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Can the electricity distribution network cope with an influx of electric vehicles?

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Abstract

Electric vehicles (EVs) are a new load for the electricity companies. They are different from other electrical loads in that they are, by their nature, highly mobile and unpredictable. This paper reviews the infrastructure requirements in order to show how the possible expansion of electric vehicle ownership and use will impact on the electricity industry. There are four key factors which will influence the effect of EVs on the network: namely the battery charger itself, the user profile, the electric vehicle; and the existing distribution network and plant. These areas will be discussed in turn within the paper.

Keywords: Applications/electric vehicles; Electricity distribution networks

1. Background

A convenient way of viewing the factors which influence the distribution network is shown in Fig. 1.

In this representation, the electricity distribution network is shown to be influenced by four main elements:

a) Existing distribution network characteristics
b) The electric vehicle itself
c) Battery charger characteristics
d) EV user profile

These elements interact with each other in a complex manner, but before considering these interactions, let us consider each of these elements individually in more detail in the following sections.

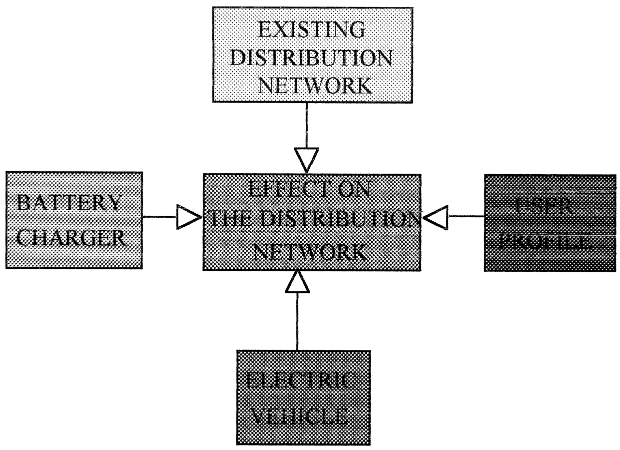

Fig. 1. Factors influencing the electricity distribution network.

2. The existing electricity distribution network

An important question to ask ourselves at the very outset is: *What exactly do we mean by the electricity distribution network?* The general answer to this question is the plant associated with the distribution of electricity from the power station to our homes and offices, i.e., the overhead lines, underground cables and transformers. This equipment already exists of course, and therefore the EV infrastructure requirements already exist, at least to some extent—for example, there are more electricity outlets than petrol nozzles at service stations. However, when we look at the situation in more detail, we see that there are many more questions that need answering, such as:

a) Does the existing distribution network have the necessary capacity to cope with this new load?
b) What new plant will need to be installed to cope with the particular needs of EV chargers?
c) Are new billing systems necessary to cope with this 'mobile' electrical load?
d) Who will own the batteries and battery chargers?

Each of the above questions is likely to provoke many more questions in turn. Thus, before the situation becomes impossibly complex and confusing, I intend to limit the

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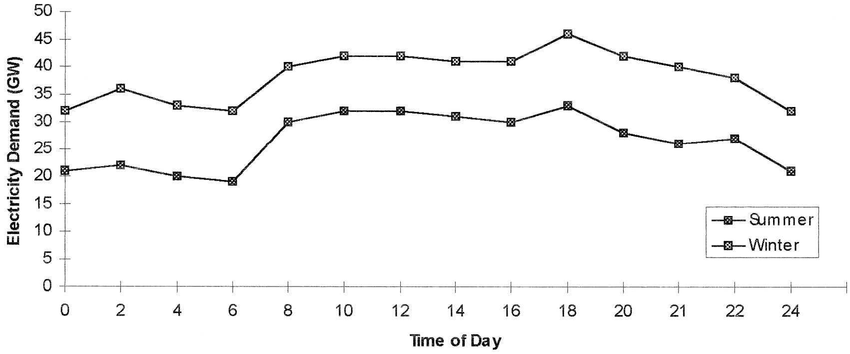

Fig. 2. Typical summer/winter load profiles.

definition of the electricity distribution network to the implications of EV use on the plant itself.

3. Electricity generation and demand

In the UK, there are slight regional variations, but on the whole the electricity supply chain can be considered in terms of generation, transmission, distribution and supply. The peak demand for electricity in the UK is governed by the weather due to the additional heating load which occurs in winter—Fig. 2. The daily pattern of demand has certain characteristic features. In summer, the typical base load is around 20 GW, which ramps up to 30 GW between 06:00 h and 08:00 h. The plateau then carries on through the day, with a slight dip after lunch (13:00 h) and a slight peak about tea-time (18:00 h), before trailing off. There is a slight peak about 21:00 h, when it starts to get dark, but demand then continues to reduce until base-load is reached at about midnight. In winter, the profile is similar in shape, but about 25% greater in magnitude. Also, the evening peak is more pronounced and an additional peak appears between 01:30 and 03:30 h due to off-peak storage heaters, etc. (e.g., Economy 7 tariff).

