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A Modelling Tool to Investigate the Effect of Electric Vehicle Charging on Low Voltage Networks

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Abstract

The market for electric vehicles (EV) is currently limited, but this is expected to grow rapidly with the increased advances in technology, particularly battery technology. Due to their high energy capacity and potential mass deployment, EVs will have significant impact on power networks. This paper presents a novel, user-friendly modelling tool which uses universally accepted, mathematically robust software to allow analysis of the effects of typical loads, microgeneration and EV charging on the distribution network, mainly the low voltage (LV) feeders, 11/0.4 kV substation and also part of the 11 kV section. Network asset ratings, voltage limits and thermal overloads are determined over a 24 hour period. The model allows the user to input any number of houses, schools, shops, microgeneration and EV charging posts which may be connected at each 400 V node. The EV charging post is modelled using pre-set connection times, battery capacity and battery state of charge (SOC). The effects of different EV battery charging scenarios on the LV network are investigated and presented in this paper. Comparison of different charging regimes demonstrates the effectiveness of the modelling tool and gives guidance for the design of EV charging infrastructure as more drivers choose EVs for their travelling needs.

Keywords: EV battery, smart charging, LV distribution network, power quality

1. Introduction

In order to meet carbon reduction targets agreed by EU countries for 2050, it is recognised that 90% of transport will need to be electrified [1]. Thus, electrical power distribution networks need to be able to meet the anticipated demand for EV charging as the use of EVs increases. There are issues for the Distribution Network Operator (DNO) if EV charging is allowed to take place without any control on time of day, duration or charging rate [2]. Specifically, the network voltage may fall below prescribed limits at times of peak demand and power flows may cause thermal overload of assets. Some restrictions to EV charging may be needed in order to avoid these issues, including delayed domestic charging (until after the evening peak), controlling the number and location of charging posts and restricting fast charging.

The battery in an EV may also be used for storage. Storing electricity in batteries at the distribution level is considered too expensive [3], but the capital cost is avoided by using EV batteries when the vehicle is connected. This can have implications on the network performance and battery state of health (SOH) [2]. Therefore, there is a need for a modelling tool to allow evaluation of the network performance for different operational scenarios in the presence of low carbon technologies expected to be connected in future power networks [4]. Existing modelling tools employ professional and mostly academic software, e.g. Matlab/Simulink, or commercial software, unique and exclusive to the company which require the user to have specialized knowledge, access and skills.

The proposed modelling tool, described in section 2, is designed to be used by those who wish to analyse the implications of different load profiles and employs universally accepted commercial software (Excel). It allows the user to input the type of network topology from a range so as to create a bespoke section of network, on which to overlay domestic loads, domestic generation and EV charging. The domestic loads follow a typical winter and summer daily load profile for domestic customers in the UK, as shown in Fig. 1 [2]. This profile is based on DNOs After Diversity Maximum Demand (ADMD) referenced to a nominal 100 consumers and measured at the 11/0.4 kV distribution substation on an outgoing feeder. Heat pumps can be added along with typical load scenarios for light industry, schools and shops which might be found on a LV network.

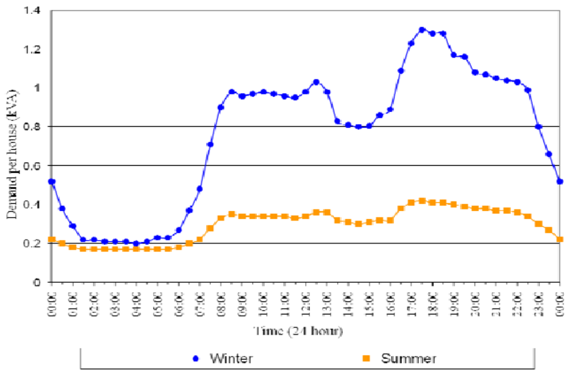

Figure 1: ADMD profile [2]

The proposed tool allows modelling of EV charging at two different domestic charging rates (3 kW and 7 kW) at any home and also allows the introduction of fast charging (23 kW) at each node and super-fast charging at the 11/0.4 kV substation. The tool also allows the user to specify when the EV is needed next and how much charge is required for the next trip. Accordingly the tool performs analysis using these charging scenarios ensuring that enough energy is available for unanticipated journeys (including emergencies). Details of the proposed modelling tool are given in section 2. Typical results are described in section 3 and conclusions are given in section 4.

