AN INVESTIGATION INTO THE IMPACT OF ELECTRIC VEHICLE LOAD ON THE ELECTRIC UTILITY DISTRIBUTION SYSTEM

S. Rahman
Senior Member

G.B. Shrestha
Member

Bradley Department of Electrical Engineering
Virginia Polytechnic Institute & State University
Blacksburg, VA 24061
EMAIL: SRAHMAN @VTVM1.CC.VT.EDU

ABSTRACT

The electric utility's interest in electric vehicles lies in the anticipated/expected benefits beyond the simple increase in energy sales. It is expected that the EV load will be contained within system off-peak hours without affecting the peak demand, thus increasing the sale of low cost electricity. However, the impact of electric vehicle charging on the energy and power demand is determined not only by the number of EV's in use and their usage pattern, but also by the number of EV's being charged at an instant and the charging profile of the battery module. The daily energy consumption by an EV will be limited by the range/cycle and the charging time, while its impact on the system demand will depend on the hour and pattern of charging. The case studies in this paper have revealed several important issues which can potentially reduce the freedom to shift the charging loads completely to off-peak hours. These details cannot be captured in a system wide analysis. Therefore, the classical modification of system load curves to derive the maximum benefit, as adopted by Montedonico et al. [2], may not be realized. These optimistic approaches simply assume EV load to conveniently fill the valley in the system load curve without regard to localized effects. Such assumptions have to be substantiated with adequate analysis at the distribution level where EV loads may show up in an uneven manner.

Moreover, there is considerable uncertainty regarding future penetration of EV's and their charging energy requirements. It would be difficult to employ the traditional methods of forecasting for this purpose, since no historical data exists regarding the likely number of EV's and their electricity consumption profiles. The emphasis in this paper is to investigate the likely impacts the EV charging load will have on the distribution level. The nature of these impacts, and ways to address them properly for the best results, will also be studied.

1.0 INTRODUCTION

Increasing environmental concerns, the consequent regulatory requirements, and the geo-politics of oil have made the fuel independent electric vehicle (EV), with low and controlled emissions, increasingly more attractive as practical and economical alternative to the conventional gasoline car. The present state of EV's and the current developmental activities in this field are summarized by Moore in a recent paper [1]. The key issue of adequate battery system for EV's to compete with the range and performance of conventional cars remains to be fully addressed. While the recent cooperation among automakers (e.g., the formation of US Advanced Battery Consortium) is expected to produce advanced EV batteries, the support of electric utilities will be essential in developing appropriate infrastructure standards and technology to make EV's attractive to the consumer.

It is expected that the EV load will be contained within system off-peak hours without affecting the peak demand. From the electric utility operation aspect, this potential to fill the valley in the load curve will result in more electricity sales for the same system capacity. This implies more effective utilization of all equipment in the system, thus potentially reducing the per unit cost of electricity.

However, such system wide expectations may not be easy to achieve. The authors believe that it would be necessary to study the impact of EV's on the system operation at substation level. Such micro level analysis is important in the context of EV's for several reasons.

1. First, the EV charging load cannot grow uniformly in the whole utility service area. Significant growth can only be expected in certain areas. For example, they are more likely to develop in residential areas, but not so much in commercial or industrial centers. This can result in significant overloads on certain distribution systems, even though the utility system as a whole may have sufficient or excess capacity at any instant of time. Secondly, battery modules require certain charging characteristics which can potentially reduce the freedom to shift the charging loads completely to off-peak hours. These details cannot be captured in a system wide analysis. Therefore, the classical modification of system load curves to derive the maximum benefit, as adopted by Montedonico et al. [2], may not be realized. These optimistic approaches simply assume EV load to conveniently fill the valley in the system load curve without regard to localized effects. Such assumptions have to be substantiated with adequate analysis at the distribution level where EV loads may show up in an uneven manner.

