The impact of plug-in electric vehicles on distribution networks

by G Brand and J Roesch, NETGroup SA

The current market penetration of plug-in electric vehicles (PEVs) is limited. However, the market for PEVs is expected to grow rapidly with increased concern about the environment, advances in technology and, as electricity is one of the least expensive transportation fuels, the cost of energy [1].

Due to the high energy capacity of PEVs, significant deployment will potentially introduce substantial demands on power distribution networks. This paper suggests a model for the inclusion of PEV loads in long range (15 – 25 years) spatial demand forecasts and tests the impact of the introduction of PEVs on the metropolitan distribution network of eThekwini. As a result a view is obtained on the extent to which capacity of existing and planned plant will be affected in a typical urban network within the South African context under various PEV market penetration scenarios. This is an area of significant interest to a number of stakeholders – from PEV fabricators and distributors through to the electricity supply industry that will in effect fuel these vehicles.

Study objective

A major question faced by electric distribution utilities is whether the current and currently planned network will cope with the introduction of PEVs and what network reinforcement will be required.

The objective of this study is to utilise an existing long range (20 years) load forecast that was created in the absence of recognition of PEV load contributions and to apply a PEV load forecast model to this forecast. Baseline forecast results are then compared to baseline plus PEV forecast results to assess the impact on existing and planned network capacity.

PEV forecast model

A PEV load forecast model differs somewhat from conventional forecast models in that it is significantly influenced by changes in both consumer adoption as well as technology shifts.

Variables that influence the proposed PEV model are:

- PEV market penetration
- Vehicle efficiency
- Current and forecasted charge capacity of batteries
- Current and forecasted charging rates of batteries and residential chargers
- Distances travelled by PEVs (utilisation behaviour)
- Consumer charging behaviour (time of day)
- Home charging vs. charge at office vs. public parking charging vs. top-up-and-go charging stations.

Vehicle efficiency

For the purpose of this study an efficiency of 5.44 km/kWh (similar to the Nissan Leaf) [3] is assumed for all electric vehicles throughout the study.

Charge capacity forecast

Over the next five to ten years, battery and electric drive train components are expected to improve significantly. Between 2017 and 2020, with expected technology advances (primarily in batteries), PEVs can be expected to become mainstream [1].

When comparing battery technology the two most important factors to consider are energy density and cost. In today’s automotive market, technology is continuously improving and it can be expected that batteries will continue to become smaller (Wh/L) and lighter (Wh/kg). Based on the chemistry used, theoretical maximums indicate potential ceiling values of the various chemistries.

Evident from Fig. 1 is that technologies...
like lead acid, Ni-Cad and Ni-MH have already reached maturity and that additional advances aren’t expected. Currently, Li-ion and Li-polymer hold the most promise for energy density increases in the next couple of years. What can also be seen is that the established technologies can potentially reach a maximum density of 300 Wh/kg. Emerging technologies are expected to breach the 300 Wh/kg barrier.

Historic energy density (Wh/kg) data for Li-ion batteries shows that density has increased at an average rate of 6% during the last 20 years while costs have come down [2]. Applying the same rate of increase, established technology will continue to improve over the next ten years until the theoretical ceilings are reached (see Fig. 2).

Assuming that today’s emerging battery technologies will become mainstream contenders and will be ready for use when the 300 Wh/kg ceiling is reached, future energy density can be between 420 and 520 Wh/kg when extrapolating the data using linear and exponential methods. The implication is that PEVs of the near future will be able to travel between 2.6 and 3.2 times further than today.

**PEV utilisation behaviour**

For the metropolitan study area under consideration, an average daily commute of 50 km per day is applied which is consistent with US-based commuter studies or metropolitan areas [1].

For all years of the study a travel distance distribution density peak at 50 km is assumed (see Fig. 3), but deviation is gradually increased towards year 20 of the forecast to simulate extended vehicle use due to increased battery capacity and charging rates (see Fig. 4).

These are admittedly rather clumsy assumptions and research and survey data in this area could improve forecast accuracy.

**Charging profile**

This paper assumes a linear charging characteristic for residential charging equipment.

The current study is limited in assuming that all charging will take place at home. The
Two home charging scenarios are considered – uncontrolled charging and time-of-use charging.

Uncontrolled charging

Uncontrolled charging assumes that PEV owners plug in and recharge their vehicles as soon as they arrive home and the vehicles remain connected until fully charged (see Fig. 5 for average home arrival times).

Applying current and forecast recharge requirements (kWh), transfer capability (kVA) and battery capacities to the home arrival time profile expected after diversity, average load profiles can be inferred. Year by year the profiles differ in magnitude and shape due to extended traveling distances (from higher capacity batteries) and improved charge transfer technology and rates (the study assumes that domestic charge currents grow from 20 A in base year to 125 A in 2029).

For the uncontrolled scenario charging profiles peak at 1.4 kVA per vehicle in base year and 4.55 kVA in year 20 of the forecast (see Fig. 6).

Time of use tariff charging

The time of use (ToU) charging scenario assumes that PEV owners will be on a residential time of use tariff with an off-peak window commencing at 22h00 and that the majority of vehicles will start charging during this window. In the ToU charging scenario, 80% of vehicles would start charging as soon as off-peak rates start applying, while the remaining 20% would still charge in an uncontrolled manner. This creates a significant peak effect on the off-peak ToU commencement interval. This peak is

Table 1: EPRI scenarios.