The electricity generating mix in the UK is important for assessing the total life-cycle emissions for EVs among other items. The 1998 mix is shown in Fig. 3 [1].

Electricity generated in the UK was 345 TW h in 1997. Generating capacity is around 73 GW, with a peak demand of 55 GW. This can be split up into the various sectors, with 32% industrial customers, 36% domestic consumers, 22% commercial users, 2% transport sector, 7% public administration and 1% agriculture, as shown in Fig. 4 [2]. At present, the transport customers are railway traction. Obviously EVs offer the potential to grow this transport sector dramatically. The majority of the new load caused by EVs is likely to fall in the domestic and commercial sectors.

3.1. The domestic sector

The UK has a population of approximately 60 million, and there are approximately 25 million electricity customers (24.5 million domestic customers). The average consumption per domestic customer was 4256 kW h in 1997 [2]. The general breakdown of electricity use in the domestic sector is shown in Fig. 5.

3.2. The commercial sector

The service sector is the fastest growing sector of the electricity market, with the breakdown of end-use shown

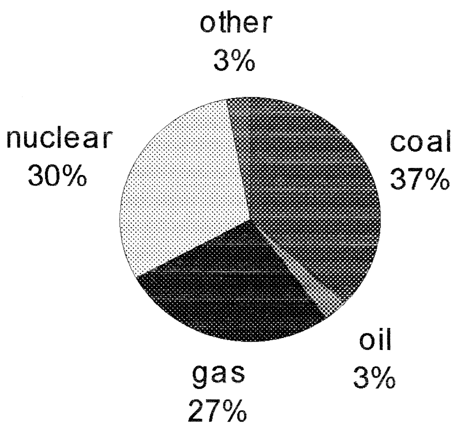

Fig. 3. UK generation mix.

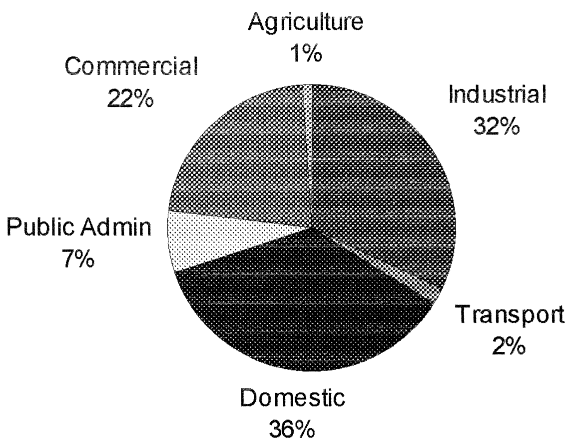

Fig. 4. Demand breakdown for UK electricity.

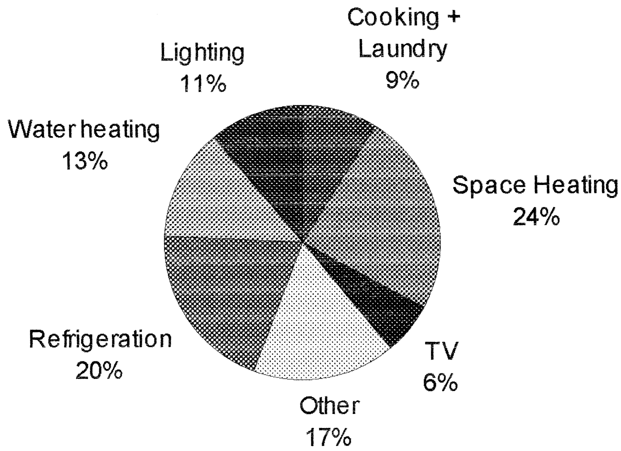

Fig. 5. Breakdown of domestic electricity use.

in Fig. 6. One key application area for EVs is as lightweight delivery vans on prescribed routes. This will add to an already fast growing sector in terms of electricity demand.

The average consumption of a commercial customer is about 34,000 kW h per annum. The strongest growth is amongst the retail shops and offices, whilst the single most important use in the commercial sector is lighting (43% of total sales).

3.3. The industrial sector

The industrial market is dominated by a few energy-intensive industries with large individual sites, such as chemical, coal and steel works, paper printing and publishing industries. In general the demand for electricity in the industrial sector is on the decline, due to a general decline in heavy UK industry and improvements in energy efficiency. The largest single use of electricity in the industrial sector is motive power applications (60%) (Fig. 7).