Moreover, there is considerable uncertainty regarding future penetration of EV's and their charging energy requirements. It would be difficult to employ the traditional methods of forecasting for this purpose, since no historical data exists regarding the likely number of EV's and their electricity consumption profiles. The emphasis in this paper is to investigate the likely impacts the EV charging load will have on the distribution level. The nature of these impacts, and ways to address them properly for the best results, will also be studied.

2.0 OBJECTIVE

The auto industry is ready to produce their first electric vehicles on a commercial basis in the near future [1]. However, the success of this venture remains uncertain with respect to the extent of its acceptance by the public, and their pattern of usage. Precise estimates of these factors are hardly possible. The penetration level will depend on the suitability of EV characteristics to local conditions. For example, Hawaii is expected to provide a natural setting for EV's because of: (a) lack of traditional fuel sources, (b) abundance of renewable energy sources, and (c) relatively limited driving range requirements [4]. Similarly, the energy demand of an individual EV will be determined by: (a) the driving habits of the user, and (b) the state of technology of EV (including the battery system). A method to utilize expert opinions to estimate these factors and combine them to forecast the EV charging load has been presented in [3].

The daily energy consumption by an EV will be limited by the range/cycle and the charging time, while its impact on the system demand will depend on the hour and pattern of charging. Though it would be logical to do the charging only during the off-peak hours so as to fill up the valley in the load curve, it may not always be feasible. This paper investigates the likely causes of these limitations and evaluates the impacts on the distribution system.

1. First, the charging load cannot be expected to develop uniformly in proportion to the capacity of the distribution system. Some locations such as residential areas will have to provide the most of the charging load, while commercial and industrial sections of the utility service area may be slightly affected.

2. The second limitation arises due to the charging characteristics of the battery module. Better battery modules with high energy density (Wh/kg), and better charge/discharge characteristics are being developed [5]. While short charging times are desirable for quick recharging, present design considerations call for low current overcharge with longer charging times to prevent the drop in battery capacity and life.

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3. Finally, the driving habits and the charging preferences remain very uncertain. At present, the driving habits and the gas filling preferences of the public have little effect on the fuel supply system. With limited driving range per charge, and fixed desirable charging hours (non-peak hours), these aspects will be significant in terms of their impact on the distribution system.

The purpose of this paper is to analyze these issues, and to evaluate the likely impacts of the introduction of EV's on the existing distribution system. Specifically, we will study the impact of EV load in terms of:

a. The time of the peak load;

b. The size of the peak load;

c. The shape of the load curve;

d. The total energy sales; and

e. System load characteristics (e.g. the load factor).

We will use hourly load data for a college town and superimpose reasonable forecasted EV charging load on them. In the process, we will develop charging profile of an individual battery module and the charging preferences of the public by properly distributing the starting time of battery charging throughout the possible/likely charging hours. This town has distinct residential and commercial/academic area loads served by different distribution substations. Separate sets of load data are available for these individual substations, which will be used to study the differential impacts at the distribution level as outlined in item (1) above.

3.0 ANALYSIS OF THE IMPACT OF EV CHARGING ON THE SYSTEM

The analysis presented in this paper is based on the current state of EV's, EV battery modules and their recharging systems. The background necessary for the case studies discussed in the next section is presented here.

3.1 The System Load Data

This study uses data from the town of Blacksburg in Virginia with distinct campus and residential sector. Load profile of the campus area is like that of the commercial sector. The 15-minute load data is available separately for the residential area, and the total area including the campus. This is utilized to study the impacts of EV load on these two different distribution systems.