2. The Modelling Tool

The modelling tool allows changes to the network topology, load and generation profiles on a section of the low voltage (LV) network [5]. The values for each part of the model can be varied to see the effect on network performance. The network includes an 11/0.4 kV transformer supplying several feeders; one feeder is modelled in detail (with variable cable size/ material and lengths which can be defined by the user), as shown in Fig. 2. At each node it is possible to specify the number of houses, together with shops, schools and/or light industry. The ADMD summer or winter domestic load profile for the UK are used along with typical loads for the shops, light industry and schools which can be attached to any node.

Renewable distributed generation (DG) consisting of photovoltaic panels (PV), wind turbines or micro combined heat and power units (μCHP) can be added and each generation profile is based on typical seasonal weather data for the UK.[6] Predicted values for micro-generation for 2020 or 2050 can be chosen or the user can input their own mix. Electric vehicle charging can be added at different charging rates, start times and staggered charging to support the network. One standard 50 kW fast charger has been added at the transformer substation and street chargers (23 kW) may be added at each node together with the option of a slow domestic charger (3 kW or 7 kW) for each home. The input page of the modelling tool, showing the network model and input variables is shown in Fig. 3.

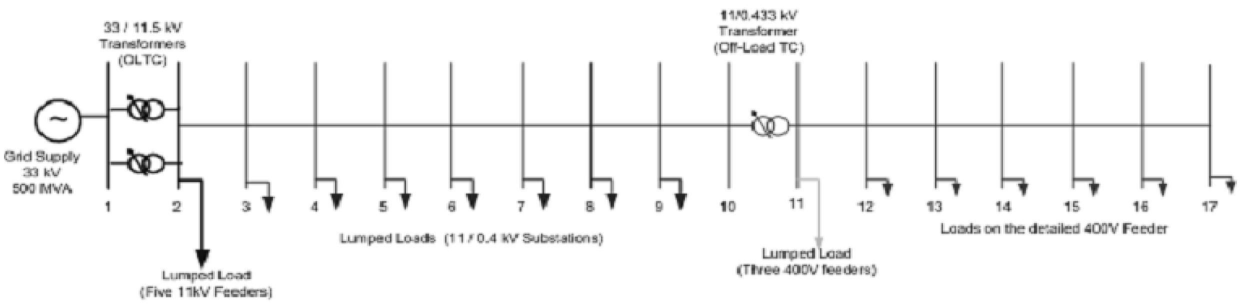

Figure 2: typical network outline [2]

