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The Simulation of Vehicle-to-Home Systems – Using Electric Vehicle Battery Storage to Smooth Domestic Electricity Demand

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Abstract: *We present a study into the feasibility of vehicle-to-home technology. A model of a single house and single electric vehicle operating vehicle-to-home was developed in MatLab Simulink ®. The model takes an input household appliance demand profile and vehicle use data and controls the power flow between the electric grid, the appliances and the vehicle. Running the appliances off the vehicle battery in an attempt to reduce the household peak power demand is the aim in vehicle-to-home. Three commutes of distance 2 miles, 30 miles and 80 miles were simulated to investigate the effect of vehicle use on vehicle-to-home. The two shorter distances allowed vehicle-to-home to work with no problems. The 80 miles journey was at the limit of the electric vehicle range and therefore caused a small problem when operating vehicle-to-home. All three cases reduced the peak power demand and increased the load factor. These modifications to the household demand profile would potentially be environmentally and financially beneficial to the electrical generation sector.*

Keywords: Vehicle-to-Home, vehicle-to-grid, electric vehicle, electrical energy storage, distributed generation.

1. Introduction

With consumer and governmental pressure to reduce transport CO_2 emissions, and with dwindling world oil supplies, automotive manufacturers are spending vast sums of money on developing alternatively-fuelled vehicles.

The automotive industry is committed to electric vehicle (EV) development as one design solution to the pressure. The large scale plug-in field test by Daimler AG and RWE AG in Berlin is one example of this commitment [1]. Customer interest is also rising – hybrid vehicle sales in USA are up 33% from 2006 to 2007 [2] and a 2008 survey by the insurance company, eSure, revealed that 71% of British consumers would consider driving an electric car to help with environmental issues. The electric car has a bright future.

The introduction of large numbers of electric vehicles brings with it the problem of producing and distributing the electricity that they will demand. Charging strategies and schedules must take electricity generation into account; increasing electricity demand at the wrong times will increase the economic and environmental costs of electricity generation. Intelligent charging can spread this load increase and make it easier to manage. Existing bi-directional charging technology allows intelligent charging to be taken to a new level; the vehicle-to-home (V2H) and vehicle-to-grid (V2G) concepts offer an opportunity to turn the electric vehicle network into a resource. V2G requires the EV to not only charge from the electric grid but to supply power to the grid when required. The introduction of an electrical energy storage network to the electric grid, which currently has little or no working energy storage, could improve the efficiency of electric generation, be used to manage the introduction of variable output generating technologies and improve the reliability of electricity transmission. This will allow the renewable, but unpredictable, sources of power, such as wind and wave power, to be better utilised.

Factors associated with V2G include the number of available vehicles, state of charge (SOC) of the battery in a given vehicle, length of time a vehicle is available for, how long it is needed for and for what purpose within the wide ranging V2G tagline. These variables are determined by driver use and demand from the V2G operator. The driver needs the vehicle to be available and have sufficient charge for any journey they may undertake and the grid operator wants sufficient vehicles connected to the grid to utilise effectively; a happy medium must be achieved. Kempton claims that vehicles are parked, and therefore available for V2G, 96% of the time; this is yet to be verified in practice [3].

This challenge raises the question of how many vehicles are required to achieve statistical certainty that enough vehicles are available for V2G without jeopardising driver satisfaction. Deducing a relationship between the factors described is a major challenge.

Control of the vehicle and electrical networks provides the next major barrier. Both systems will need to be organized to work in harmony to the demands of all parties. Technical barriers will also need to be overcome. While bi-directional power units are available, they are yet to be the standard on plug-in vehicles. The effect of the additional cycling a battery will undergo due to V2G is also not yet fully understood.

This paper considers the simplest vehicle-to-grid case: vehicle-to-home. A discussion of the differences between V2G and V2H follows. The paper then describes the V2H model that has been developed. Finally, vehicle-to-home is tested with three different vehicle use levels.