3.2 EV Penetration Levels

Rahman and Shrestha [3] have presented a method to assess EV penetration levels for specific niche markets using expert opinions. This was done by separately estimating the likely number of EV's and their likely daily energy requirements. Traditional techniques of forecasting are not useful for this purpose because of (a) lack of any historical data, and (b) considerable uncertainty regarding the future of EV's. The demand will depend on the future course followed by many factors such as (i) technical developments regarding the kinds of vehicles and their important components like the battery module, energy storage etc., (ii) market conditions and public acceptance, (iii) production schedule and other related infrastructure, (iv) battery charging profile, (v) availability of charging facilities, and (vi) impact on the existing distribution system. Therefore, it becomes imperative that we study the likely paths of developments related to EV, and establish a set of likely scenarios of EV load. When major trends are underway, experts in the field generally have reasonable estimates on such developments, even though they cannot provide scientific data in absolute terms which can be used in the forecasting models currently in use. A comparative analysis of these estimates (expert judgments) regarding different scenarios can be carried out to estimate reasonable values of the EV load. Details about the technique to utilize expert judgments to forecast point estimates and confidence limits have been presented in Rahman and Shrestha [3]. The emphasis in this paper is to evaluate the impacts of reasonable levels of EV penetration on the distribution system.

For an assumed daily driving range of 50 miles and an energy consumption of 0.6 kWh/mile, daily energy requirement of an EV comes out to be 30 kWh [4]. The study area consists of about 5700 households. The EV energy demand used in this study for 10 % and 20 % penetration levels are as shown in Table 1.

<table>
<thead>
<tr>
<th>EV penetration level</th>
<th>10%</th>
<th>20%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of EVs</td>
<td>570</td>
<td>1140</td>
</tr>
<tr>
<td>Daily consumption per EV</td>
<td>30 kWh</td>
<td>30 kWh</td>
</tr>
<tr>
<td>Total EV energy requirement</td>
<td>17 MWh</td>
<td>34 MWh</td>
</tr>
</tbody>
</table>

3.3 Battery Modules and Rechargers

Batteries have been the key limiting technology for EV's. The recent cooperation among auto companies is directed at producing advanced battery systems for EV's. Similarly, many aspects of rechargers and recharging facilities are still under development. The data and parameters used in this study are representative of the current state of knowledge and technology in this respect.

3.3.1 Recharging Cycle: This study will adopt the most likely charging cycle on the basis of current technology and knowledge. One prime requirement of EV battery is to provide rapid and efficient charging. The charging process must be simple and without any potential damage to the battery or the consumer. Therefore, automatically regulated systems avoiding over currents at the beginning and overvoltages towards the end of charging (such as the Spiegel control [5]) would be the most likely features. The power drawn by a recharger with these characteristics can be represented by a charging cycle shown in Figure 1. It shows a total charging period of 8 hours. The first two hours show controlled constant charging followed by two hours of tapered charge. This results from decreasing charging current due to rising battery voltage. The last four hours are assumed to draw 25 % of total energy which represents slow charging after the battery attains normal voltage level.

With specifications for the charging cycle of Figure 1, the temporal variation of the charging load per unit of recharging energy can be specified by the constants,

\[ a = \frac{0.625}{2} \quad b = 0.125 \]

3.3.2 EV Charging Load: The profile of charging load depends on the EV penetration level, the pattern of charging, and the charging cycle of the EV's. The charging profile used in this study conforms to the following specifications.

![Figure 1. Typical Charging Cycle for EV Battery Modules](image-url)
a. The charging will be performed completely within the overnight off-peak hours of 8 PM to 8 AM. The pattern of charging will conform to the requirements that: (i) the charging cannot start until the peak hour is over, and (ii) no charging should start if the charging cycle cannot be completed by the off-peak hours.

b. Three charging models conforming to these conditions are considered. The resulting load profiles are shown in Figure 2. The step charging load assumes that recharging of all the EV's start at the beginning of the off-peak hour. The interval charging load profile is based on sequential application of equal EV load at an interval of 2 hours. The uniform charging load profile is based on a steady and continuous application of EV load over the possible hours.

c. These charging load profiles, shown in Figure 2, represent the EV load at different hours of charging for a unit of charging energy. The step load profile is simply the charging cycle of the recharger. The interval load profile is obtained by super-imposing three charging cycles beginning at 8 PM, 10 PM and midnight, and then normalizing it. The uniform charging load profile is analytically derived from the charging cycle. The method and other details are given in Appendix A.

4.0 CASE STUDIES AND OBSERVATIONS

The framework and the criteria developed in section 3 are used to perform specific case studies. Several notable impacts on the system are observed.