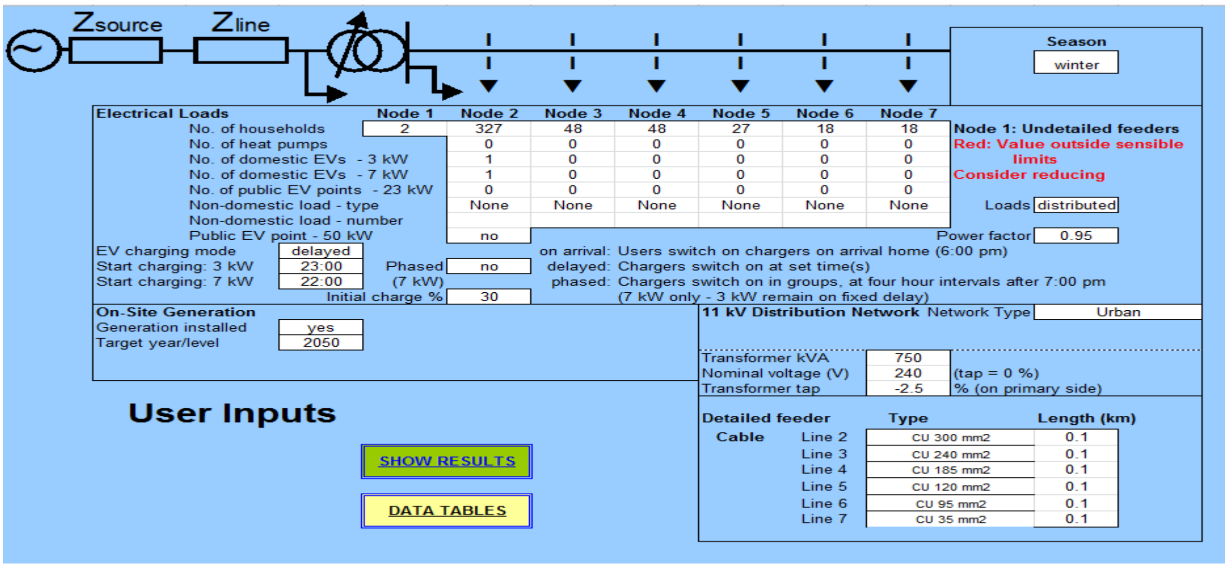

Figure 3: Outline of user input page

The modelling tool uses the load and on-site generation values to calculate the node voltage, cable currents (and thus thermal limits) and transformer power flow based on 24 hour load and generation profiles. The results are calculated and are displayed in graphical form, as shown in Figure 4. Any issues regarding specific network parameters exceeding the statutory limits are highlighted on the results page in red. The dotted lines on the graphs represent the limits for each parameter in per unit.

It is then possible to vary the inputs to the model to identify the factors that can cause problems and how they can be alleviated. For instance, the tool will highlight a cable at a node which is overloaded and will need to be upgraded, it will identify whether a transformer can accommodate the required power flow for the inputted scenario by comparing the required power flow with the rating. It can identify at what times of day the node voltage drops below the statutory limits and needs support, such as changing the tap on the transformer.

The opportunities for the use of this tool are numerous, so this paper will present examples pertaining to EV use, showing the problems caused by EV charging on the LV network and offering some solutions.

