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Impact Assessment of Varying Penetrations of Electric Vehicles on Low Voltage Distribution Systems

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***Abstract*—Advances in the development of electric vehicles, along with policy incentives will see a wider uptake of this technology in the transport sector in future years. However, the widespread implementation of electric vehicles could lead to adverse effects on power system networks, especially existing distribution networks. This work investigates some of the potential impacts from various levels of uncontrolled electric vehicle charging on a test distribution network. The network is examined under worst case scenario conditions for residential electricity demand in an effort to assess the full impact from electric vehicles. The results demonstrate that even for relatively modest levels of electric vehicle charging, both the voltage and thermal loading levels can exceed safe operating limits. The results also indicate the importance of assessing each phase on the network separately in order to capture the full effects of uncontrolled electric vehicle charging on the network.**

***Index Terms*—electric vehicles, load flow analysis, power distribution**

I. INTRODUCTION

ELECTRIC vehicle technology is seen by many countries as a key component in the effort to reduce harmful greenhouse gas emissions, while also reducing the dependence on imported petroleum for use by the transport sector. As a result, many automotive manufacturers have begun to place increased emphasis on the development of various types of electric vehicles (EVs). These include battery electric vehicles, which operate purely from battery power, and plug-in hybrid electric vehicles, which operate on power from a combination of an on-board battery and a combustion engine. The batteries for both types of technology can be recharged from external energy sources, e.g. an electricity network. The government in the Republic of Ireland has set out targets for reducing overall greenhouse gas emissions as well as specific targets of 10% of the Irish transport fleet to be fully electric by 2020 [1]. Similar targets and incentives have been set out in other countries also [2], [3]. Such government targets, along with the likely increase in the cost of fossil fuels over the coming years, will see EV technology become more widespread. Increasing numbers of EVs will not only have a major impact on the transport sector but also that of the energy sector, and in particular the electricity delivery networks.

The amount of electrical energy required by EVs will cause significant changes to the way in which power systems are operated. Various studies have been carried out to assess whether future power systems will have the required generating capacity and infrastructure to accept large penetrations of EVs [4]–[6]. They conclude that, for the most part, existing/planned generation capacities should be sufficient to meet the added demand from EVs. However, this may not be the case when this added demand coincides with existing peaks. This type of analysis is particularly relevant in countries that are planning to produce large amounts of their electrical energy from renewable energy sources [7]. Confining the charging of EVs to off-peak periods could see an increase in the utilisation of existing plant, although the extent to which the charging of EVs is controllable remains uncertain.

Further issues arise at the distribution level of a power system. Distribution networks are rated (kVA limit) to deliver electricity depending on the number of customers in any given area and the historical electricity demand data for each of those customers. The introduction of EVs will introduce new customer demand patterns and large penetrations could result in adverse effects on the network, in terms of exceeding current and voltage limits and increasing the likelihood of large amounts of coincident electricity demands.

Since distribution networks are, for the most part, radial, the impact of adding relatively large loads could potentially be greater than that seen on meshed networks. Investigations into the potential impact of EVs on load patterns at the distribution level of networks have been conducted since as early as the 1980s [8], [9]. More recent work in this area has sought to investigate the network limitations of large numbers of EVs on network infrastructure in terms of increased loading and loss of life for network assets [10], [11]. Other work has assessed the impacts on low voltage (LV) transformers in terms of efficiency and overloading, and concluded that large penetrations of EVs can create new peak loads from an LV transformer's point of view [12]. Coordinated charging techniques to improve losses and voltage deviations have been investigated in [13]. The work described in [14] examines the impact of EVs on distribution networks in terms of supply/demand matching, voltage deviations and power quality.

This paper investigates the extent to which EVs could impact on existing distribution networks, with a specific focus on residential LV networks. As a result of the large additional

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load that will be introduced to the network, the main issues that can be anticipated are excessive voltage drops and overloading of networks assets (e.g. power lines and transformers). The sensitivity of these impacts to changes in the point of connection of EVs is also analysed, as it is potentially a key factor in determining permissible levels of EV penetration.

Residential households are connected to the distribution system via a single phase connection. This has the knock-on effect of creating voltage and current unbalance at the 3-phase level of the network. The uncontrolled charging of EVs on a section of network could lead to levels of unbalance which exceed allowable limits. Results from initial investigations into the interdependency of network phases are outlined in this paper.