4.1 Case Studies

The estimated charging loads for 10% and 20% EV penetration levels under three loading assumptions are computed by multiplying the charging load profiles of Figure 2 with the respective total EV energy requirements shown in Table 1. These loads are superimposed on the present system load for the residential area as well as for the whole town (including the campus). Figures 3(a) and 3(b) show the addition of charging load (for 10% penetration level) to the total and residential loads respectively. It appears from Figure 3(a) that this addition of charging load is comfortably absorbed by the whole system without any adverse effect under any of the three charging models. In fact, the addition appears to improve the performance since it helps to fill up some portion of the off-peak valley without increasing the peak load.

However, if we consider the residential load separately, it is clear from Figure 3(b) that the new peak with step charging model is higher than the natural peak without the charging load. Since the residential area is served by its own distribution system, it may require upgrading to supply the additional charging load. Thus, EV load, even at a low penetration level of 10%, may not be absorbed without any adverse effect on the distribution system, if applied indiscriminately. However, it is clear from Figure 3(b) that the new residential peak including charging load can be maintained within the present peak just by adopting interval loading or uniform loading models. This suggests the need to devise and provide proper incentives to achieve distributed charging during the off-peak hours, even at low levels of EV penetration.

Effects of EV load at 10% penetration level are shown in Table 2. It shows the peak load, peak hour, energy sales, and the load factor for the system without EV load and with various loading models for EV charging. The load factor for the total area load shows consistent improvement. In the case of the residential load area, however, there is no significant load factor improvement for step charging.

It is to be noted here that the load shape used in this paper has a 9:00 AM peak load. This is offered as a best case to support the EV charging load as this load is over well before the 8:00 AM peak occurs. If, on the other hand, a winter load shape with an evening peak is considered, the effect of the battery charging load will cause more severe impacts on the distribution system with respect to hardware capacity limitations. In other words, the EV charging related problems can be more severe than what is shown here.
Figure 4(a) and 4(b) represent a similar analysis with 20% EV penetration level. Figure 4(a) shows that the step charging load will result in a significantly higher new peak. At the residential level, shown in Figure 4(b), even the uniform level of charging produces loads of near peak magnitude. Thus, this system cannot absorb EV loads above 20% penetration level without exceeding the natural peak load under any charging model. Without strict control over temporal distribution of EV charging, the new peak may be considerably higher for 20% penetration level, as indicated by the peak load under step loading model. Effects on the peak load, peak hour, energy sales, and the load factor for the system without EV load, and with various loading models for 20% EV penetration, are shown in Table 3.

![Figure 4(a). Total Area Load with EV Charging Load at 20% Penetration Level](image1)

![Figure 4(b). Residential Area Load with EV Charging Load at 20% Penetration Level](image2)

<table>
<thead>
<tr>
<th>Total Area Load</th>
<th>Residential Area Load</th>
</tr>
</thead>
<tbody>
<tr>
<td>W/O EV</td>
<td>Step</td>
</tr>
<tr>
<td>Peak Load (MW)</td>
<td>31.61</td>
</tr>
<tr>
<td>Peak Hour</td>
<td>9:00</td>
</tr>
<tr>
<td>Energy Sales (MWh)</td>
<td>638.7</td>
</tr>
<tr>
<td>Load Factor (%)</td>
<td>84.2</td>
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</tr>
</tbody>
</table>
4.2 Observations and Discussion

The case studies have revealed several important issues regarding the impacts of EV load may have on utility distribution systems. First, it is not adequate to have only sufficient generation capacities during off-peak hours to assure a system’s ability to absorb EV loads without adverse effects. The constraints at the distribution level must be studied properly. Secondly, a sizable EV load can introduce a peak or near peak load in early off-peak period. It may have scheduling implications, and completely throw any load management programs of balance. Thirdly, at the present state of EV technology, including those of battery modules and chargers, a typical distribution system may not be able to supply EV loads beyond 20% penetration level.

