlled charging, if not appropriately implemented, may lead to increased battery degradation (reduced life).

The results presented also demonstrate that EV batteries can provide grid support without shortening battery life. Battery degradation will happen with time and with cycling, but these results demonstrate that grid support, even V2G, need not shorten battery life beyond that experienced with uncontrolled charging. Thus the case is strengthened for a 'smart charger' that can meet the driver requirements while providing support to the grid and protecting battery life.

Acknowledgments

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