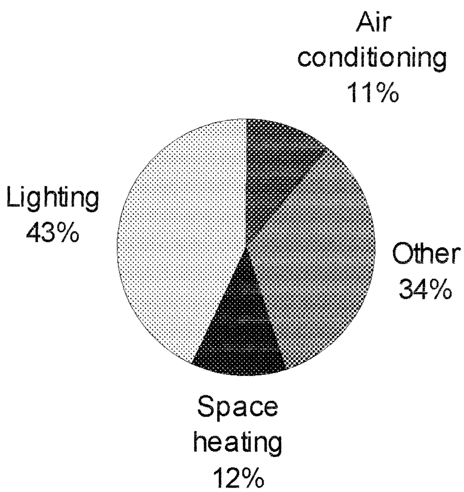

Fig. 6. Breakdown of commercial electricity use.

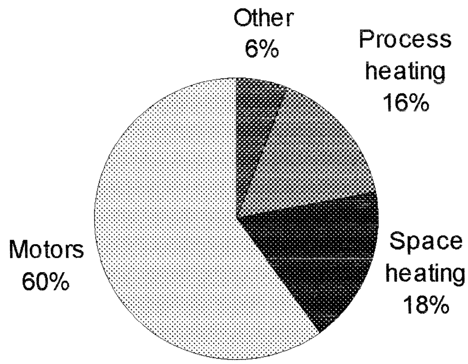

Fig. 7. Breakdown of industrial electricity use.

3.4. Transport energy consumption

To complement the figures for the use of electricity; this section gives some figures for transport use. Ninety-nine percent of the energy used in transport comes from petrol and diesel. Rail is the only transport medium whereby electricity is used. One third of the energy use in the rail sector is electricity, the remainder is diesel. Two thirds of road transport fuel is for cars and taxis and most of the rest for heavy goods vehicles. The share of buses and coaches is now under 3%. Transport energy consumption has increased by 80% and road transport use by 92% since 1970 and the breakdown by usage for 1996 is given in Fig. 8 [1].

4. Electricity transmission and distribution

The bulk transmission of electricity from the generation centres to the demand centres is carried out by the 'supergrid' at 400 kV and 27 5 kV, under the control of the National Grid Company (NGC).

The majority of electricity distribution in the UK is carried out at 11 kV (MV, medium voltage) and 400 V

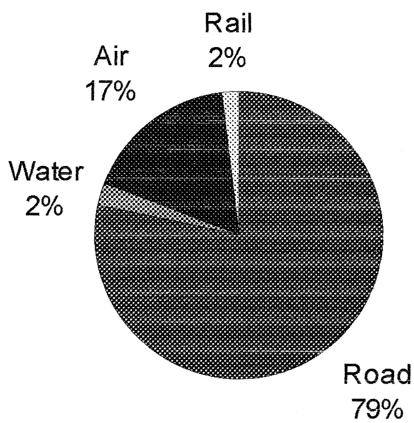

Fig. 8. Transport energy consumption in 1996 [1].

three-phase (LV, low voltage), i.e., 230 V single-phase. Nationally, this distribution is split evenly between overhead lines and underground cables at both MV and LV. The number of primary substation transformers in UK is about 5000, with about 425,000 secondary (distribution) transformers. The main distribution voltage level is 11 kV. A 'typical' primary substation would serve approximately 5–10,000 domestic consumers with two primary transformers, each rated at 6 MV A.

Thus, the firm capacity of the primary substation would be about 12 MV A. The after-diversity maximum demand (ADMD) of a typical home on a housing estate would be 2 kW (for a typical housing estate) and so a cluster of 200 homes could be served by a 400 kV A–1 MV A transformer. Smaller transformers would be found in more rural areas. 25 kV A is now normally the smallest size that would be fitted, typically supplying a single farmhouse whilst a cluster of half-a-dozen houses would be supplied from a 50 to 100 kV A transformer.

In addition to considering the plant itself, the plant utilisation also needs to be assessed. The initial plant ratings are specified according to the predicted worst case scenarios, whilst also allowing for a safety margin and a margin for future load growth. For instance, the primary substation transformers are rated such that if one of the two transformers should go off-line, either due to a fault or routine maintenance, the full substation load can be taken by the single remaining transformer. Thus, it can be logically deduced that during low load conditions, the plant is significantly under-utilised. Thus, the scenario whereby an EV is charged overnight is seen by electric utilities as an ideal new load.

Electricity companies world-wide are constantly assessing the need to renew or add to existing infrastructure. New plant is extremely costly, thus much thought and analysis is required when considering this option. Techniques such as Demand Side Management have been developed which are measures to modify customer demand patterns to benefit energy suppliers and distribution companies.

Investment in new infrastructure can sometimes be avoided and this saving in expenditure is then passed onto the customer through lower prices. The assets owned by the electricity companies are constantly being managed to give the highest rate of return.