2. Comparing Vehicle-to-grid with Vehicle-to-home

Vehicle-to-home avoids the infrastructure and tariff problems associated with vehicle-to-grid, this has therefore been studied as a first case. V2H would be used to level the house electricity demand profile; sharp power increases associated with running high power appliances for short periods would be controlled. The resulting smoother demand from the grid would give electric suppliers a more manageable load. With energy storage in place the peak demands could be shifted such that electric load remains more constant throughout the day. This would allow more efficient and cost effective electricity generation to be used. Vehicle-to-home would improve the effectiveness of renewable energy sources; excess generation can be stored and used when generation is low.

Vehicle-to-grid (V2G) is parallel i.e. within a grid any car can be used to power any house by feeding its power back to the grid. In contrast, vehicle-to-home is more limited; a single vehicle is used to supply a single house. The trade-off is simplicity versus flexibility; more vehicles working together offer flexible storage but will be more difficult to control.

A further discussion point is locality. V2G and V2H are a form of distributed generation; the electrical load is geographically close to the electrical source. Transmission is therefore minimal compared to centralised generation so costs of transmission infrastructure and transmission losses are reduced. V2H represents the simplest case with regards to infrastructure and transmission. A single house operating V2H will have simple infrastructure requirements and negligible transmission losses.

V2G can vary in infrastructure complexity and transmission distance depending on the number of vehicles involved and the geographical area serviced. A group of vehicles acting en masse as an electrical source is a more technically challenging situation than V2H and opens up the possibility of larger transmission distances.

It is important to know the number of vehicles needed to operate an ideal case between the extremes of a simplistic V2H and overly complex V2G. Further, since vehicle-to-grid is a new technology, it would be useful to know the level of V2G required to make a meaningful contribution to the electric grid.

3. Model Description

Previous studies [3-8] into vehicle-to-grid have justified its feasibility based on many vehicles acting together to provide grid services. The studies use average data in their assumptions. Vehicle-to-home does not require many electric vehicles working together; it is a simple first step towards mass vehicle-to-grid. The development of a V2H model allows the basic idea to be fully understood before considering the more complex technical and statistical challenges facing V2G.

MatLab Simulink ® was used to simulate vehicle-to-home. Broadly, the model was split into three parts: house, vehicle and control.

The house section simulates the demand from the electrical appliances in the household. Household load profile could be built up from individual appliances or input as power demand versus time. Vehicle presence was input to the model; the user selected the periods the vehicle was parked or in use before the simulation was run. Vehicle use was simulated via a power drain on the vehicle battery. A constant power drain over the entire journey simulated the vehicle use but any drive cycle, converted to power drain versus time, could be input to the model.

Control was the decision making process of the simulation. The simplest case operated no vehicle-to-home; the electrical appliances ran directly off the mains at all times and the electric vehicle was charged until the battery state of charge (SoC) was 0.95; where 1 was a fully charged battery. The Charging rate was fixed at 3 kW, a rate which is achievable with a standard 13 A plug.

Introducing vehicle-to-home increases simulation complexity. The extent of the V2H was governed by the "mains target"; a number set before the simulation begins. If total instantaneous appliance demand was less than the mains target the appliances were run directly from the mains. However, if the appliance demand was greater than or equal to the mains target the appliances were run from the electric vehicle battery. The mains target essentially caps the peak power seen by the electric grid. If V2H can operate correctly, the most the grid will ever have to supply the household is the 3 kW drawn by the vehicle charger and the total power drawn by appliances below the mains target. For example, if the mains target was 300 W, the vehicle was charging and two 100 W light bulbs were being used the power drawn from the grid would be 3.2 kW. If four 100 W light bulbs were in use then 100 W would be drawn from the vehicle battery pack.

Supervisory controls protected the battery from misuse: the appliances could not drain from the battery beneath a "range buffer" set at 0.3 SoC or approximately 15 miles. Vehicle-to-home facilities were also limited to when the vehicle was present, for obvious reasons.

