A Modelling Tool for Distribution Networks to Demonstrate Smart Grid Solutions

Bentley E.[1], Putrus G., Lacey G.
Northumbria University, Newcastle upon Tyne, UK
[1] Corresponding author edward.bentley@northumbria.ac.uk

***Abstract* — The increased deployment of low carbon technologies in power distribution networks, particularly at the distribution level, is expected to cause significant problems to network operation unless existing networks are appropriately adapted and actively controlled as part of a smart grid. This paper describes the development of a modelling tool to examine Smart Grid solutions to a number of issues affecting low voltage power distribution networks. Use of the tool in the context of transformer overload, line overvoltage, active load control, Grid storage and Black Start analysis is examined.**

Keywords—Power system modelling; excel; Smart Grids; electric vehicles, simulation

I. INTRODUCTION

Increasing concern over the effects of the climate change resulting from increasing global demand for energy and the persistent reliance on fossil fuels has led world leaders to set a target of a 50% reduction of greenhouse gas emission by 2050 (the UK has an even more ambitious target, . 80%). In the UK, the contribution to CO_2 emissions from the surface transport sector is some 21% of the total, leading to recognition of the need to electrify transport to allow the UK to meet its 2050 emission targets [1]. Once the transport sector becomes largely electrified, it will be possible to use the energy storage capability of the Electric Vehicles (EVs) employed to mitigate problems arising or anticipated within the national power grid and local distribution systems, as well as to provide storage to optimise the use of renewable energy sources (RES). Examination of this potential using a modelling tool forms the subject of this paper.

A. Electric Vehicles and Power Networks

A range of electric vehicles is already on the market, chiefly comprising Plug-in Hybrid Electric Vehicles (PHEV) and small fully rechargeable Electric Vehicles (EVs), the latter are usually powered by Lithium ion batteries with a capacity of a few tens of kWh [2]. At present the market for EVs is limited, in view of their high price and limited range, but the market is expected to grow with rises in the price of petrol and advances in battery technology which will result in EV price reduction that will make the EV option more attractive. Uncontrolled charging of EVs can cause problems for the electric power network due to the associated heavy electrical demand during charging [3]. However, EVs are able to support the grid if their charging schedule is managed appropriately [3, 4]. EV batteries have considerable energy storage capacity and controlled charging can allow a schedule whereby they can be charged at a time when the grid has surplus capacity, discharged when the grid has a shortfall in capacity in order to meet peak demands and provide a storage facility for supply/demand matching. Large enough numbers of EV batteries can be used to effectively balance the network frequency, 'shave' peak demand and provide emergency power in case of generation failure, in the concepts known as "Grid to Vehicle" (G2V) and "Vehicle to Grid" (V2G). As to whether a national power system is able to support large numbers of EVs, Taylor et al. [5] found that if 90% of Australia's peak annual generating capacity is available during off-peak periods, there would be enough energy available within the system to provide charging for EVs to make all existing urban passenger vehicle trips. However, while the supply-demand matching for a region as a whole might be adequate to allow the use of sufficient numbers of charging points to support the EVs there may be an impact on specific parts of the distribution system, particularly at the Low Voltage (LV) level. Local distribution substations and feeders for different areas may not be strong enough to handle the increased load created by EV charging. This problem may be analysed using the modelling tool described to demonstrate the effects of time delayed or phased charging (G2V) [3].

Assuming that charging may be supported, a very inviting prospect would open once sufficient EVs become available, sources of Renewable Energy such as wind and PV being by their nature intermittent. At present fossil fuelled back up generation must be provided to take the place of renewable generation when it ceases to be available. However with sufficient EV storage capacity connected to the Grid, the batteries could be charged when there is a surplus of renewable generation, and discharged when there is a shortfall. A further problem arises when renewable energy takes the form of Distributed Generation (DG). In the case when renewables output is high and the demand for energy is low in a particular area, reverse power flow and line over-voltages may arise, giving Power Quality problems for the distribution network [6, 7]. Here again EVs may assist, since their charging time may be arranged to occur when there is a surplus of DG.

The above factors imply that rather than being a problem, large scale adoption of EVs will allow a much greater incorporation of renewable sources of generation into the grid than would be possible without their energy storage, given the very high costs of alternative means of energy storage, minimizing CO_2 emissions in the process. Work is being carried out on EV battery design, construction and charging/discharging regimes to render the programme economic [4].