Table 1
Battery mass required to give 1 km range

Battery	Battery weight (per 1 km range), kg
Lead-acid	6
Nickel/cadmium	3
Nickel/metal hydride	2

5. The electric vehicle

The other three influences (the EV, the user and the charger) on the impact of EVs on the electricity industry are interconnected in many ways. The choice of EV itself will influence, to some extent, the user profile, the charger and charging regime. The range of the electric vehicle (and therefore its battery type and design) will provide the biggest influence on the electricity network when considering the EV itself.

Developments in battery technology are the main hopes for improving overall speed and range. Indeed, lead-acid battery technology has improved significantly in the last 25 years, whilst alternative battery couples, such as nickel/cadmium, lithium-ion and nickel/metal hydride are providing enhanced energy densities. This is crudely illustrated in Table 1, where the figures show the typical mass of battery required to give a range of one kilometer.

The new battery technologies, whilst possessing highly desirable features, such as high energy densities, can also have undesirable features, e.g., cadmium is expensive and has environmental considerations. Lithium-ion and nickel/metal hydride are two of the great hopes for future advanced EV traction batteries. At present, however, they are simply not cost-competitive with lead-acid battery technology.

The following table summarises some of the key characteristics in battery technology (Table 2).

Battery management (i.e., controlling the environment of the battery and the way it is charged and discharged) is crucial in maintaining battery life and performance. If a battery is abused, either by drawing excess current for long

Table 2
Key characteristics of selected batteries

Battery	Specific energy ($Wh\ kg^{-1}$)	Peak power ($W\ kg^{-1}$)	Energy efficiency (%)	Cycle life	Cost (£ $kW\ h^{-1}$)
Lead acid	35–50	150–400	> 80	500–1000	75–95
Ni/Cd	40–60	80–150	75	800	155–220
Ni/MH	70–95	200–300	70	750–1200 +	125–270
Zinc/air	100–220	30–80	60	600 +	55–75
Li-ion	80–130	200–300	> 95	1000 +	125

periods of time, by deeply discharging the battery, or by over-charging, its life and performance will be greatly degraded. All these factors impinge to some degree on the electricity distribution network. Battery management devices are being developed by many companies world-wide [3,4].

Studies of vehicle use by a wide selection of the motoring public have shown that the typical range of an electric vehicle (100–130 km) is more than sufficient for the majority of journeys made in one day. (Estimated distance travelled in the UK per person per week by car is 200 km). Also, the EV is often seen as an urban vehicle, where speeds are usually limited to 50 or 65 km h^{-1}. It is thus often anticipated that the early uptake of EVs in the UK will be within households owning two (or more) cars, (28% of households in the UK own two or more cars).

Regenerative braking, whereby braking energy is returned (at least in part) to the battery, is being used to improve the efficiency of electric vehicles. This technique typically extends the range of the vehicle by between 10% and 20%.

Other factors affecting EV range and thus impacting on the electricity network include the design of the car in terms of chassis and body. Peugeot have fitted the electric motor and batteries into an existing model, in place of the petrol engine and fuel tank. In this respect, the vehicle is not optimised for lightweight/efficient propulsion. It does however, have advantages from a servicing and maintenance perspective; an important consideration for the buyer of the vehicle.

The approach taken by GM was more radical whereby they built a purpose-designed vehicle, in order to optimise EV performance. Factors such as vehicle chassis, weight reduction, air drag reduction, rolling resistance reduction and use of composites were considered. This was a much more expensive strategy (a US$350 million investment programme). The EV1, however, has not been as successful as anticipated. GM has leased only 400 EV1s in California—hardly the 10% market share imagined for the state by 2003 [5]. GM feel that this is partly due to a lack of co-operation between companies, limited standardisation of EV infrastructure and that US off-peak electricity tariffs for EV users are still too high.

6. The user profile

Issues relating to the user profile are closely linked to the EV itself, since the EV will be designed in order to best meet the needs of the user. Typical EV users can be split conveniently into three classes. These are:

a) domestic (small vehicles)
b) fleet (commercial vehicles)
c) public transport (buses)

The relative importance of each of these classes will depend largely on the country being considered. Domestic and fleet markets are potentially the largest markets and as such will attract much interest and will have the biggest impact on the electricity distribution network. Conventional public transport, however, may provide the market entry point for many of the new technologies being considered in the EV market area.