<table>
<thead>
<tr>
<th>Voltage</th>
<th>Number of substations</th>
<th>EPRI medium</th>
<th>EPRI high</th>
</tr>
</thead>
<tbody>
<tr>
<td>275 kV</td>
<td>8</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>132 kV</td>
<td>100</td>
<td>7</td>
<td>22</td>
</tr>
<tr>
<td>33 kV</td>
<td>45</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>153</td>
<td>8</td>
<td>23</td>
</tr>
</tbody>
</table>
Baseline scenario: Demand is forecast based on the most likely scenario of the 2009/2010 eThekwini master plan load forecast. The current study assumes that this forecast is still valid and provides a reasonable view on expected load levels and planned network capacity and configuration.

EPRI medium scenario: Baseline forecast plus effect of medium scenario of EPRI PEV market penetration forecast [3].

EPRI high scenario: Baseline forecast plus effect of high scenario of EPRI PEV market penetration forecast [3].

Study area

The selected study area is based on the load forecast study area of a 2009/2010 eThekwini Metropolitan Municipality electrical distribution network master plan (utilised with the kind permission of eThekwini). The forecast period of this study was 2009 – 2029. The study area covers an area of about 70 by 40 km down the KwaZulu-Natal coast around the city of Durban, South Africa (see Fig. 9). Current and forecast vehicle populations for the study area were obtained from a 2011 transportation study of the eThekwini Transport Authority [4] (see Figs. 10 – 13).

Forecast results

The impact of uncontrolled charging on the total network load is limited within the span of the study period. A 7% and 14% increase is obtained from the EPRI medium and EPRI high scenarios respectively.

Despite the demand spike introduced by ToU behaviour, the ToU scenario has no impact on the baseline forecast until 2027 when the EPRI high scenario starts increasing total supply requirements substantially. This would suggest that in the short to medium term, residential time of use tariffs may be sufficient to control PEV demand.

Impact on distribution substations

The study area is supplied by 153 substations where the primary side voltages range between 33 and 275 kV. Evaluating the 23 substations where firm capacity is not maintained reveals that for the EPRI medium PEV scenario, eight substations exist where firm capacity is exceeded. This figure rises to 23 substations in the EPRI high scenario (see Table 1).

In only four of the substations the additional PEV load growth is substantial enough to require a revision of the current proposed network expansion plan (see Fig. 15). In the uncontrolled load forecast the additional PEV load added doesn’t cause any of the substations’ installed capacity to be exceeded.

Impact on medium voltage network

In the uncontrolled scenario, significant impact on the peak demand can be seen on many MV distribution load zones from 2020 onwards. Of concern is the observation that, in these cases, the saturation load of the load zone is often exceeded by 20 – 40% towards the end of the study period as illustrated in the example zone in Figs. 16 and 17.

However, as pointed out in Fig. 18, ample opportunity exists for the utility to shift PEV overnight charging load to the valleys in a controlled charging environment. This would probably require separate charging connections together with utilisation of smart meters to control the load.

In the ToU scenario the impact of PEV load is much more pronounced and manifests as a peak at a much earlier stage than is seen at total network level (see Figs. 19 and 20). This leads us to question the viability of residential time of use tariffs to control PEV load at an MV level.

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**Fig. 20: ToU MV load 2029 profile sample.**

**PEV saturation load**

It should be noted that the current study only addresses a 20-year forecast window. It is clear that by year 20 the PEV loads have not reached saturation in any of the forecast scenarios. While the impact of PEVs on the study area’s network appears manageable over 20 years, cognisance should be taken of the fact that it is primarily limited by a 10 to 18% penetration level as shown in Fig. 8. The EPRI PEV market penetration forecast appears to be in the “innovator” dominated stage of a Bass model [5]. With maturing of technology and imitators entering the market the rate of adoption is expected to increase.

Whether electric vehicles will achieve a 100% adoption level might be debateable, but a 40 year view will yield substantially higher PEV demand forecasts than a 20 year view.

**Conclusion**

The impact of supplying additional PEV loads over the next 20 years seems negotiable at distribution network substation level where the utility currently has a long term master plan in place to cater for normal load growth. This is partly due to the fact that PEV penetration levels are expected to increase slowly – only 4% expected during the next 10 years. Between year 10 and 20 we do, however, see a 14% increase and it is during this time that loading levels at certain substations become problematic.

Design criteria for electrical equipment and associated networks are based on standard equipment sizes when planning leading to substation capacity expansion in discrete blocks. This coarse granularity helps to limit the number of substations where the network expansion and strengthening plan need to be revised in order to accommodate the new growth.

On the other hand, results from this study indicate that the effect of PEV loads at MV network level poses a serious risk to constrained networks where limited spare capacity is available. In addition, clustering could result in higher-than-average adoption concentrations in small supply areas, further exacerbating the effect on MV network capacity.

From the difference observed between the uncontrolled charging scenario and time of use charging scenario at a total system level it appears that the time of use tariff option offers benefits to the utility to increase its load factor during the short to medium term without impacting on total demand. But this benefit is negated when the PEV charging load, driven by technology improvements and increased levels of PEV adoption, increases to become the new utility system peak.

The benefit of time of use charging at MV level attenuates sooner than at total network level as MV circuits are saturated and overloaded much earlier in the forecast. For these reasons there is merit to consider controlled charging options by means of smart metering solutions paired with smart tariffs over a time of use approach.

The ability of distribution utilities to meet charging requirements in a financially sustainable manner might be dependent on the extent to which customer adoption is going to be clustered and how utilities adapt service offerings to provide intelligent charging offerings on acceptable timing and cost terms [6].

Residential design ADMD values and expected consumer consumption profile changes will need to be re-evaluated where significant PEV penetration is to be expected.

**References**


Contact Gustav Brand, NetGroup SA, Tel 012 345-6005, g.brand@netgroup.co.za