B. Smart Grids

Traditionally, power systems evolved to comprise a relatively few large generating plants linked together by a high voltage transmission system supplying power to consumers nationwide via medium and low voltage distribution networks. Such a system is relatively easy to control, and system failures are nowadays very rare. The need to reduce CO_2 emissions leads naturally to generation from very large numbers of dispersed small scale generators, since the energy density of renewable sources of energy is low compared to that of fossil fuels and Nuclear power. As a result central control of the system to ensure that power supply and demand always balance, and that statutory voltage limits are complied with becomes very complex. The solution now is the 'Smart Grid', which has attracted significant interest worldwide. The European Technology Platform for the Electricity Networks of the Future – SmartGrids (established in 2005) has defined this concept as "an electricity network that can intelligently integrate the actions of all users connected to it - generators, consumers and those that do both - in order to efficiently deliver sustainable, economic and secure electricity supplies" [8]. The future Smart Grid will automatically and reliably route electricity from wherever it happens to be produced to wherever it is required whilst controlling variables such as line voltage, frequency and power flow, while adapting to cope with uncontrolled variations in power generation from renewables. Achieving this will require two way communication links between generators and consumers, and use of artificial intelligence techniques.

II. THE MODELLING TOOL

Software packages to analyse the impacts of EVs on power networks are commercially available, however these are usually expensive and designed for general use, so time consuming and difficult to adapt for a targeted study. Therefore, the proposed modelling tool was developed using the universally available low cost EXCEL software, able to evaluate the impacts of EVs and other low carbon technologies on LV networks with variable load profiles [1]. The accuracy of the model was verified by comparison of results for a network based upon an actual area in the North East of England with those obtained for the same network modelled using commercial software, such as MATLAB/Simulink and ERACS. The principle of the new tool was to develop a mathematical model of a single phase potential divider circuit, with loads represented by complex shunt impedances, and lines by complex series impedances. This would then represent a 3-phase balanced system. Sources of generation are dealt with as negative loads. A schematic diagram of the network model is shown in Fig (1). The tool was designed to give the capability of modelling either distributed or lumped loads. To make the tool generally applicable, the user can vary the cable length and type (electrical characteristics, for instance resistance /reactance per unit length), the number of sections of each type of cable, the source impedance at the 11 kV or 400 V supply point (which can be obtained from the fault level data) and the transformer rating. At each node it is possible to specify the number of houses, together with shops, schools and/or light industrial plants. Ordinary domestic loads are based upon the After Diversity Maximum Demand (ADMD) summer and winter household load profiles shown in Fig. (2) [7]. The number of houses at each system node is set by the user. Typical loads are used for shops, light industry and schools which can be attached to any node. Heat pumps may also be allocated to each node.

Renewable distributed generation (DG) consisting of photovoltaic panels (PV), wind turbines or micro combined heat and power units (µCHP) can be added. Each generation profile is based on typical weather data for the UK [9]. Targets for micro-generation for 2020 or 2050 can be chosen or the user can input any mix.

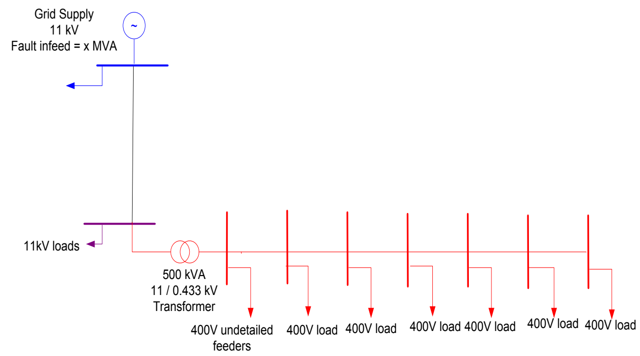

Figure 1 Low voltage distribution network with 11 kV feeder

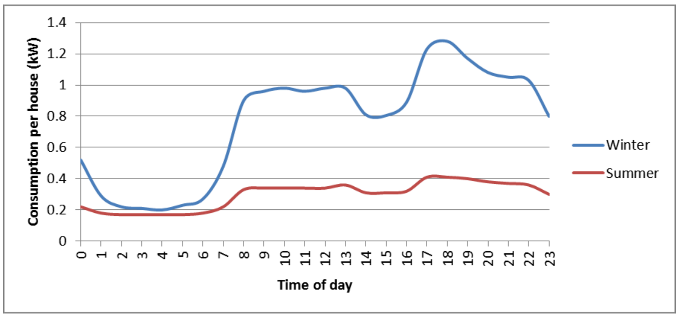

Figure 2 After Diversity Maximum Demand load profile per house for Winter and Summer