As previously mentioned, the domestic market has been identified as high income households, where the EV will be the second (or third) vehicle and will be used for the majority of local journeys (i.e., to/from work, to the shops

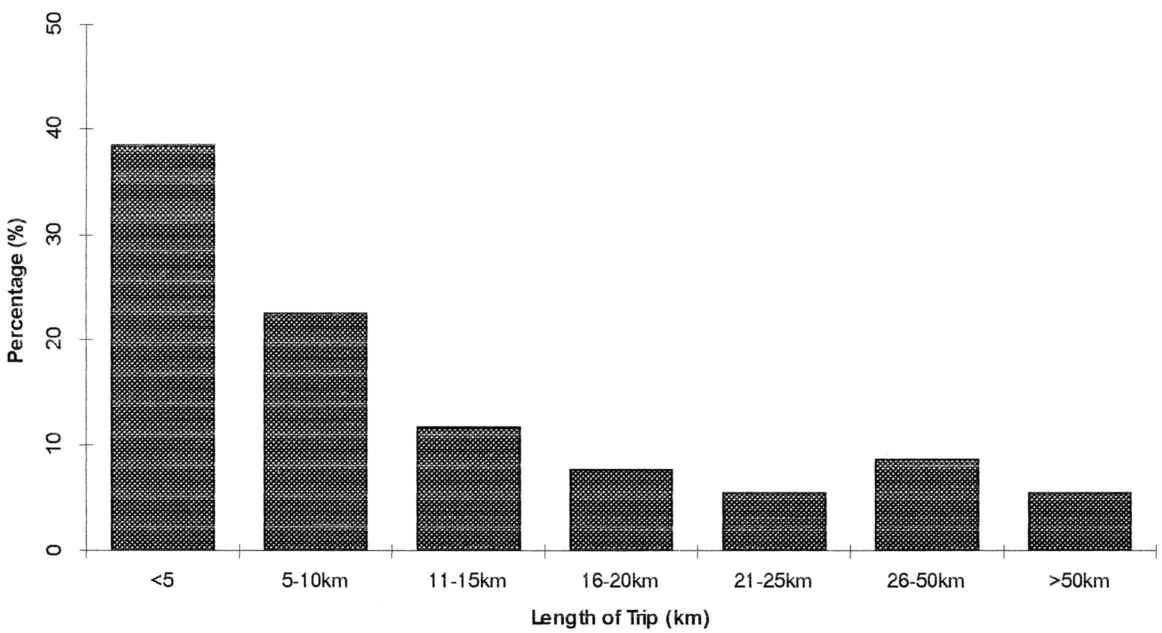

Fig. 9. User Profiles—length of trip against frequency.

and local leisure amenities). For these users, charging the EV will, in the majority of cases, take place overnight at home, with perhaps some provision being necessary at the user's place of work or at the other main journey destinations (i.e., supermarket, shopping centre, railway station or sports centre car parks).

It is also important to recognise that the actual mileage driven by an EV will be governed by the needs of the user, so, whilst an EV may be capable of 160 km a day, it is likely to be used much less than this. Typical domestic user profiles are given in Fig. 9.

The use of EVs within fleets is likely to initially take place within organisations linked with the electricity industry or which have a user profile well suited to EV performance characteristics. A user profile which involves frequent stop/start operation, combined with a short range (such as delivery vehicles) are very suitable for EVs. For example, the Royal Mail who are very active in testing and using EVs for mail delivery purposes. In addition, East Midlands Electricity are heavily involved in using electric Peugeot 106s. Public transport is a key area within the UK where EVs can provide a clean and efficient service. Electric buses would be particularly suitable for use in Park and Ride schemes, where there is potential to allow for an opportunity-charge at the end of each run, if required. The Government's White Paper on the Future of Transport (published July 1998) identifies cleaner buses as one of the key areas for lowering emissions and reducing congestion. In Birkenhead, Merseyside, six electric buses have been introduced on a short town centre route. EA Technology is supporting Merseytravel, the local Passenger Transport Executive, in this project.

7. Battery charger characteristics

The specification of a typical traction battery charger is linked very closely to the requirements of an electric vehicle and also the capabilities or capacity of the available electricity supply. There are two main factors which will affect the electricity supply that are caused by the battery charger characteristics. These are the electrical load required at any one point and the effect on power quality.

Table 3
Electrical energy requirements per kilometre

Vehicle name	Vehicle type	Energy consumption ($kW\,h\,km^{-1}$)
Renault Express	Small van	0.14
GM EV1	Sports car	0.14 to 0.16
Peugeot 106	Small car	0.2
Citroën Saxo	Small car	0.2
Tecnobus	8 passenger bus	0.5
Oxford Bus	18 passenger bus	1.4

All of the above figures are from the manufacturer's literature except the figure for the Oxford Bus which is actual measured data.

The power quality aspects can be further broken down into harmonic effects and power factor effects. In the UK, EA Technology are working with several electricity companies (namely MEB, ScottishPower, Scottish Hydro-Electric and London Electricity) on a collaborative basis to further the understanding of the effect of EVs on the network.