A hypothetical electric vehicle was simulated. The vehicle had a 26.5 kWh battery capacity and had an efficiency of approximately 7 km/kWh. All vehicle charging took place at home; this study did not investigate the potentials of charging at, for example, the workplace.

Model outputs are graphs of battery state of charge, appliance power demand, total household (or grid) power demand, car charger power drawn, appliance power drawn directly from the grid and appliance power drawn from vehicle, all versus time. The other measures are total energy from the grid, peak power drawn, average power drawn and the load factor, which is defined as average power divided by peak power.

4. Model Use

The model was used to test the flexibility of vehicle-to-home. How effective V2H is for an individual depends on their lifestyle; vehicle use and electrical use will vary from person to person and determine the feasibility of using V2H.

The most important variables affecting vehicle-to-home are the vehicle journey times, frequencies and durations and the household electrical appliance load profile, that is, the power an appliance uses and its frequency of use. The closer these two profiles coincide, the more effectively an electric vehicle can provide the appliance power.

The problem arises when a single house V2H simulation is tested using real electricity demand data; which real data are most suitable?

National data is readily available from the National Grid, ELEXON and the UK Department for Business, Enterprise and Regulatory Reform (BERR); the accuracy and reliability of the data can therefore be trusted. Data can be found for any 24 hour period over the past few years; national average power demand is recorded in thirty minute intervals.

A national (or multi-building and multi-vehicle) approach could be adopted using this data but nation-wide data would need to be scaled down in order to fit into a single house framework. This can be done by choosing a day demand profile, multiplying this by 29% – as per the fraction domestic use according to BERR – then dividing by the 26,434,000 households supplied nationally, also according to BERR.

However, an individual house will have power spikes in the demand profile that an EV is well suited to soak up; such spikes can last minutes at tens of kilowatts. The national data loses these spikes for two reasons: thirty minute intervals reduce resolution, and adding up all the households will smooth out the peaks to some degree. The result is a smooth curve which, when divided sufficiently to calculate an "average" household use, gives the impression that an average household has a low and reasonably constant electrical demand profile. This effect can be seen by comparing Figure 1 with Figure 2. The former is measured electrical load versus time for one day in a house with four working occupants. Figure two is a hypothetical load for a single house calculated from ELEXON and BERR data from Wednesday August 1st 2007. The energy consumption for the two households is 7.84 kWh and 9.09 kWh, respectively. The average power consumption is also similar at 326 W and 379 W, respectively. However, the nature of the loads is highly different. The measured power demand is erratic; it varies from low base-load demands to high but short-lived demands when, for example, the shower is used.

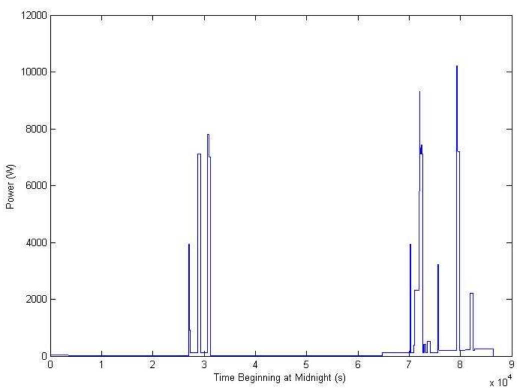

Figure 1: Measured appliance load of a single house with four occupants over 24 hours (midnight to midnight).

The calculated load shown in Figure 2 is smoother. Details of individual appliance use events are lost; the temporal resolution is not suitable. It must also be noted that the power demand of industry is not removed properly from the national use. The timing of commercial power use – particularly office work – will often differ from domestic use; the "average house" calculation is therefore flawed on two counts.

A single household demand profile should be used to test the model. The difficulty is defining a typical use profile. There are no typical use profiles since individuals lead different lives but patterns that can be seen from the nation-wide data provide a starting point for analysis. Figure 2 retains the shape of the national data but with proportionally lower magnitude. From here we can see that demand begins low at midnight, falls to a low at about 6am, before rising as people wake for work.