There are two possible approaches to deal with this situation. First, a new advanced battery may be developed with shorter charging cycle. This will permit charging in the late off-peak hours, resulting in more uniform distribution of the EV charging load. The development of the proposed battery module for General Motor’s electric car, the impact with recharging time of 2 hours and energy consumption of 0.1 kWhr/mile, is a step in this direction. A second method to shift the charging load to late off-peak hours is to only partially charge battery modules which can be given additional charge during the day. But, such a technique is detrimental to the life and efficiency of the battery. On the other hand, with the increasing range of EV’s, the energy requirement per charge of EV battery will keep rising. This will make the attempt to shift the charging load to late hours even more difficult.

5.0 CONCLUSION

The electric utility’s interest in the commercial production of EV’s lies not only in the increased energy sales, but also in the anticipated system improvements due to the EV load during off peak hours. As a result, the electric utility may need to contribute in the development of the infrastructure for supporting the EV battery charging activities. This paper has indicated and discussed some problem areas which need attention to assure the utility’s ability to provide adequate charging facilities. Specifically, the distribution systems may pose bottle-necks in utilizing the excess energy available during off-peak hours to charge EV batteries at specific locations. Even low penetration levels of EV’s can create new peak loads exceeding the natural peak if sufficient attention is not paid to distribute the charging load throughout the off-peak period. EV load up to a 10% penetration level can be absorbed by the residential distribution system when properly distributed the charging load throughout the off-peak period. Higher peak loads were observed when the charging load was not distributed. A penetration level of 20% is found to be the upper limit which could be managed by the utility. Improvements in the present technology of batteries and their charging characteristics, or innovative approaches to recharging (e.g., re-filling the electrolyte instead of directly charging batteries) may be necessary to supply higher levels of EV penetration.

6.0 REFERENCES

1. Moore T. “They are now. They are clean. They are electric”, EPRI Journal, April/May 1991.

7.0 ACKNOWLEDGEMENTS

A part of the work reported in this paper was supported by a grant from the Core Research Program (Coal and Energy Research) at Virginia Tech.

APPENDIX A

Charging Load Profile from Charging Cycle

The charging load distribution during off-peak period under different charging load models are presented in this Appendix. The charging load at any instant depends on the charging cycle of the batteries and the switching pattern during the period of one charging cycle prior to that instant. For discrete application, such as step and interval charging cycles, the charging load can be computed simply by super-position of the charging cycles starting at appropriate instants. The continuous model needs to compute the cumulative effect of all charging loads switched prior to any particular instant. The charging cycle of a battery module adopted in this study is shown in Figure 1.

(a) Step Charging Load Model

Under this model, the charging load per unit of charging energy will be identical to the charging cycle of the batteries. Therefore,

\[ L_T = a \]

\[ L_T = \frac{b}{4} \]

\[ L_T = 0 \]

(b) Interval Charging Load Model

The charging load per unit of charging energy under interval loading can simply be computed as the cumulative effect of different charging cycles spaced according to the interval adopted. With the two-hours interval adopted in this study, the normalized load profile is computed to be:

\[ L_T = \frac{a}{2} \]

\[ L_T = \frac{a}{2} - \frac{b}{2} \]

\[ L_T = 0 \]

(c) Uniform Charging Load Model

The computation of the charging load under continuous uniform application can be explained using a general charging cycle shown in Figure A-1, where:

\[ T_1 \]

\[ T_2 \]

\[ L(I) \]

Counting the charging time from the beginning of charging, the latest hour of charging is \( (T_1 - T_2) \) so that the charging could be completed within \( T_1 \). The load at any instant \( T \) after the beginning of charging will be the cumulative contributions of all batteries charged prior to the instant \( T \). The chargers started between \( 0 \leq t \leq T_1 - T_2 \) will contribute to the load at the instant \( T \) if \( 0 \leq T \leq T_2 \). The contributions of chargers started at instants \( 0 \) and \( (T_1 - T_2) \) to the load at time \( T \) will be \( L(T) \) and \( L(T - (T_1 - T_2)) \). Therefore, the total charging load at time \( T \) will be:

\[ L_T = \int_{0}^{T} L(t)dt \]

\[ L_T = \int_{T_1 - T_2}^{T} L(t)dt \]

\[ L_T = \int_{T_1}^{T} L(t)dt \]

\[ L_T = \int_{T_1 - T_2}^{T} L(t)dt \]
Figure A-1. Computation of Uniform Charging Load