7.1. Electrical load requirements

Each vehicle will have different electrical load requirements which depend on the route, how laden the vehicle is and the type of vehicle. The following table gives some idea of the variety of requirements (Table 3).

It can be assumed that the largest effect of EVs on the electricity distribution network will be caused by domestic cars and commercial vans; as these could represent the largest market share. Taking the figures above, 0.2 kW h of energy supplied to the batteries of a small EV car or van will give 1 km of usable range. Assuming a range of 100

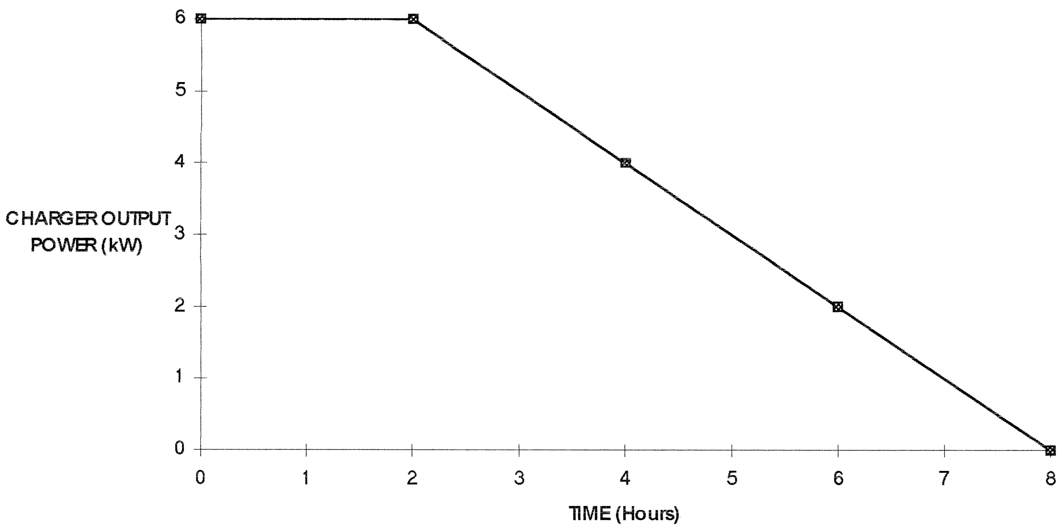

Fig. 10. Charging characteristic of a 6 kW battery charger.

km and allowing for 50% inefficiencies a total of 30 kW h may be required in one charge session. Unlike a petrol tank, which fills at a uniform rate, batteries get most of their charge early in the process. For most batteries, the rate of charging is determined by the state-of-charge of the battery. Thus, when the battery is deeply discharged it will accept charge at a high rate, whilst when the battery is nearly fully charged, it will accept additional charge at only a slow rate.

It is normally true to say that the rate of charge of a deeply discharged battery is limited by the electricity supply available at domestic premises. Indeed, a standard wall plug in the UK is fitted with a 13 A fuse (i.e., gives up to 3 kW) whilst a purpose-wired circuit would give a 30 A supply (i.e., 6 kW). Some UK domestic appliances go above this (electric shower units up to 8 kW, for example). If it is assumed that a 6 kW battery charger is used, the charging profile would look something like that shown in Fig. 10.

In this example, the charger delivers its maximum power for the first two hours (i.e., supply limited), then after this the charge rate is governed by the battery state-of-charge (SOC). In this example, the battery is restored to 40% SOC in 2 h and 60% SOC in 3 h. This is similar to statements made by battery manufacturer SAFT that 60% of charge is recovered in 3 h and 100% in 8 h. It is significant that a large percentage of the battery charge is restored in the first hours of charge. If left solely to the vehicle user, it is likely that the charger will be plugged in and switched on as soon as he or she arrives home from work. This coincides with the existing evening peak load; obviously, an undesirable situation for electricity companies. Thus, as a minimum requirement a battery charger 'tariff' could be used to delay the start of charging until after the evening peak. It would also be desirable for electricity companies to stagger the start-up times of the chargers, since battery chargers draw their highest load at the beginning of a charging cycle.

For comparison a scenario using a 3 kW (maximum battery charger is described. In this case, the charger is likely to be running at its full rating for 8.5 h, and needs nearly 12 h to completely recharge the batteries (compared with 8 h in the previous case). This time duration is marginal in terms of being able to recharge the batteries completely overnight and reduces the flexibility of any Demand Side Management (DSM) measures that could otherwise have been used to control the load (Fig. 11).