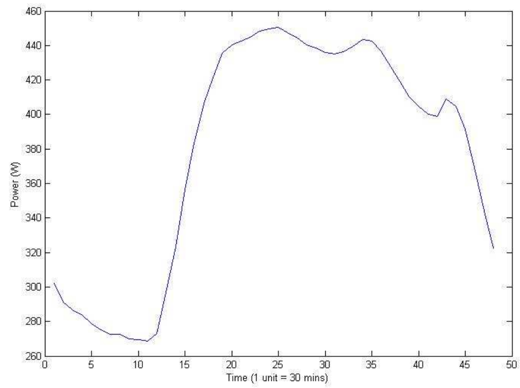

Figure 2: Calculated appliance load profile using ELEXON and BERR data from Wednesday August 1st 2007.

The load continues to rise during the day to its peak at approximately 12.30pm at which point it falls off to a low at 3.30pm. Load rises again until 5pm before falling to another low at approximately 9pm. A final rise follows, peaking at approximately 9.30pm before the load falls sharply until midnight. As previously mentioned, this data is skewed by commercial power consumption.

High resolution load profiles are not easily obtained. This problem, coupled with the problem of defining a typical use, leads to the use of models to predict load profiles. Indeed, accurate load prediction models have received much interest recently as a necessity in distributed generation and demand-side management research. Testing the effectiveness of distributed generation, such as micro-combined heat and power, requires similar temporal resolution of load profiles as testing of the vehicle-to-home. Recent literature suggests basing electrical load profiles on resident occupancy [9-11]. Resident occupancy models lend themselves logically to V2G modelling also; it is a fair assumption that a vehicle is not in use when its owner is at home and, unless the owner has travelled by other means, that it is in use when the owner is out. They are therefore a promising avenue for research into the timing limitations associated with the coordinated effort required in vehicle-to-grid.

A hypothetical electrical load profile was used in the V2H simulations. The load profile was created using observations from relevant literature [9-11] and measurements from a real household. The basic profile was based around a 9am to 5pm work shift. As per the occupancy models, most of the activity occurs while the occupants are at home, that is, outside of work hours. Baseload power demand from appliances on standby and appliances that automatically cycle, refrigerators, for example, continues when the household is not occupied. The profile represents a household in which the appliances consume 10 kWh of electricity. It represents an average family household consumption on a winter weekday – a period of traditionally high demand. High consumptions were chosen to test V2H in a "worst case scenario".

Vehicle use is the other important variable. It, like electrical use, depends upon an individual's lifestyle. A single daily journey – a commute for example – was considered. 1 mile was chosen for the short distance and 15 miles for the long distance based on data from Andre *et al* [12]. Since the daily commute was the journey under scrutiny, the distances simulated were 2 miles and 30 miles. For clarity, the power consumed during vehicle use was represented by a constant power drain during the hours of use. An extra long distance commute of 40 miles each way was also simulated to test the limits of V2H.

It is important to note that the combinations of vehicle use and electrical load profiles will not cover all eventualities. Human nature will, at times, render V2H ineffective; the test cases were chosen as a guide to the flexibility of the technology. Real world vehicle use is more complex than the daily commute. For completeness, the appliances were run at times when the vehicle was not present. Such cases test the advantages of V2H in the real world and go some way towards understanding the previously discussed crossover between vehicle-to-home and vehicle-to-grid. Simulations were run with an initial battery state of charge chosen so that it approximately matched the final state of charge. This way the day becomes a closed unit, finishing in the same state as it began. An improvement to the simulation would be letting it run over many days with a random element introduced to simulate the variation in vehicle use and appliance use in a given household from day-to-day.

An initial simulation was run with the short commute and lower appliance demand. The grid demand – the electrical power demand as seen external to the household, that is, from the point of view of the grid – with no V2H in operation can be seen in Figure 3. The profile was similar to the appliance demand profile except for the vehicle charging that occurs at 61200 seconds or 5pm. Peak power for the day was 10720 W while average power consumed was 420 W. Large but short lived peak demands feature proudly and result in a load factor of 0.039.