Fig. 3 shows the data input page of the modelling tool, set up in its base position with solely domestic loads, no renewables, EVs or heat pumps being present. Fig. 4 shows the results page, where graphs of the transformer power flow, line currents and node voltages are shown for a 24 hour period. This page indicates that the basic network is adequate for the purpose, there being no transformer or line current overload, node voltages all being within permitted tolerances.

Figure 3 The Data Input Page of the Tool

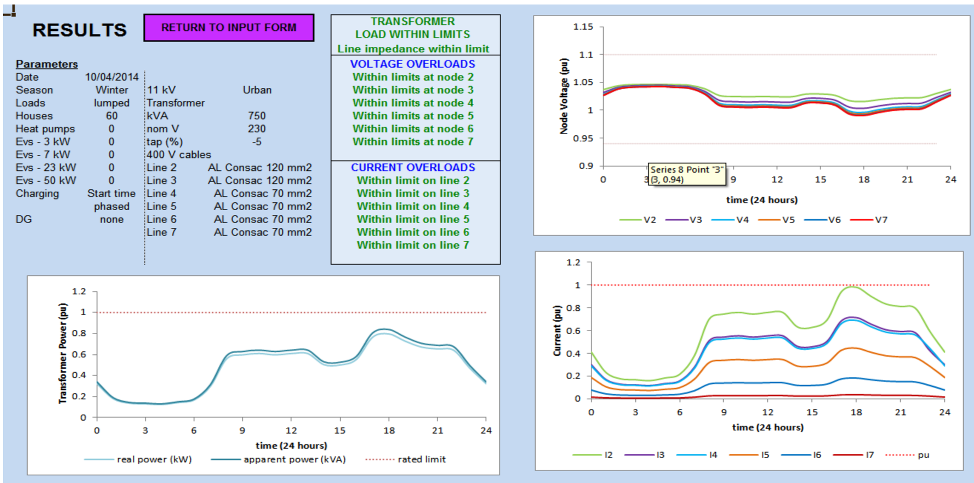

Figure 4 Results Page of Tool

III. Results and Discussion

Smart Grid solutions to network problems involve an 'intelligent' use of elements present on the network to correct network problems.

A. Dealing with transformer overload due to uncontrolled charging

Fig. 5 shows the effect of uncontrolled EV charging, using 7 kW home chargers, on the network with differing levels of EV adoption, assuming that most EVs would be plugged in to charge at about 6.0 p.m., on their owners' return from work [10]. As shown in Fig. 5, a serious transformer overload results around 18.00 hours. The problem may be avoided by arranging for 2/3 of the EVs to be connected in the V2G mode, discharging power into the grid upon connection at 18.00 hours, and recharging between 03.00 and 06.00, as shown in Fig. 6. For this process to happen a degree of central control is required – here one sees an example of Smart Grid operation in practice. The individual EV users would be unlikely to arrange to connect their EVs in the right numbers at the right time without Smart control.