In the longer term, it is likely that the range of electric vehicles will increase, mainly due to improvements in battery technology. Thus, if EV range is extended to say 250 km it is likely that the energy required for the vehicle will remain much the same (approximately 0.2 kW h/km) and so it will occasionally be necessary to deliver 75 kW h of energy (allowing for 50% extra requirements for inefficiencies) in a single charge. If this were to be done overnight using the domestic charger, it would need to be rated least at 10 kW to charge the vehicle in less than 8 h. An alternative scenario is that an infrastructure of 'fast-charge' stations is developed. Fast chargers already exist, e.g., the Chrysler Corp. and Norvik Technologies System provides an almost-full charge to advanced batteries in 25 min with the expectation to cut this to 10 min. Fast chargers though, will have a greater impact on the electricity distribution network, although the Norvik fast charger is known to have a beneficial impact on the life and performance of the battery [6]. Fast charging may well be necessary for many public transport schemes, unless some form of battery exchange is envisaged. In the end, just as today's motorists choose among grades of petrol or diesel, the electric car driver will be able to choose among recharging options of slow (overnight) home charging or fast charging.

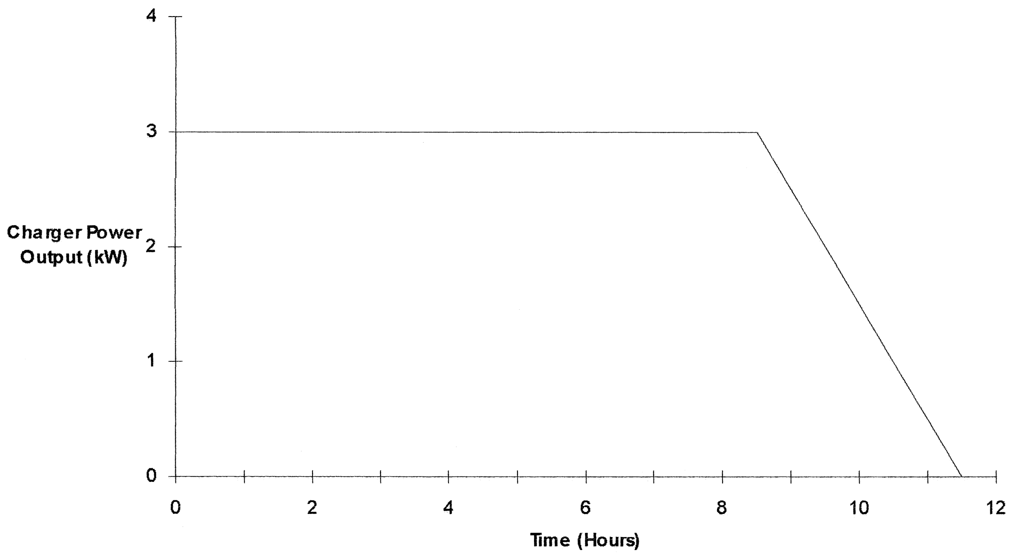

Fig. 11. Suggested characteristic for a 3 kW battery charger.

The issues of where vehicles will be charged and how fast the batteries can/need to be charged etc have made the battery charger debate one of the most intense subjects in the world of EVs, not least because of its impact on the power cord/connector. This debate enters into the realms of safety and standardisation, both at national and international levels and so progress here is necessarily slow and cautious.

7.2. Aspects of power quality

Battery chargers also affect the quality of the power on the network and this can be transferred back to the transformers and cause lack of capacity to the electricity distribution network. Much work in the area is ongoing, especially in the US, with many electricity utility companies performing tests and measurements on existing EV demonstration schemes [7]. At present there is no problem with the effects on the electricity supply, but there is concern about the future effects especially if there are clusters of EVs all charging at one particular time on one part of the network. This problem could be compounded if the charging is done in a weak part of the network such as a rural line. Care must be taken when introducing lower tariffs. If the tariff times are too restrictive; EV users could all be encouraged to commence charging at the same time.

There is concern about the existence of harmonic currents. These stray currents cause heat which must therefore be dissipated. Some studies have been conducted in the US to assess the potential impact of the harmonic currents on the network [8]. Power factor correction is another area of concern. International guidelines and standards in the area of power quality are being worked on; but necessarily this is a slow process.

8. Electric vehicle scenarios

There are many opinions as to the likely future take-up of electric vehicle transport. This is an area which is very difficult to predict, since it depends on many factors, most of which are outside our control. In this section, different scenarios will be considered and the effect on the distribution network will be estimated, both on the macro (national) and micro (local) scale.

Now that each of the four elements affecting the electricity distribution network have been discussed individually, some ball-park figures can be assumed in order to do some 'back-of-the-envelope' calculations. As a starting point, we can look at 0.1% penetration, a figure for the near term—something which could be achieved within the next five years. In the UK, this translates to 26,000 vehicles (there are currently approximately 26 million vehicles registered in the UK). Taking a more positive view, we can then look at the scenario where 1% of vehicles sold are electric and finally, we can look at the situation where 10% of all vehicles in the UK are electric.