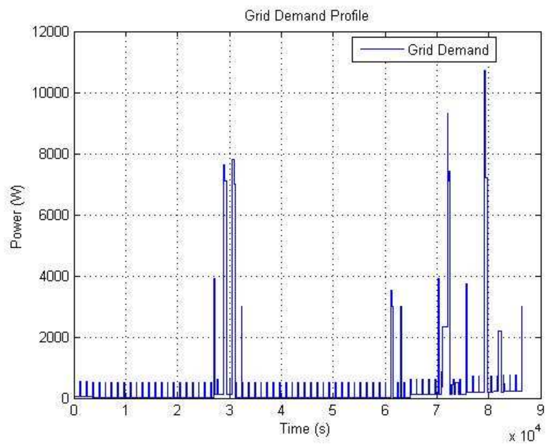

Figure 3: Grid demand for short distance commute with no V2H.

The short commuting distance leaves plenty of electric charge in the battery to use in vehicle-to-home. Therefore, the mains target can be set low. Setting the mains target at just below 3000 W instructs the simulation control to run high power appliances from the battery. The resulting flatter grid demand profile can be seen in Figure 4. Baseload appliances are run directly from the mains so low power fluctuations remain. Peak power is capped at 3922 W; it occurred when the vehicle was charging at 3 kW and baseload appliances were running in the background contributing 922 W. This low peak power caused the load factor to rise to 0.1192, a considerable improvement over the standard 0.039 load factor. The trade-off is increased energy consumption at 11.22 kWh compared with

10.11 kWh. This increase is caused by the efficiency losses, at 10% loss each way, as power is passed through the charger to the battery and back again.

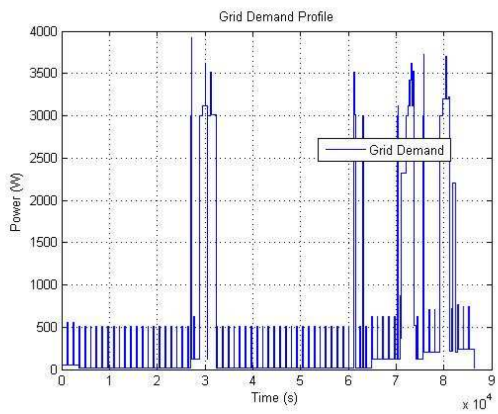

Figure 4: Grid demand for short distance commute and high power appliances run from vehicle battery.

Battery state of charge during the day can be seen in Figure 5. Since only high power appliances run for a short time their consumption has little impact on the battery. Vehicle use was limited and consumed less than 1% state of charge. SoC never fell below 0.91 throughout the day. Crucially, this battery use was sustainable, that is, the state of charge was restored to its initial point by the end of the day. A short commute leaves enough state of charge to allow vehicle-to-home a more prominent role.

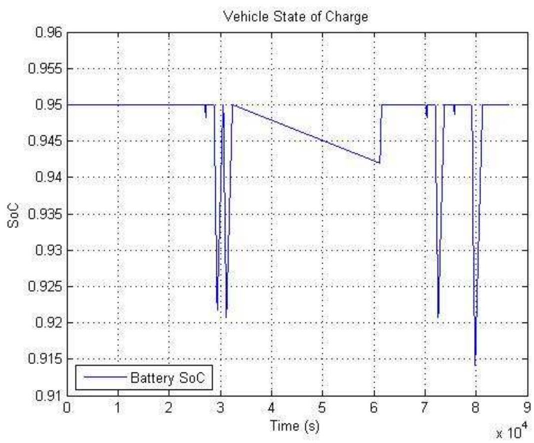

Figure 5: Battery state of charge for short distance commute and high power appliances run from vehicle battery.

