DEMAND SIDE MANAGEMENT FOR DOMESTIC PLUG-IN ELECTRIC VEHICLES IN POWER DISTRIBUTION SYSTEM OPERATION

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ABSTRACT

The market for electric vehicles (EVs) has been rapidly expanded in the last few years due to the developments of battery technologies. It is expected that wide deployment of domestic owned electric vehicles offer the opportunities to both reduce carbon emission (CO2) and re-fuelling costs for domestic drivers. The batteries of these plug-in electric vehicles (PEVs) can initially be charged at home, from a standard domestic socket, or a special charger installed by the electricity supplier. A Monte Carlo Simulation (MCS) model based on details of UK domestic car use data has been developed in order to analyse the impact of battery charging demand on the power distribution system. These additional battery charging loads can act as responsive load on the system if appropriate control algorithms are applied to them. Demand Side Management has been regarded as one of the most effective approaches to manage EVs charging demand on power distribution system. This paper illustrates the potential for domestic electric vehicles to act as responsive load in order to prevent overloading the power distribution network.

INTRODUCTION

Since the first successful model of plug-in hybrid electric vehicles (PHEV) occurred back in 1997, the market of electric vehicles has been developed rapidly. Several major automobile manufactures continue producing new types of electric vehicles in the past decade, such as General Motor Chevy Volt, Toyota Prius, BMW MINI E, Mitsubishi i-MiEV, etc. Battery technology has mainly shifted from Nickel-Metal Hydride to Lithium-ion type, which has larger energy density ratio and lightweight comparing with previous type. These larger capacity batteries offer longer-range limits for either full electric vehicles (EV) or plug-in hybrid electric vehicles. These changes in terms of electric vehicles configuration offer opportunities to reduce both re-fuelling costs and carbon emissions from PHEVs tail pipe. For instance, the first version of hybrid electric vehicle can only offer approximately 3 miles of its journey on full electric driving mode and recharge its on-board battery through re-gen braking technology, [1]; in contrast, new type of PHEVs can be driven on full electric mode for approximately 35 miles on a single charge, [2].

In the UK, transport contributes a significant portion of domestic carbon emission as 21%; carbon emission from domestic transport will be reduced by up to 14% over the next decade, [3]. Widely deployment of electric vehicles can offer significant environmental benefits on reducing carbon emission compared with existing internal combustion engine vehicles (ICEVs). UK government provides incentive scrap schemes for domestic consumer to purchase electric vehicles. Department for Transport (DfT), as one UK government body, has released a document, ‘Low carbon and electric vehicles’, in 2009, [4]. It states that the government has plan to create a £250m scheme to reduce the price of electric and plug-in hybrid cars, from 2011 onwards, to help consumers purchase them. Approximate £20m of the £250m will be used to develop an electric vehicle charging infrastructure framework helping create a UK network of electric car cities.

By 2010, there are nine electric vehicles so far confirmed as qualified for the subsidy scheme, the three that will be available for delivery in January 2011 are the Mitsubishi i-MiEV, the Smart fortwo electric drive and the Peugeot iOn. The Mitsubishi is being advertised for sale from £24,000, after the £5,000 government grant. The Smart and the Peugeot electric cars will initially only be available through four-year leases. The Nissan Leaf and Tata Vista will then follow in March, while the Citroen CZero is currently only confirmed for “early 2011”. The Toyota Prius Plug-in Hybrid and the Vauxhall Ampera, which will also be sold – with some modifications – as the Cheverolet Volt, are due to see their first UK deliveries in early 2012. [5]

Domestic use of EVs and PHEVs could make a significant impact on the power distribution system with higher penetration level of electric vehicles deployment. Demand Side Management (DSM) has been regarded as one of the most effective approach to manage EVs charging demand on power distribution system. In [6] to [9], these studies of PEVs and PHEVs battery charging impact have illustrated that the potentials of PEVs and PHEVs act as either responsive load or distributed energy resources (DERs) would make significant contributions to power quality improvement and utilised in the context of demand side management.

This paper illustrates the potentials that domestic electric vehicles act as responsive load in order to overloading the power distribution network. It is necessary to implement appropriate battery charging strategies to minimise the impact on the system without violate either domestic user and power system operation constrains. Objective of this paper is:

- Develop a probabilistic model of UK domestic car use.
- Develop a Monte Carlo Simulation (MCS) based on the probabilistic model for developing EVs battery charging profile.
- Provide an impact analysis on power distribution system and potentials of PEVs as responsive load.

STOCHASTIC MODELLING OF PEV BATTERY CHARGING DEMAND

A probabilistic model has been structured based on Monte Carlo Simulation (MCS) to investigate the impacts of PEVs on-board battery charging demand on power distribution networks in the UK. The model uses a simulation of daily typical domestic loads on 3-phase distribution networks representing urban area. The PEV batteries charging model simulates individual domestic cars charging in an uncontrolled strategy. The outcome of the model states the estimation of potential impacts on specific power quality issues on power distribution system operation, such as system peak demand, substation transformer overloading. Uncertainty analysis also has been established in order to investigating the spatial and temporal impact of these PEV batteries charging demand.