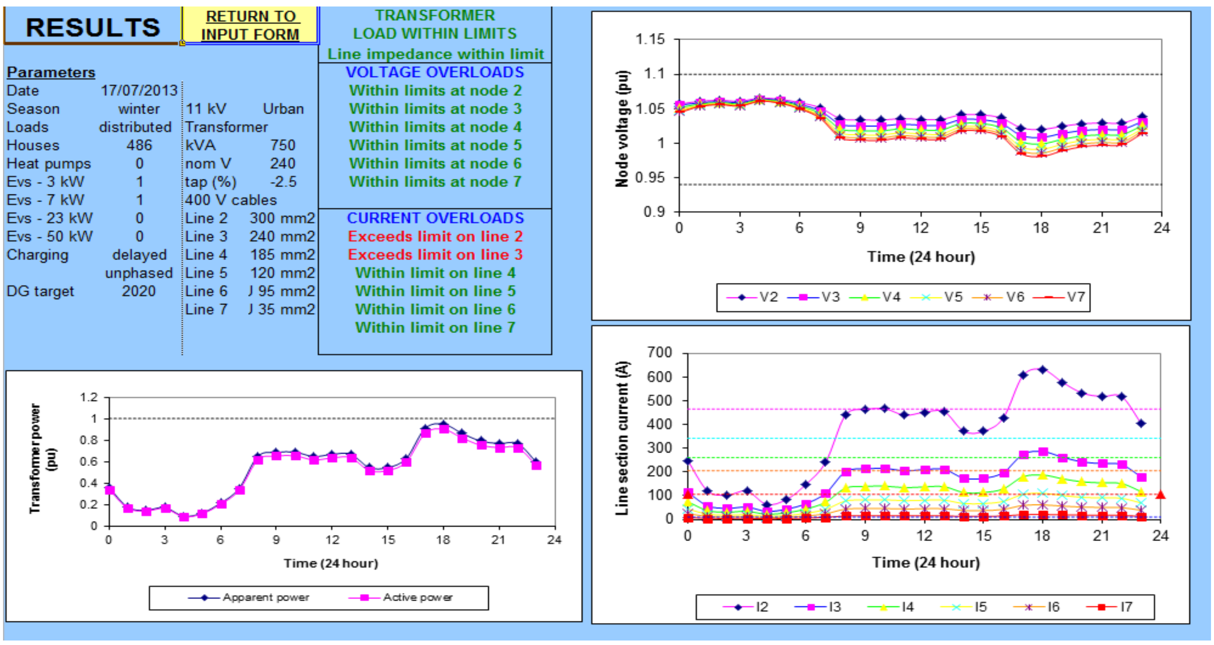

Figure 4: outline of results page showing graphs of power flow, node voltage and node currents

3. Results and Discussion

3.1 20% low carbon homes

In this scenario an urban network is used with corresponding cable and transformer ratings. It is envisaged that 20% of homes will have some type of DG and 20% will have heat pumps. This would be in line with carbon cutting targets as homes move away from fossil fuels for heating. [4]

3.1.1 No EVs

This scenario is used as a base case, when homes have 20% DG and heat pumps, but no EV charging.

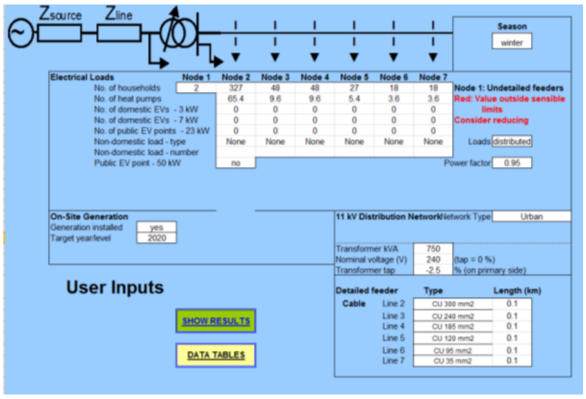

Figure 5: Standard urban network with 20% renewables including heat pumps - no EVs

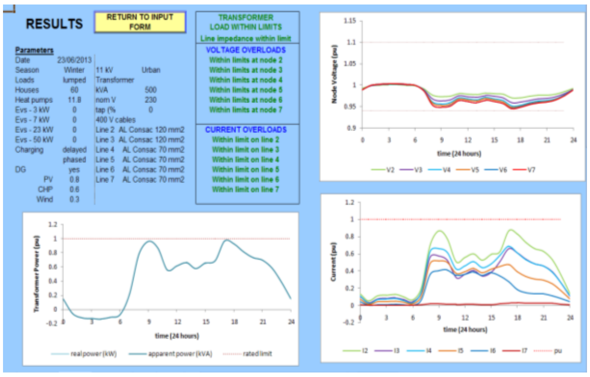

Figure 6: Results of power flow, voltage and current.

It can be seen from Fig. 6 that the power flow stays just within limits, voltage is at the lower end of the limit and currents stay within thermal limits of the feeders.

3.1.2 20% EVs

If 20% of EVs are added which are allowed to charge at 3 kW at any time; research shows that most will be plugged in to charge on return from the evening commute [7]. This is inputted as 06.00 pm into the model and the results are shown in Fig. 7.