The simulation controller increased the influence of the vehicle battery when the mains target was set lower. Setting the mains target at 300 W ensured that, in this appliance profile, all the appliances with higher power consumption than the baseload were run from the battery pack. The refrigerator – with power consumption 500 W – was partially run from the battery. At 300 W mains target the grid demand and battery state of charge were as in Figures 6 and 7, respectively. In this setup the peak power was capped at 3262 W and the load factor was 0.1633. A 15% load factor represents a marked improvement in the predictability of the demand profile. This improvement comes at a cost of 12.49 kWh consumption, a 2.38 kWh increase over no vehicle-to-home.

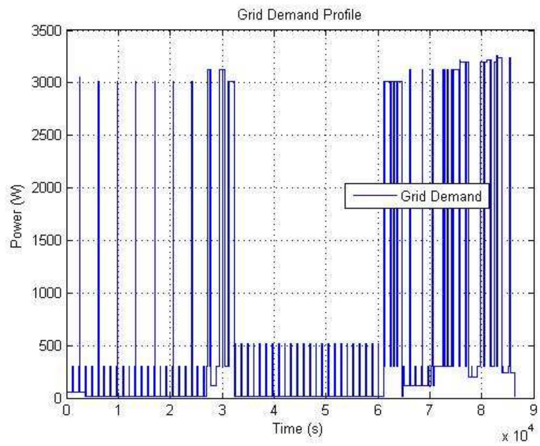

Figure 6: Grid demand for short distance commute and V2H operating appliances over 300 W.

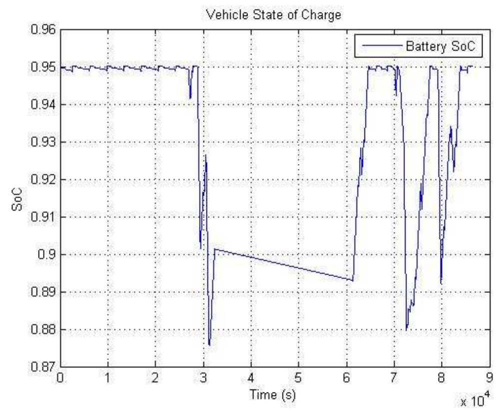

Figure 7: Battery SoC for short distance commute and V2H operating appliances over 300 W.

Setting the mains target at 0 W instructed the simulation to run appliances off the vehicle battery when the vehicle was present. This resulted in unsustainable battery use; the battery is never charged as long as some baseload appliance demand exists. Battery SoC in this case can be seen in Figure 8. While this may seem like a trivial example, it may apply in some circumstances. Particularly in rural areas, there may be some interest in using vehicle batteries as an emergency storage; thus replacing polluting diesel generators. All parameters remaining the same, and assuming the vehicle was present at all times, the simulated battery had sufficient SoC for approximately two days appliance use. Renewable energy sources – which are inherently intermittent – could use this flexibility.

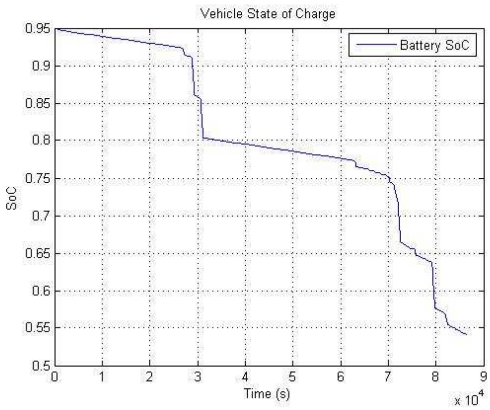

Figure 8: Battery SoC when appliances are run from vehicle at all times.

A longer vehicle journey limits the amount of stored energy available for V2H in favour of the battery's primary function, which is to propel the vehicle. Figure 9 shows the battery SoC when the commute was 30 miles total. The longer journey consumed approximately 25% of the battery capacity. Vehicle-to-home at a mains target of 300 W was still sustainable. Peak power was capped to 3262 W. Since the mains target and the appliance demand below the mains target determine the peak power, it was the same as for the shorter journey. The load factor was 0.2642; a further improvement over the similar test conducted with the shorter journey.