Probabilistic Model for UK PEV Daily Driving Pattern

Time of Use UK Survey (TUSUK) 2000 provides detail information relative to domestic car users driving habits in the time period of 24 hours. In the TUSUK database, there are thousands diaries filled by individual domestic participants and recorded their daily activities with a 10 minutes time resolution. The specific coded data means clear identification of private owned car movements, the purpose of journeys and location where the domestic car is parked. These useful information structures the probabilistic model of UK domestic car daily driving pattern. More details of the statistics covering individual domestic car ownership and overall car use derived from TUSUK 2000 can be found in Huang and Infield. [10, 11]

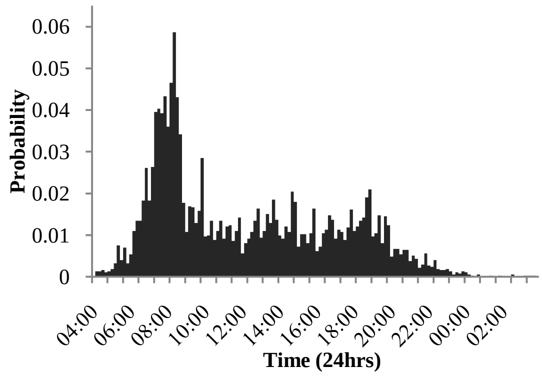

Fig. 1. Probability distribution of car left home throughout a typical weekday.

In this study, several probability distributions of domestic car use have been used as the input of MCS model to simulate the domestic car use pattern. Fig. 1 shows the probability distribution of domestic car left home throughout a typical weekday. For each ten minute time interval throughout 24 hours, the probability of a given domestic car leaving home, PL_i, is calculated for all weekday data, directly from:

$$PL_i = NC_{left} / NC_{total}$$

where, NC_{left} is the number of cars leaving home at time step i, NC_{total} is the number of cars in the sample population

In the TUSUK data, it states the individual domestic car status as ten minutes basis. Therefore, the probability of a given domestic car away home period of time, PA_i, is calculated by the number of cars who left home for the same amount of time at interval i divided by the total amount of cars is away from home at time interval i. The formulation is shown as below:

$$PA_i = NC_{away\_hr} / NC_{away}$$

where, NC_{away_hr} is the number of cars left home for the same amount of time at time interval i, NC_{away} is the total amount of cars is away from home at time interval i.

Fig. 2 illustrates three example probability distributions of car away home period of time at 0830, 1000, 1430 hours respectively. At these three examples time step, cars are more likely to be driven away from home within two hours instead of five hours. Fig. 3 shows three examples of conditional probability distribution of car journey time given by car away home period of time up to 2 hours at 0830, 1000 and 1430, respectively.

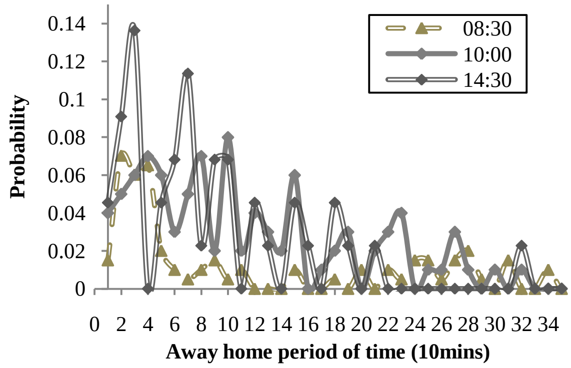

Fig. 2. Probability distribution of car away period of time at 0830, 1000 and 1430 hours.

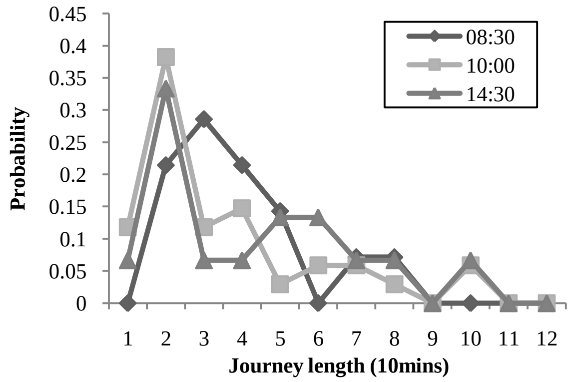

Fig. 3. Conditional probability distribution of car journey time given by

car away home period of time at 0830, 1000, 1430 hours, respectively.

The conditional probability of car journey time given by car away home period of time at time interval *i* allocated in car away home group function is calculated by journey time at time interval *i* allocated in each car away home period of time group function divided by total number of journey at time interval *i* for all weekday data. This approach to calculating the conditional probability of car journey time given by car away home period of time at time interval *i* is due to the nature of TUSUK dataset as in time interval *i* holds insufficient data to derive probability density function. Therefore, weekday dataset has been clustered into several groups based on car away home period of time and thus the new dataset allows us to calculate the conditional probability of car journey time given by car away home period of time between certain hours group. As the time duration is a discrete random representing the number of ten minute periods. It is obvious that journey times are only accurate to the nearest 10 minutes, consistent with the TUSUK data. It is important to note that this modeling approach is based on total driving time rather than distance due to the nature of TUSUK database.