The methodology of this work is presented in Section II. Section III describes the modelling of the test network, the residential load and the electricity demand profiles of EVs. Results are presented in Section IV along with a discussion of the findings. A summary of planned future work and conclusions are presented in Section V.

II. METHODOLOGY

When assessing the limitations of a distribution system, it is normal practice to test models of the system for a worst case scenario. For LV residential distribution networks, this typically implies that the network is examined under conditions of maximum load. However, it should be noted that this may not be the case in future networks where there is a large penetration of localised micro-generation units [15]. The maximum system demand is usually determined from historical load data. The main concern from a distribution system operator's (DSO) point of view is that a network can deliver this maximum electricity demand in a safe and reliable manner. With an increase in EV charging on the network in future years, the level of electricity demand that will define a network's 'worst case scenario' will undoubtedly change significantly.

The purpose of this work is to assess the potential impact on the distribution network due to the charging of EVs. The effects of varying penetration levels of EVs connected to a network are assessed in terms of impacts on voltage levels and thermal loading. In order to perform this analysis, a model of a section of LV distribution network was built using power system analysis software [16]. Details of the model are given in Section III. Steady-state analyses were performed using unbalanced load flow calculations and the changes in voltage and thermal loading levels at various parts of the network are recorded. Details of the methods used in performing the load flow calculations can be found in [17].

III. MODELLING

A. Test Network

The test network is based on a LV residential distribution feeder in a suburban area in Dublin, Ireland. A simplified version of the feeder, as it appears in the power system software, is given in Fig. 1. In the actual test feeder each household and EV is modelled individually. The points marked A, B, C, D, Y and Z are nodes of the network at which voltage levels are recorded for the analyses, as explained further in Section IV. The model incorporates a LV substation supplying a total of 134 residential customers through 1.2 km of 3-phase copper mains cables and 980 m of single-phase copper service cables.

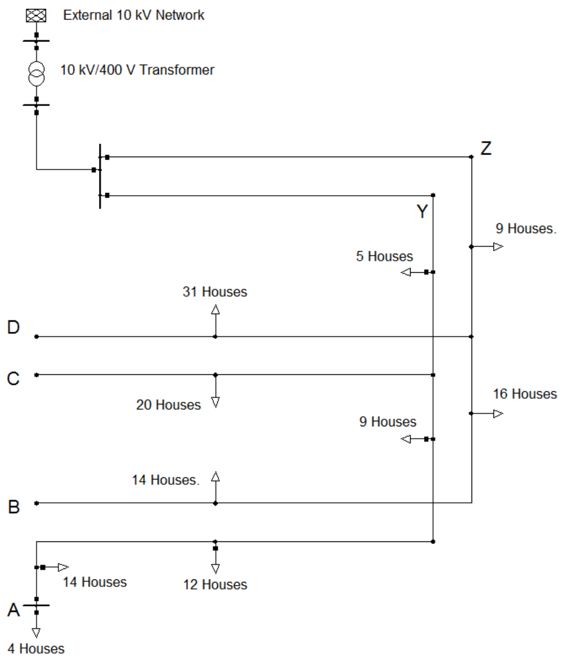

Fig. 1. Simplified single line diagram of test network

In Ireland, the LV distribution network is operated at a nominal voltage of 230/400 V with a voltage range tolerance of +/-10%. The sending voltage at the substation bus is set at +5% of nominal. For the most part, LV substation transformers in Ireland do not have tap-changing capabilities, which is the case for the transformer used in the test network. Specifications for the network model components were supplied by Electricity Supply Board (ESB) Networks, who are the DSO in the Republic of Ireland. They are responsible for the operation and maintenance of all distribution networks in the Republic of Ireland.

B. Residential Customer Load Modelling

Typical load data for domestic electricity demand customers was obtained from the DSO. It consists of 15-minute time-series demand data for high, medium and low use customers over a one year period. Different electricity demand profiles were randomly assigned to each of the houses in the test network. In order to confirm that these load profiles portrayed an accurate representation of the power demanded by a real distribution feeder, the coincidence factor, (1), of the test network was determined to ensure a realistic load diversity.

$$\text{Coincidence Factor} = \frac{\text{Max. Diversified Demand}}{\text{Max. Non-coincident Demand}} \qquad (1)$$

The maximum diversified demand is defined as the maximum of the net demand imposed by a group of loads over a certain period, while the maximum non-coincident demand of a group of loads is defined as the sum of the individual maximum demands, without the restriction that they must occur at the same time [18]. From assessing the yearly load profiles for each of the households on the network, the coincidence factor was found to be 0.32. This value compares favourably with typical coincidence factors for similar residential load networks [19].