The longer journey used more battery capacity, as expected. For the vehicle use to remain sustainable the capacity was replaced. More charging was required and, as such, the average power used increased. This explains the increase in load factor when vehicle use increased. Figure 10 shows the grid demand for the 30 mile journey. Increased activity during late evening features as the simulation controller attempts to recharge the battery at any opportunity.

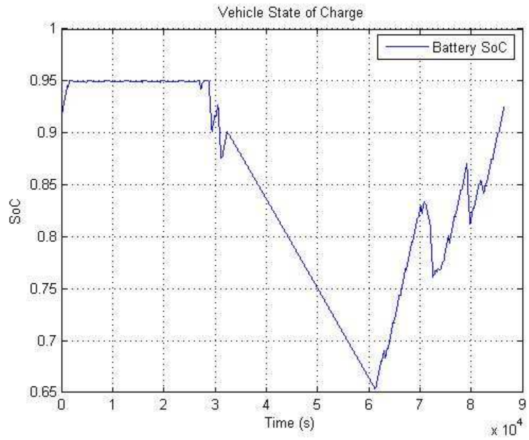

Figure 9: Battery SoC for long distance commute and V2H operating appliances over 300 W.

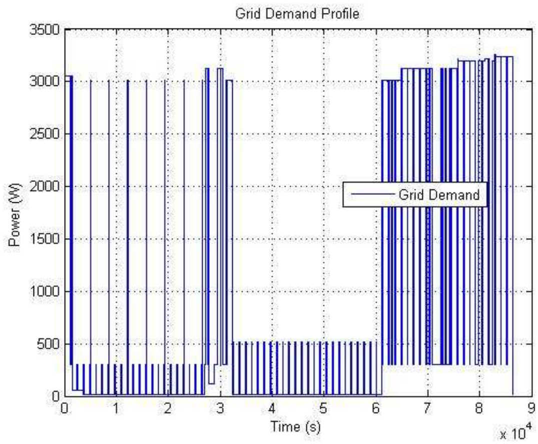

Figure 10: Grid demand for the long distance commute and V2H operating appliances over 300 W.

For a failure of vehicle-to-home due to lack of battery capacity a considerably longer commute was required. An 80 mile round trip consumed almost 70% of battery SoC leaving little room for V2H. This vehicle-to-home operating strategy was still sustainable from the vehicle point of view. There was however a glitch as can be seen in Figure 12.

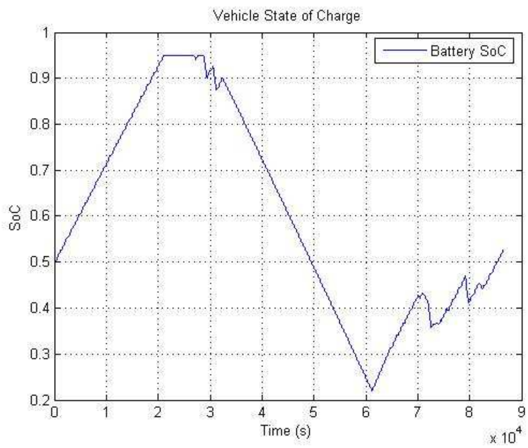

Figure 11: Battery SoC for an 80 mile journey and V2H operating appliances over 300 W.

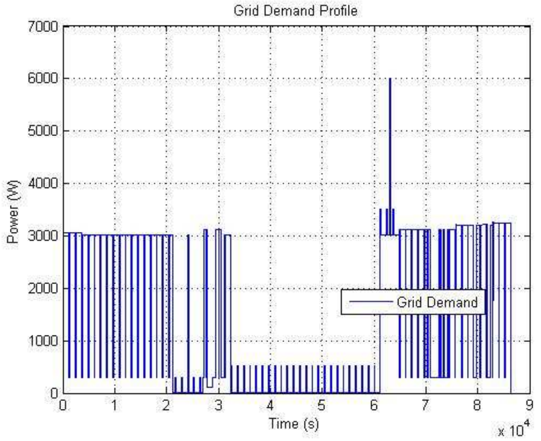

Figure 12: Grid demand for an 80 mile journey and V2H operating appliances over 300 W.