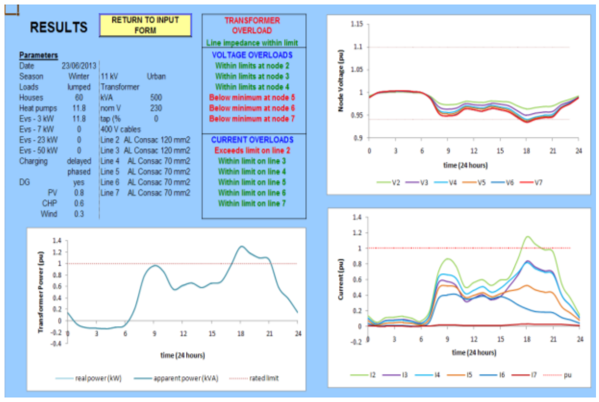

Figure 7: 20% EVS on 3 kW charging at 6.0 pm

In Fig. 7, the results page shows the transformer, and node 1 cable have exceeded their rating and voltage has dropped below the statutory minimum of 0.94 pu at nodes 5, 6, & 7. Note that voltage tends to decrease at nodes further from the transformer and currents are at the maximum near the transformer where the cables are designed to have a larger rating.

In order to accommodate 20% of EVs without controlling charging times, it would be necessary to replace the transformer with a larger one. The power flow can be seen to drop below zero in the early hours and this reflects power flowing back into the grid from renewables when demand is low; the transformer needs to accommodate this. In addition the transformer must have the ability to tap change the voltage to rectify the voltage issues due to charging. The cable nearest the transformer also needs upgrading to a larger rating.

All these upgrades carry a significant cost, so the DNO might look to control EV charging to offset or delay asset upgrades.

3.1.3 Delayed charging

One way of avoiding asset upgrade would be to delay all EV charging to start at midnight. Fig. 8 shows the results when using the Nissan LEAF as an example. [8]

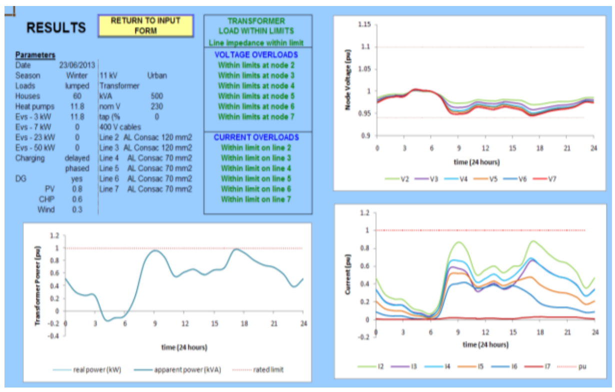

Figure 8: delay charging to midnight

In Fig. 8, all the values are within limits, although the power flow is reversed in the early morning.

Most, but not all transformers can cope with two way power flow and any subsequent voltage issues further into the network. Thus it can be seen that a relatively simple measure such as fixing the start of charging to a set time can alleviate most issues.

3.1.4 40% EVs

In Fig. 9 the number of EVs has increased to 40%, with half being charged at 7 kW. If charging is delayed until 10.00 pm (which is after the domestic evening peak demand), then there is a network issue at that time.

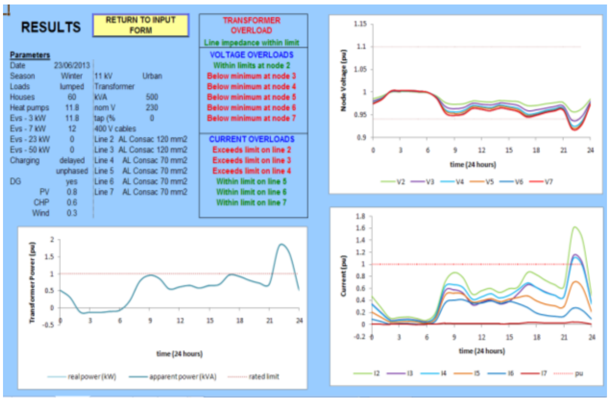

Figure 9: 20% EVs on 3 kW and 20% on 7 kW, all with charging start time of 10.00 pm

This shows that fixed time charging at off peak is not a solution when the percentage penetration of EVs becomes higher. At this point staggered charging becomes necessary. Deilami and Singh [10, 11] developed a real-time charging controller which effectively shifts the EV charging time to smooth the EV charging load profiles.