Following the assignment of load profiles to each house in the test network, the maximum demand period for the network was determined. This was considered to be the worst case scenario of residential load demand for this network model. This assessment is restricted to times of day when there would be a higher probability of simultaneous EV charging, i.e. between the hours of 4 pm and 8 am. It was found that the maximum diversified demand on the test network under these restrictions was approximately 203 kW, while the maximum non-coincident demand was found to be 632 kW. This value for maximum diversified demand was subsequently used in each of the steady-state analyses to assess the capability of the network to accommodate EVs. Each of the houses in the test network is modelled as a constant power load with a power factor of 0.97 inductive.

C. Electric Vehicle Load Modelling

Although the possibility exists for fast, 3-phase charging, for the most part EVs charging at customer households will do so by means of a standard single-phase AC electrical socket. Therefore, it is assumed that EVs will be connected to the network at the same point of connection as the residential household. Charging profiles for EVs can vary depending on the particular technology employed: battery type, charging equipment and the electricity supply network can all affect the EV charge profile. For the purposes of this work, it was not necessary to consider the energy required by the EV batteries. Instead, The main focus here is on voltage levels and the thermal loading of network components. Therefore, only the power demand for charging EV batteries is considered. Depending on the type of charging equipment used, the level of power that can be delivered to a battery can vary considerably. A demand of 3.5 kW per vehicle is assigned as a typical EV charging power demand. This value is appropriate in terms of the power delivery capabilities of existing LV distribution networks in Ireland and also for potential EV conductive charge couplers [20]–[22]. EV batteries are assumed to be based on lithium-ion battery technology and are represented as constant current loads at unity power factor.

IV. RESULTS

Unbalanced load flow analyses are carried out at various levels of EV penetration for the worst case scenario of residential load. For each case examined, EVs are added to individual households in the network in 10% increments with respect to the total number of households. For example, at 20% penetration there are 27 households each with an EV connected. Two cases are examined for each level of penetration: case (i) locates the EVs at households which are furthest from the substation bus, while case (ii) locates the EVs at households nearest to the substation bus. Performing the analysis in this manner should display the boundaries of possible values recorded due to the point of connection for EVs to the network. Six points on the test network have been chosen in order to assess the impact on the voltage levels, marked A, B, C, D, Y and Z in Fig. 1. Four of these points are located at the end of branches where the voltage drop is likely to be greatest due to the radial nature of the network. The remaining 2 points are located at households nearest to the substation bus. Voltage levels at these points and the thermal loading levels of the substation line and feeder transformer were recorded for each test and the results are outlined below. Due to the phase imbalance that is typically present in distribution networks, both the 3-phase line voltages and the single-phase voltages are examined.

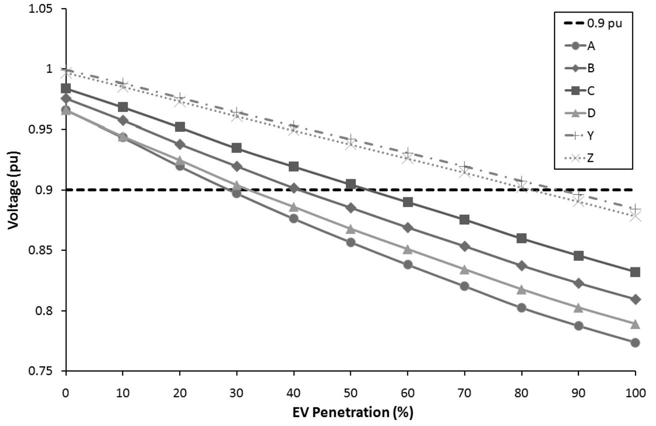

Fig. 2. Line voltages for varying levels of EV penetration

A. Impact on 3-Phase Voltage Levels

Fig. 2 shows the voltage level at the 6 points of interest for various penetrations of EVs for case (i). It can be seen that point A experiences the most severe voltage drop and reaches the lower limit of 0.9 pu at an EV penetration level of approximately 28%. Fig. 3 compares the voltage level at point A for both cases with different amounts of EVs connected to the network. For case (ii), the voltage drop is not as severe, reaching the lower acceptable limit at an EV penetration of approximately 42%.