Secondly, we need to make some assumptions about the electric vehicle itself and the way it is likely to be driven. Let us assume a fairly inefficient vehicle which is only capable of travelling 3 km for every kilowatt hour of energy and that the typical daily mileage is 50 km for 7 days a week (it is likely that the daily distance travelled for an EV will be less at the weekend, but is assumed to be the same in this case, for simplicity). We will also assume that vehicles are charged predominately at home via a 6 kW domestic charger.

It is assumed also that the number of vehicles in the UK will remain fairly constant over the next 10 years, with approximately 4 million new vehicles being sold every year.

8.1. Case 1: 0.1% EV penetration

In this case, only one in every thousand vehicles is electric and so the effect on the macro scale will be minimal. If it is assumed that all 26,000 vehicles are plugged in at the same time, then this translates to an additional load, nationally, of:

$$26{,}000 \times 6\ \text{kW} = 156\ \text{MW}$$

This is less than 1% of the summer base load and so, whilst it would be beneficial to move this demand away from the evening peak, it is not going to have any significant impact on the reserve generating capacity of the UK. However, this extra load is unlikely to be spread evenly throughout the country and so if these vehicles were concentrated in small areas (as is likely to be the case) then some impact at the primary substation level is likely, since 156 MW can be equated to the equivalent of about 13 primary substations! This emphasises the importance of using the off-peak capacity available. As far as the LV distribution network is concerned, it is likely that distribution transformer capacity is likely to be the principal limiting factor rather than LV cable ratings.

From an individual EV user's point of view, the EV charger is likely to be the highest energy-consuming electrical appliance in the home, typically consuming about 16 kW h of electricity every day. This equates to 5475 kW h a year, more than doubling the user's overall electricity consumption.

8.2. Case 2: 1% EV penetration

This scenario requires much more careful consideration, since 260,000 electric vehicles equates to 1560 MW (equivalent to two large power stations!). At this level of penetration, whilst there is enough generating capacity in the UK to meet the demand at peak times, it is most important that these vehicles are charged at off-peak times to ensure that the most cost-effective generators are used.

In classical economic terms this means that more power will be produced by the existing system which will spread the costs and bring down the cost of each kilowatt hour. Electric vehicle users could thus lower everyone's electricity tariffs. It is probable, however, that power quality could start to become an issue at this level of penetration.

8.3. Case 3: 10% EV penetration

Whilst even the most optimistic predictions of EV take-up do not expect to see EVs exceed 10% penetration rate within 10 years, it is a case worth considering for its impact on the distribution network, since asset lifetimes of between 25 and 50 years are expected for some of the major plant items in the distribution network.

In this case, the peak additional load could be in excess of 15 GW. Obviously, at this level of load, demand-side measures are of paramount importance. Some percentage of this load is bound to appear during the peak times, due to customer demand. Also, with an annual consumption of approximately 5500 kW h per year per vehicle, this translates to:

$$0.1 \times 5500 \times 26{,}000{,}000 = 14.3\ \mathrm{TW\,h}$$

as the total annual electricity consumption for electric vehicles. Current annual consumption in the UK is approximately 350 TW h, and so EVs would represent about 4% of overall electricity consumption at 10% penetration.

9. Summary

Obviously, the figures presented in this paper are based on very loose assumptions for example, that people's driving habits will remain essentially unchanged so that the journey distances travelled each day also remain the same. Three further major assumptions have been made. Firstly, that the average daily distance travelled for an EV will be 50 km. There is very little UK data available to support this estimate, but this figure was chosen, taking into account typical user profiles for conventional vehicles and the typical range of current EVs. Secondly, it was assumed that typical EV efficiency would produce a vehicle capable of travelling 3 km per kW h. Vehicles like the GM EV1 are more efficient than this, (see Table 3) but it is likely that improvements in efficiency will result in increased range and therefore will increase the daily range of the vehicle. This would leave the actual energy requirement essentially unchanged. Finally, it has been assumed that a 6 kW domestic charger (of unspecified efficiency) will be used and that the vast majority of EV charging will take place at night.

10. Conclusions

Much work is being performed by electricity companies and others on a world-wide basis to cover the four key aspects which will influence the effect of EVs on the electricity distribution network. These are: the user profile, the electric vehicle, the battery charger and the existing electricity distribution plant.

As with any new technology there are many unknown factors, but these are being addressed and assessed to ensure a smooth introduction of EVs onto the market.

The introduction of any EV scheme, should involve an electricity distribution company or specialists such as EA Technology. In this manner the most appropriate charging system can be devised in a collaborative manner to the benefit of all parties concerned, including the customers and/or users.

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