A 300 W mains target should – with this appliance profile at least – limit the peak power to 3262 W. At 63,000 seconds or 5.30pm during the simulation the grid demand rose to 6 kW. This failure occurred because the journey reduced the battery state-of-charge to below 0.3. When the vehicle SoC falls below the pre-set minimum – the range buffer – the model controller prevents any vehicle-to-home. A kettle being used at 5.30pm was therefore powered from the mains and this, together with the 3 kW drawn for charging the vehicle, caused the 6 kW peak.

This failure illustrates the importance of timing in V2H. It is reasonable to expect any appliance use after arriving home from a journey. A more intelligent model controller could defer the vehicle charging for the duration of the high appliance use; this idea requires further research. In this case, a kettle caused an increase in peak power still below the peak power if no V2H was operating. Indeed, the load factor for the 300 W mains target was 0.244. This was still a marked improvement over the load factor of 0.099 observed when no V2H was in place. Note the load factor remains high; aided by the long charging times required to fill the battery after the long journey.

The data suggests vehicle-to-home is not a realistic option when the vehicle is used for regular long commutes. However, such long journeys are rare. According to Andre *et al* [12], journeys of this length account for less than 4% of total journeys undertaken.

5. Opportunities for Further Work

Several areas require more research. This paper has argued that using vehicle-to-home to reduce the peak grid demand for a household is beneficial for the generation sector. Qualitatively, this argument is sound. If power is capped for each household by essentially buffering the high power appliances using a vehicle battery, the least efficient power stations – which are currently reserved for times of peak demand – can be used less often. This situation would reduce monetary and CO_2 costs. Further research is required to quantify these costs to properly define the economics of V2H. Noting that using V2H increases load factor but also increases energy consumed depending on the mains target chosen, a best case can be determined given suitable constraints. One must also consider the advantages of using vehicle-to-home in terms of local emissions.

Renewable energy is also a potential avenue for V2H. Renewable energy sources are intermittent in their nature. As they are introduced into the national electricity grid, energy storage will be required in order to match supply with demand. V2H and V2G are potential solutions to this problem.

The failure observed during the 80 miles simulation highlighted the importance of timing in vehicle-to-home. A further study should therefore look at how appliance demand profiles vary between households and within a given household over time. This study would give a more comprehensive view of the flexibility of vehicle-to-home and its application in the real world.

Understanding the statistical nature of vehicle and appliance use will be necessary when extending the simulation over many days. It will also be necessary when scaling the simulation up from a single household to a street of houses and vehicles and to a city-wide model and beyond. As previously mentioned, this model is a starting point in understanding where vehicle-to-home is feasible and when the extra flexibility of vehicle-to-grid becomes a necessity. The statistics will therefore determine the success of V2H and V2G as they operate over many houses and many vehicles.

Battery cycling is also an area for further research. Increased battery cycling through using V2H will degrade the battery. The financial and environmental cost of such cycling must be included in a study into the economics of vehicle-to-grid and vehicle-to-home.

6. Conclusion

A MatLab Simulink ® model was developed in an effort to understand the feasibility of vehicle-to-home technology. The model was run to test V2H when the vehicle was used for 2 mile, 30 mile and 80 mile commutes. For the two shorter distances, V2H proved successful. Peak power demanded of the electric grid was reduced from 10 kW to 3 kW using the vehicle battery. Load factor, a measure of how constant the electrical demand was, increased by as much as a factor of four. Such modifications to the grid demand profile make environmental and economic sense for the generation sector. With a commute at the limit of the electric vehicle range vehicle-to-home proved more challenging. The simulation controller could not operate vehicle-to-home properly. Nevertheless, V2H still improved the peak grid demand and load factor over the no V2H case.

Acknowledgements

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