Calculation of PEV Battery Charging Demand on Electric Substation

As described in previous section, duration of each journey has been derived from TUSUK database; however, this information only present period of time that each individual domestic car has been driven on the road rather than distance travelled. Monte Carlo Simulation (MCS) model perform to identify the typical weekday driving pattern, as a proportion of PEVs penetrations and these PEVs on-board battery State of Charge (SOC) status. SOC provides information regarding to battery energy reservation and also has been used in the calculation of period of time and magnitude of PEVs battery charging demand in order to bring battery's SOC to either fully charged to partial charged. Table 1 shows the vehicle configuration of a specific module, BMW MINI E, [12]. For simplicity, a constant charging rate is used and PEV users start to charge their cars immediately on arriving home as predominantly assumption. In this study, home is the only place for PEV users to charge up, although working places and public parking lot would be considered in the future research.

Table 1. MINI E SPECIFICATIONS

Battery	Type		Lithium-ion
	Capacity	kWh	35 kWh, approx. 30kWh of which useable
	Charging time	hour	at 240 V/32 A (7.7kW) 4.5
Range		mls (city)	156 under ideal conditions
		mls (city/hwy/comb)	109/96/104 estimate under normal driving conditions
Consumption	City driving	kWh/mls	0.22

Fig. 4 illustrates the structure of Monte Carlo simulation (MCS) modelling for calculating individual electric vehicle on-board battery charging demand. In the substation case study, the urban distribution network of a complete 11 kV feeder and all associated LV (400/230 V) network including six distribution transformers, providing power to 1,262 connected customers, has been used as a guide to a distribution system supplying predominantly domestic housing. Initially all 1,262 households are considered as a group to examine the additional PEV battery charging load on the substation transformer. [13]

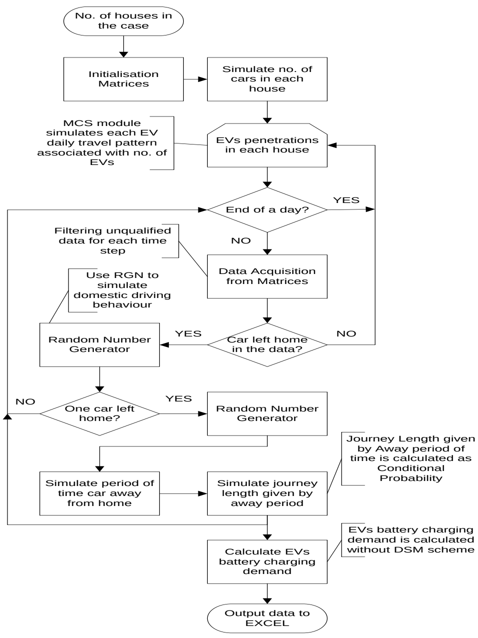

Fig. 4. Advanced model of Monte Carlo simulation structure for calculating individual electric vehicle on-board battery charging demand.

Fig. 5 gives the calculated additional PEV battery charging load as a function of time for a typical day with PEV penetrations of 10 per cent, and is shown together with a typical daily load profile for UK domestic load profile taken from UK GDS, [14].

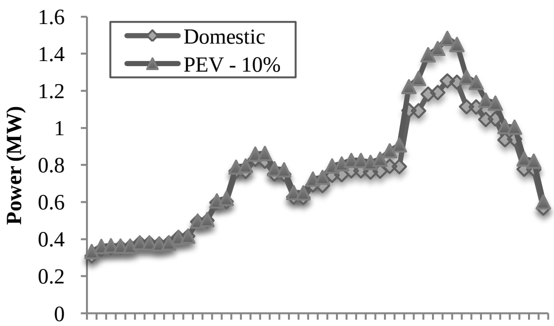

Fig. 5. Additional load due to PEV charging demand for a population of 1,262 houses with PEV take-up of 10 per cent.

CONLUSION

The probabilities of travel to/from home, period of time for driving and parking duration provide valuable information relevant to that the amount of electricity needed for charging the PEVs, whether overnight at home or at work places. These probabilities have been used to calculate the amount of energy used for moving the car and thus energy left in the on-board vehicle energy storage device. A Monte Carlo simulation methodology has been developed based on detailed data regarding vehicle use that allows an accurate forecast of the additional electricity loads placed on the distribution system for different assumed scenarios of EV take-up. Application of Monte Carlo analysis to the low voltage part a typical UK urban distribution system shows that distribution transformers, and also the associated distribution lines, will need substantial upgrading if any significant use of PEVs develops. UK Generic Distribution System (UKGDS) provides daily domestic electricity load profile, which has been used to investigate the impact of EVs battery charging with different penetrations at the substation point. Control strategies of EVs on-board battery charging has been implemented in order to prevent the additional EV charging demand overloading the power distribution system based on UK electricity tariff. Domestic owned electric vehicles have the potential to participating in power system operation as responsive demand and benefit the domestic users to minimise the charging costs.

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