These results indicate that, at best, for EV penetration levels greater than 42% that there will be sections of the network where the voltage level will have dropped below the acceptable limit. They also show that depending on the location of the points of connection, there can be a significant difference, i.e. 28% vs. 42%, in the amount of EVs that can safely be connected to this particular network before the voltage levels drop below safe limits.

B. Impact on Single-Phase Voltage Levels

It is highly likely that there will be a certain amount of unbalance present on a distribution network at any given time

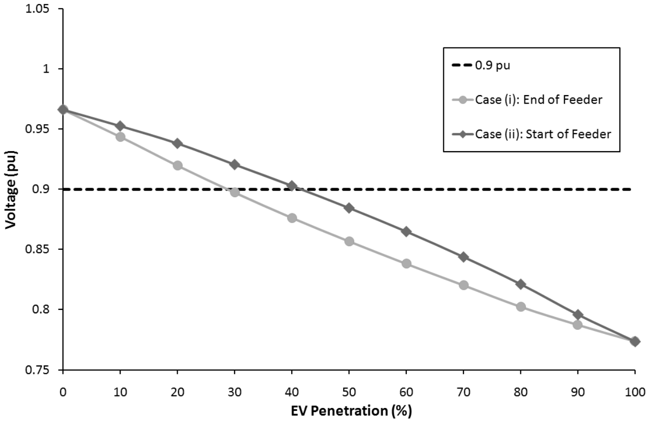

Fig. 3. Line voltages for varying levels of EV penetration at point A for cases (i) and (ii).

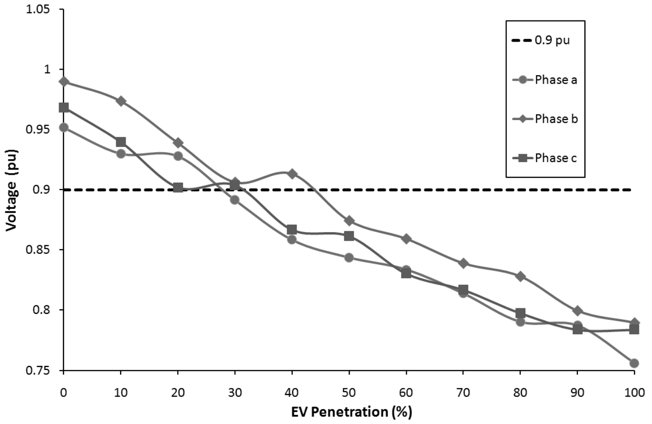

Fig. 4. Phase voltages for varying levels of EV penetrations at point A

due to the varying loads on each of the phases. Therefore, each of the phase voltages were examined separately. Measurements were recorded at the connection point for one house on each phase at the points of interest in the network. Fig. 4 compares each of the phase voltages at the most severely impacted point on the network for case (i). It can clearly be seen that the voltage level for each phase can vary greatly due to the connection of EVs to the network. The voltage recorded on phase ‘c’ reached the lower limit at an overall penetration of 20%, while the corresponding values for the ‘a’ and ‘b’ phases were 27% and 44% respectively. A different initial allocation of loads across the phases could, of course, alter the phase thresholds. While a certain portion of this unbalance can be attributed to the residential demand for each household, the results show that uncontrolled connection of EVs at single-phase points can significantly degrade this unbalance due to the additional load on the phase. It also demonstrates the need for voltage levels to be monitored at individual household connection points, as opposed to simply at the 3-phase supply level where the lower allowable limit was reached at 28%.

The characteristics shown in Fig. 4 are not smooth due to the allocation of EVs at each penetration level. The location of EVs on the feeder is chosen as a result of their geographical position and is not dependent on which phase they are connecting to. As a result, it is possible that the additional load, for each increment of EV penetration, is not spread evenly across the phases. A slight voltage rise on some of the phases is also observed at certain EV penetrations. Reasons for this occurrence are explored in Section IV-C.

C. Phase Interdependency

The level of influence that adding EVs on a particular phase can have on the other phases of a feeder was also examined. EVs were added incrementally, as before, but only to those houses connected to phase ‘a’. Voltage levels were recorded at each of the points of interest in the network. It should be noted that such a scenario is highly unlikely to occur in reality. If such a scenario were to arise, the DSO would more than likely reconfigure the network in order to spread the load as evenly as possible across the phases before such a situation could occur. These results are shown as an indicator of the extent to which excessive loading of one phase in a network can affect the other phases.