3.2 Fast charging

The tool has an option of allowing charging at 23 kW at every node and 50 kW at the transformer busbar. These scenarios show the effect on the network of these two types of fast charging. The fast charging is overlaid on the 20% phased charging scenario.

3.2.1 23 kW fast charging at each node

The tool allows one 23 kW charger at each node. The time of the charge can be any time of day, but in order to highlight the issues, the results shown are for 06.00 pm charging start time.

3.2.1.1 23 kW charging at node 1

One EV using the 23 kW charger at node 1 is simulated in the tool and the results are shown in Fig. 10. This scenario has the effect of causing transformer overload and also shows that the cable (line 1) which supplies the charging current will exceed thermal limits.

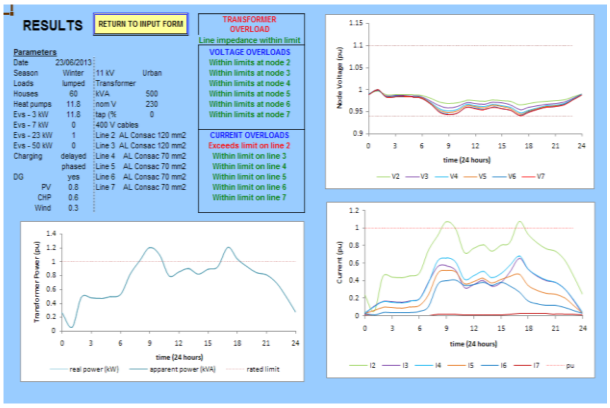

Figure 10: One 23 kW charger in use at node 1

3.2.1.2 23 kW charger at node 6

Fig. 11 demonstrates the additional effect on the LV network if the 23 kW charger is placed at node 6. The impedance of the cables to node 6 is known to reduce the voltage at successive nodes, so the likelihood of the voltage falling below regulatory limits is increased as the power flows further from the transformer.

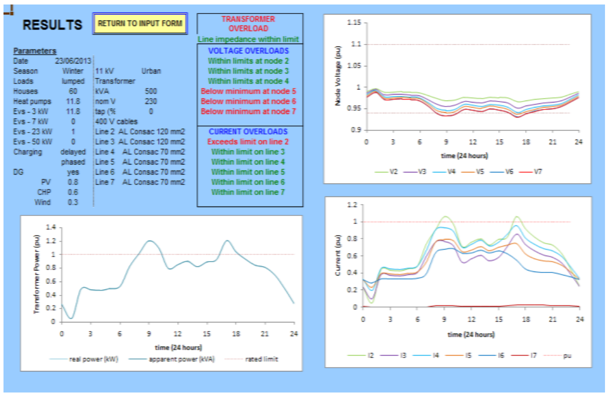

Figure 11: One 23 kW charger in use at node 6

3.2.1.3 20% 23 kW charging at each node

This scenario is shown in Fig. 12. The power flow is increased as there are more EVs, but the voltage and current issues are similar to 1 EV charging at

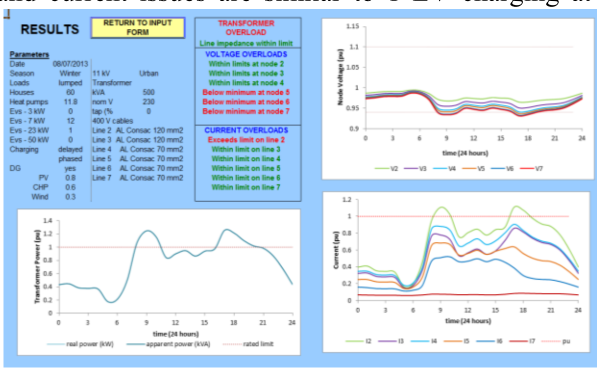

Figure 5: 20% EV charging at every node

node 5.