To make the loads correspond to unit energy, these loads need to be normalized by dividing the total energy under $L_J$, i.e.,

$$\int_0^{T_1} L_J dt$$

For the particular charging cycle adopted in this study (Figure 1), we have

$$T_1 = 12 \text{ hours}$$
$$T_c = 8 \text{ hours}$$

and the charging cycle is specified by the constants $a = 0.625$ and $b = 0.125$ and is defined by three different segments:

- $F_1 = L(t)$ for $0 \leq t \leq 2$ = $a$
- $F_2 = L(t)$ for $2 \leq t \leq 4$ = $a - \frac{(a-b)}{2} (t-2)$
- $F_3 = L(t)$ for $4 \leq t \leq 8$ = $\frac{b}{2} (8-t)$

The charging loads $L_J$ derived for different periods of charging hours under these specifications are:

- $L_J = \int_{T-4}^{T} F_1 dt = aT$ for $0 \leq T \leq 2$
- $L_J = \int_{T-2}^{T} F_2 dt + \int_{T-2}^{4} F_3 dt$ = $aT - \frac{(a-b)}{4} (T-2)^2$ for $2 \leq T \leq 4$
- $L_J = \int_{T-4}^{T} F_1 dt + \int_{T-4}^{2} F_2 dt + \int_{4}^{T} F_3 dt$ = $(T-T_a) + \frac{b}{8} (18T - T^2 - 40)$ for $4 \leq T \leq 8$
- $L_J = \int_{T-4}^{T} F_2 dt + \int_{T-4}^{2} F_3 dt$ = $\frac{a}{4} (T-8)^2 + \frac{b}{8} (40T - 37T^2 - 112)$ for $6 \leq T \leq 8$
- $L_J = \int_{T-4}^{T} F_3 dt$ = $\frac{b}{8} (T-12)^2$ for $T \geq 8$

Total energy for this recharge loading is,

$$\int_0^{12} L_J dt = 4$$

Therefore, loads computed using above derived equations should be normalized by dividing by a factor of 4 to obtain the proper charging load for unit energy consumption during the 12 off-peak EV charging hours. An example is provided in Table A-1. The uniform charging load profile presented in figure 2 is obtained from this table.

Table A-1 Charging Load for Uniform EV Charging

<table>
<thead>
<tr>
<th>Hour</th>
<th>Expression</th>
<th>Numerical Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>$a$</td>
<td>0.052</td>
</tr>
<tr>
<td>2</td>
<td>$2a$</td>
<td>0.104</td>
</tr>
<tr>
<td>3</td>
<td>$a + \frac{1}{4} b$</td>
<td>0.151</td>
</tr>
<tr>
<td>4</td>
<td>$3a + b$</td>
<td>0.188</td>
</tr>
<tr>
<td>5</td>
<td>$2a + \frac{15}{8} b$</td>
<td>0.163</td>
</tr>
<tr>
<td>6</td>
<td>$3a + \frac{3}{8} b$</td>
<td>0.130</td>
</tr>
<tr>
<td>7</td>
<td>$\frac{1}{4} a + \frac{21}{8} b$</td>
<td>0.095</td>
</tr>
<tr>
<td>8</td>
<td>$2b$</td>
<td>0.063</td>
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<tr>
<td>9</td>
<td>$\frac{3}{8} b$</td>
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<td>10</td>
<td>$\frac{1}{2} b$</td>
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</tr>
<tr>
<td>11</td>
<td>$\frac{1}{8} b$</td>
<td>0.004</td>
</tr>
<tr>
<td>12</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Saifur Rahman (IEEE S-75, M-78, SM-83) graduated from the Bangladesh University of Engineering and Technology in 1973 with a B. Sc. degree in Electrical Engineering. He obtained his M.S. degree in Electrical Sciences from the State University of New York at Stony Brook in 1975. His Ph.D. degree (1978) is in Electrical Engineering from the Virginia Polytechnic Institute and State University.