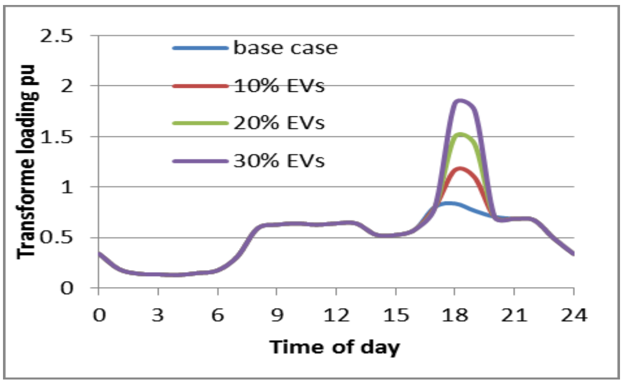

Figure 5 Transformer loading for uncontrolled EV Charging

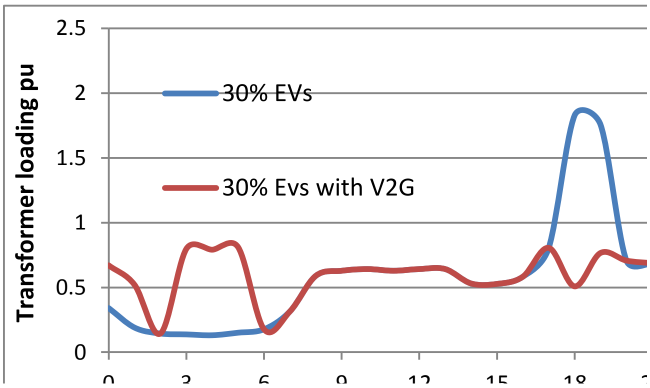

Figure 6 V2G to avoid transformer overload

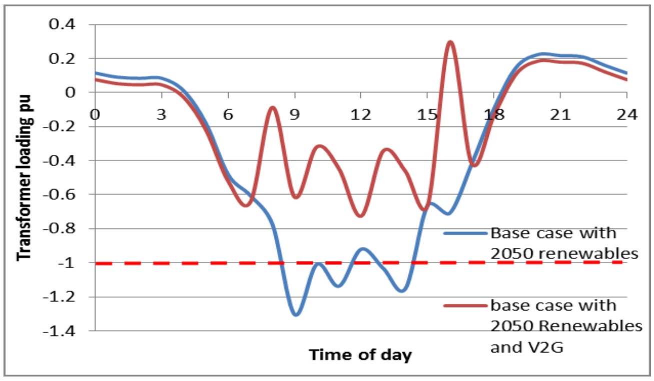

Figure 8 Transformer overload caused by excess DG and its mitigation using V2G techniques

B. *Avoiding voltage rise on lines due to effects of renewables*

In summer when the load on the system is light, but with a significant degree of DG, one experiences unacceptable levels of voltage rise at various point on the local network, especially at node positions far from the transformer. Fig. 7 shows the effects of a 2050 level of DG on the line voltages, and the solution of the problem using Smart techniques. These comprise phased charging (G2V) and appropriately timed V2G, such that power is absorbed during the period of overvoltage between 10.00 a.m. and 2.0 p.m., and discharged when load increases at 6.00 p.m.

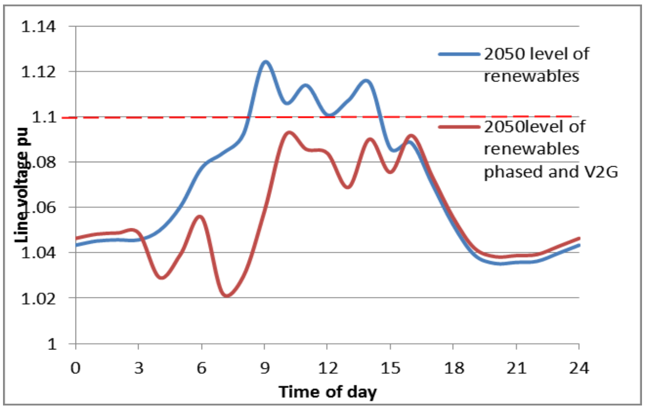

Figure 7 Line overvoltage removed with V2G and phased charging.

C. *Avoiding transformer overload caused by oversupply of Renewables*

The amount of Renewable DG expected to be produced per house on a 2050 level is such that the 11kV/400V transformer may be overloaded due to the amount of reverse power flow taking place in the middle of the day. Fig. 8 shows this effect, and the mitigation of the problem using smart techniques involving V2G to arrange for the connected EVs to draw power during the period of excess supply, and release it when there is adequate load on the network to accept it, at 16.00 onwards.

D. *V2G as active load control*

The tool has the capability to treat the modelled EV batteries as energy stores. The model is able to measure the size of the EV battery storage capacity at each node, and then calculate the degree to which the power flow through the transformer differs from the average value. The EV batteries then either absorb or supply energy to equalize the load curve; this is a more sophisticated application of a smart technique. Fig. 9 shows the effects of differing numbers of EV batteries (0%, 50% and 100%) connected to a network incorporating 2050 levels of Renewable DG and their equalizing effect on the voltage at the far end of the network from the transformer.