Fig. 5 compares each of the phase voltages with increasing penetration of EVs at point A, which is the most severely affected point in the network, as seen in Fig. 2. Voltage levels are only shown for penetrations up to, and including, 50% as the load flow calculations fail to converge for higher levels. While phase ‘a’ experiences a much greater voltage drop than in the previous tests, phases ‘b’ and ‘c’ experience a voltage rise. This effect can be attributed to the way in which the loads are represented and the unbalance present in the network. The household loads are represented as purely constant power loads, which is unlikely to be the case in reality. A more realistic representation of the loads would be to model them as a mixture of constant power and constant impedance.

In order to investigate the importance of the residential load modelling, the test was performed again with household loads modelled as constant impedances. Fig. 6 shows a comparison of the voltages of the 3 phases at point A for varying EV penetration levels. There is a similar impact on the voltage levels, as in the previous test, although the scale of the effect is not as great. For the case where the households are modelled as constant power loads, the lower allowable voltage limit is exceeded at a penetration level of approximately 13%, whereas for the case with constant impedance loads the penetration level is approximately 25%. It can also be seen that the voltage rise experienced on the remaining phases is not as severe in the constant impedance case as it is in the constant power case. This suggests that the load composition is a significant factor in determining acceptable EV penetration levels and that load modelling should form part of any EV study.

D. Thermal Loading of Network Components

The thermal loading of certain parts of the test feeder were recorded for the same residential load conditions as applied in the previous tests. Both the transformer and the line connecting the substation busbar to the first terminal along the feeder were examined, as these were anticipated to be the network components which would experience the highest loading levels. Fig. 7 shows that the thermal loading

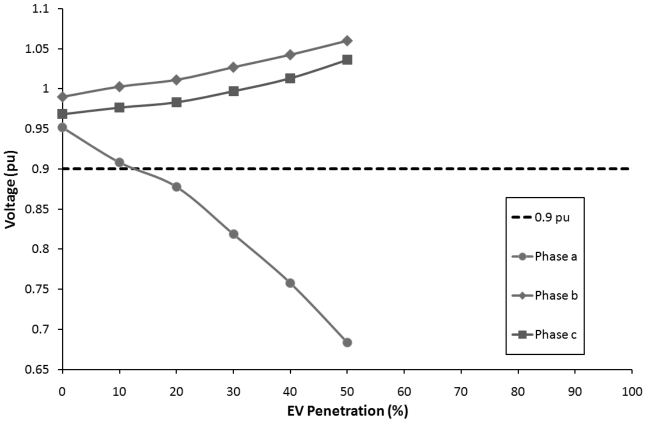

Fig. 5. Phase voltages at point A for varying levels of EV penetrations applied to phase a only. Household loads are modelled as constant power loads

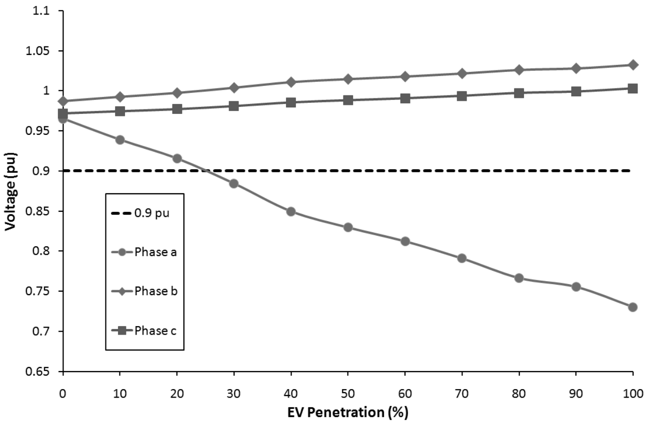

Fig. 6. Phase voltages at point A for varying levels of EV penetrations applied to phase a only. Household loads are modelled as constant impedance loads