Saifur Rahman has taught in the Department of Electrical Engineering, the Bangladesh University of Engineering and Technology, the Texas A&M University and the Virginia Polytechnic Institute and State University where he is a Full Professor. He also directs the Energy System Research Laboratory at VPI. His industrial experience includes work at the Brookhaven National Laboratory, New York and the Carolina Power and Light Company. He is a member of the IEEE Power Engineering and Computer Societies. He serves on the System Planning and Demand Side Management subcommittees, and the Long Range System Planning, the Load Forecasting and the Photovoltaics working groups of the IEEE Power Engineering Society.

His areas of interest are demand side management, power system planning, alternative energy systems and expert systems. He has authored more than 150 technical papers and reports in these areas.

Govinda B. Shrestha (IEEE S-88, M-90) graduated from Jadavpur University, Calcutta (India) in 1975 with a B.E.(Honors) degree in Electrical Engineering. His graduate degrees consist of MBA from University of Hawaii at Manoa, Honolulu, Hawaii, in 1985, MSc in Electrical Power Engineering from Rensselaer Polytechnic Institute, Troy, NY, in 1986 and Ph.D. in Electrical Engineering from Virginia Polytechnic Institute and State University, Blacksburg, VA, in 1990.

Govinda Shrestha has 8 years of industrial experience in utility companies of Nepal. He was involved in wide ranging activities in power industry. He has worked in various aspects of design, operation and planning of power systems. He has also worked in the construction and management of power projects like transmission lines, sub-stations and generating plants. Presently, he is a Research Associate at Virginia Polytechnic Institute and State University. His main areas of interest include various aspects of power engineering and the topics of uncertainty, specially relating to power system operation and planning. He has authored a number of publications in these fields.
The authors have concluded that up to 20% penetration level can be managed without impact on distribution system. This may be true for the impact on system peak demand. However, the penetration of electric vehicles will not be uniform throughout the system. Even with average penetration of 10%, there could be areas where the existing distribution systems will be overloaded. For a typical EV charger that I made measurements, the load was about 9 kW for the first three to four hours followed by half the load for the rest of the charging cycle. A typical distribution transformer serves 6 to 10 homes. If even half of the customers served by one transformer acquire electric vehicles, which is a possibility, the load on this transformer can double. This will require significant revamping of the distribution facilities.

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S. RAHMAN and G.B. SHRESTHA

The authors are thankful to Norton Savage and Rao Thallam for their comments which brought out some implicit assumptions and features in this paper. With respect to Mr. Savage's comments, penetration meant the percentage of households which may have electric vehicles. In the paper we used the load data for a substation serving 5700 households. Thus 10% penetration refers to 570 electric vehicles. Also, if we assume that on the average each household has one vehicle, the penetration will represent the ratio between electric vehicles to total vehicles. An assumption was made in this paper that the battery charging will take place only during off-peak hours to minimize the impact on the distribution network. If, on the other hand, the charging takes place during daytime at commercial and industrial facilities, the distribution loading problem will be aggravated especially during the summer. Figure 1 relates to how the charging load will be distributed over the eight-hour charging period. It is assumed that a certain unit of charge is needed to fully charge the EV battery. The full charge occurs during the first two hours, followed by partial charging during the next two hours. Only trickle charging occurs during the last four hours, consuming 25% of total energy. Values of 'a' and 'b' are determined to reflect these conditions.

With respect to Mr. Thallam's comments we would like to add that fine tuning of the daily rate cycle will provide new opportunities to increase energy sales. However, the expected demand from EV's must be studied before these rate structures are adjusted. Mr. Thallam's additional comments about overloading the distribution system is very relevant. These comments point out the fact that there may be other issues that need to be looked at than what this paper has addressed. The paper, however, shows how these issues can be addressed and their effects quantified.

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