Table 1: The power quality issues as they vary with node position of 23 kW charger

Position of fast charger	Power quality issues		
node	Transformer power flow	Thermal cable current	Voltage limit violated
0	0.959	0.866	0.945
1	1.201	1.077	0.940
2	1.201	1.071	0.937
3	1.201	1.068	0.934
4	1.201	1.066	0.933
5	1.201	1.064	0.930
6	1.201	1.062	0.924
all	1.254	1.109	0.931

An analysis of the power quality issues of one 23kW charger being used at any node shows that there is no effect on power flow at the transformer, but the thermal currents increase and the voltage decreases as the charger is placed nearer the end of the feeder. The results can be seen in table 1.

3.2.2 50 kW fast charging

As expected, the effect on the LV network is increased if the 50 kW fast charger is used. The 50 kW charger is not likely to be used all the time, but the network needs the capacity to allow its use regardless of the other demands upon it if it is to have the confidence of the EV user.

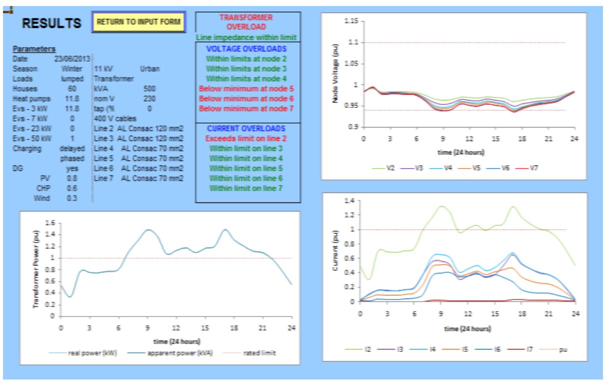

Figure 13: effect of 50kW fast charger

These results show clearly what upgrades need to be made to the network in order to install fast chargers. It is clear which cables need upgrading, under what percentage of EV chargers and their ratings would trigger a replacement of the transformer with a higher power rating and when the tap changer on the transformer needs moving to increase voltage.

4. Conclusions

A user-friendly modelling tool is described in this paper. The tool uses universally accepted, mathematically robust software (Excel) to allow analysis of the effects of typical loads, microgeneration and EV charging on the distribution network.

Depending on the strength of the network, adding EV charging posts on the low voltage network is shown to increase the likelihood of power quality issues occurring. These issues are identified as the power rating of transformers being exceeded, the thermal rating of LV feeders being exceeded, and violating regulatory statutory voltage limits. Since the UK is experiencing a need for more housing and average domestic load is increasing, [2] this is an increasing problem for the DNOs. In addition, carbon cutting targets are encouraging the electrification of domestic heating and transport. [4] All these changes increase the demand on the network.

This model demonstrates that uncontrolled charging increases the likelihood of thermal limits and voltage limits being exceeded. It shows that asset upgrade of transformers will be needed sooner as EV penetration increases. In addition, a simplistic measure like timed charging for a fixed time of day is shown to cause problems for the network at that time, regardless of the domestic demand, if EV penetration is high. Delaying daily slow EV charging until after the evening peak or connecting fast chargers only at nodes close to the transformer is shown to alleviate the problem. Staggering the charging start time gives the best results for network health. This demonstrates that the concept of smart charging, which allows charging only if the network is not stressed will become essential if EVs become ubiquitous. [9]

Fast charging is shown to exacerbate the network problems, indicating which cables will need to be upgraded to prevent thermal overload. It also causes excessive voltage drop, particularly if chargers are used at the end of the feeder.

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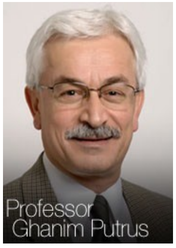

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