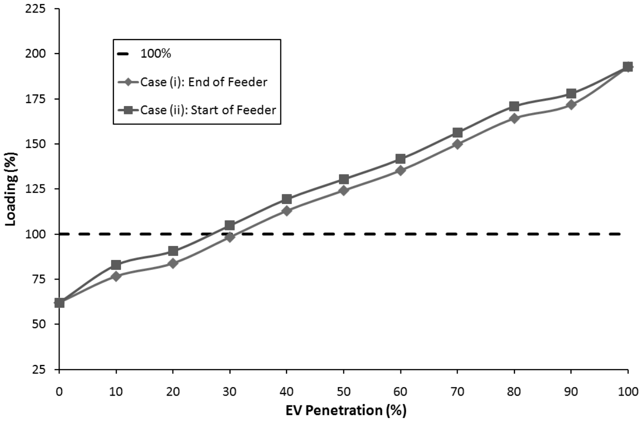

Fig. 7. Thermal loading of feeder transformer for varying levels of EV penetrations

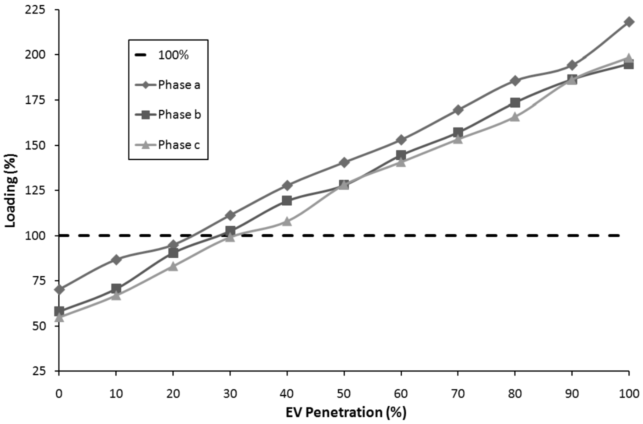

Fig. 8. Thermal loading on each phase of substation line for varying levels of EV penetrations

of the transformer reaches 100% of its rated value with an EV penetration of approximately 25%. Similarly, Fig. 8 shows for the same conditions the loading of each of the phases of the substation line. The individual phases exceed their rated loading capability for EV network penetrations of approximately 23-30%, indicating that the thermal loading of network components must also be considered as a barrier to the number of EVs that can charge simultaneously on a particular network. As discussed in Section IV-B, the characteristics shown in both of these figures are not smooth due to the manner in which the EVs are allocated to the feeder.

V. CONCLUSION AND FUTURE WORK

This paper presents an analysis of some of the potential impacts on existing distribution networks from EV charging. For this particular test network, it has been shown that for a 20-40% penetration of EVs, the test network reached the limits of safe operation. In such a situation, DSOs would be forced to curtail the delivery of electricity to EVs in order to maintain secure and reliable network operations. The work has also highlighted the significance of the location of the connection points of EVs to the network in terms of voltage impacts. It has also been shown that due to the unbalanced characteristics of a distribution system, it is important to analyse each phase separately in order to capture the most extreme effects on voltage and thermal loading levels.

Given the variability in the physical and technical characteristics of distribution systems, the level of EV penetration attainable for any particular network could vary greatly. The findings of this work serve as indicative results for a typical suburban LV distribution feeder. Future work will develop models representative of rural networks, where it is anticipated that voltage drop will be more significant due to the longer lengths of lines and greater distances between loads.

This analysis is performed for a worst case scenario of maximum residential load, with the network impacts dependent on the amount and type of residential demand on the feeder. With the introduction of EVs, the scale of coincident charging and the location of the points of connection of the EVs also become significant factors. In order to fully investigate the effects of EV charging, the energy demanded from the batteries must also be incorporated into the analysis. The analysis of such temporal aspects requires a time-series assessment of the test network, incorporating such variables as time of connection and battery state of charge for individual EVs.

With the implementation of advanced metering devices in households, charging of EVs could potentially be controlled remotely, and it will be critical to explore various techniques for implementing such strategies. They could allow DSOs to employ some form of control capability, which would allow large numbers of EVs to connect to the distribution system simultaneously. There are a number of potential benefits that could be achieved from the use of such technology. Along side maintaining safe operation of the system, control of EV charging would allow DSOs to maximise network utilisation while reducing the need for costly network upgrades.

The development of optimisation techniques for the charging of EVs will also be explored in future work. Along with the network issues described in this paper, it is intended that these techniques will incorporate other aspects of the power system such as system operations, reserve requirements and wind variability.

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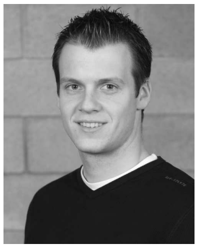

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