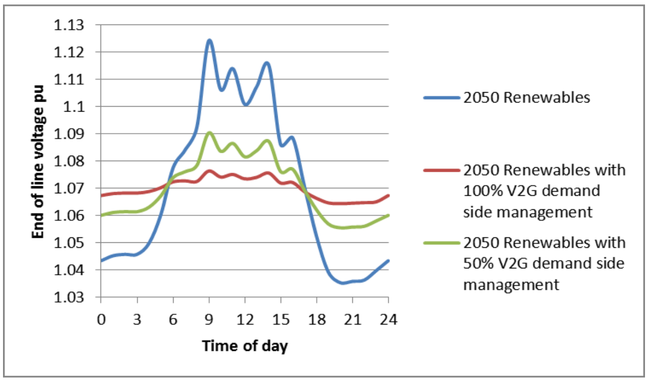

Figure 9 2050 Renewables (Summer) showing stabilizing effect of active load control

E. *Grid storage and Black Start*

Given the capability of the EV batteries to store relatively large quantities of electricity, one may use the model to carry out 'Black Start' analysis. In this situation the amount of power capable of being drawn from the total number of EV batteries modelled on the system is compared to the demand for power set by the load schedule. A graph may then be produced showing the times of day when the EV batteries have sufficient power output capacity to supply the network total load. One may then determine when a 'Black Start' would be possible. Fig. 10 shows the results of running a

‘Black Start’ analysis with 100% of houses having an EV the households being split with 50% having 3 kW chargers and 50% having 7 kW units. Two plots are shown, one demonstrating the possibility of a ‘Black Start’ when the EVs are connected to the system with 20% State of Charge (SOC), the other when the EVs are connected with an 80% SOC, giving a longer window of opportunity.

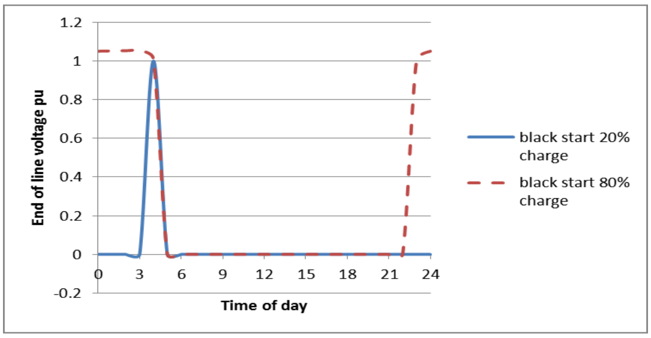

Figure 10 ‘Black Start’ analysis for 20% and 80% initial SOC

Presently, some DG has to be switched off when demand is low and generation is high because the effect on the network is unacceptable. Optimising renewables on the network is possible if the generation which would overload the transformer, cause reverse flow greater than rated or unacceptable voltage rise is stored to be used at another time when the demand is greater and the generation is less. This can be done at a house by house level as shown, but grid storage at the transformer is a more effective method of control as it allows for diversity and can accommodate some lumped generation such as a medium wind turbine. Figure 11 shows the effect of 500kWh of storage at the transformer which corresponds to some 26 second life EV batteries installed.

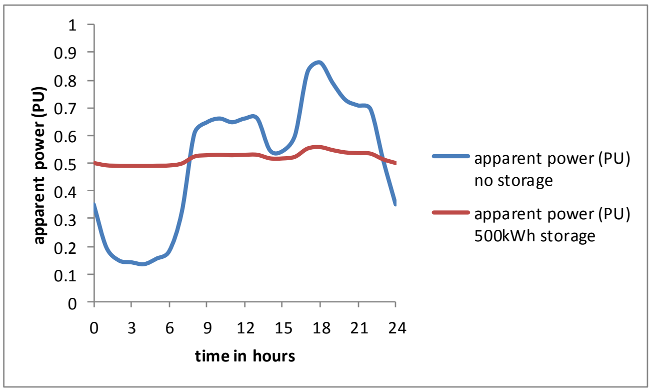

Figure 11: power flow at transformer with and without 500kWh storage

IV. CONCLUSIONS

A new user friendly modelling tool has been developed using universally accepted mathematical modelling, which may readily and accurately be used to investigate the effects of low carbon technologies on LV power networks. A number of scenarios related to the intelligent operation of a Smart Grid may also be investigated. Smart Grid solutions to problems of transformer overload caused by uncontrolled charging and heavy use of renewable DG are investigated, as are the use of the tool to model Smart measures, V2G and active load control to mitigate line overvoltage under conditions of high renewable DG. Finally the use of the tool to investigate ‘Black Start’ scenarios is examined.

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