AN INVESTIGATION OF RELIABILITY IMPACTS OF V2G-CAPABLE VEHICLES IN MUNICIPAL PARKING DECKS

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ABSTRACT

The capability of electric vehicles (EVs) in injecting the stored power back into power system has caused a new paradigm shift in the area of electricity storage. Anyhow, this paradigm has not yet been furnished with comprehensive technical and financial studies. This paper proposes an analytical approach for adequacy studies of distribution networks in presence of vehicle-to-grid (V2G) programs offered by parking decks. In this regard, a multi-state model is extracted for assistance of EVs parked in the parking to be utilized in emergency conditions. Both of EVs characteristics and driving behaviours are considered in obtaining the assistance model of parking decks. Afterwards, reliability studies of distribution systems has been revisited taking into account this new auxiliary unit. The numerical results of this paper demonstrates the abilities of the proposed method in assessing the potential capacity of EVs in improving the reliability level of distribution systems.

INTRODUCTION

In the upcoming years, given that a huge number of Electric Vehicles (EVs) are expected to be connected to the distribution networks at any instant, their aggregated effects as some dispersed energy storage systems on network operation, if properly aggregated as an ensemble, will be significant [1]. Considering the EVs with bidirectional capabilities, i.e. grid-to-vehicle (G2V) and Vehicle-to-grid (V2G), many new challenges and opportunities will be brought into existence [2]. The V2G concept plays the role of a bridge between two important technological structures, i.e. transportation and power systems. This may address some unresolved problems for both of these systems. The V2G capability of the electric vehicles can provide new opportunities for the system operators in facing with issues such as reactive power support, active power regulation and peak load shaving [3]-[5].

Before adopting this intrinsic feature of the EVs as ancillary services in electricity markets, it should be investigated that how V2G programs can affect the reliability level of power systems. However, there are a few works in which the researchers have discussed the impacts of aggregated EVs fleet on reliability indices of power systems at the generation or composite levels [6]-[8]. The authors in [6] proposed a simulation-based approach to estimate the reliability effects of V2G capable EVs under battery exchange (BE) mode. In this paper, the authors shown that existence of EVs in power system can improve the reliability level of system at hierarchical level one (HLI). The reliability studies of composite power systems in presence of EVs fleet has been studied in [7]. The Monte-Carlo Simulation (MCS) approach has been applied to evaluate different reliability indices of the power system. However, to the best of our knowledge, none of the past works has focused on reliability effects of V2G programs in distribution systems specially proposed by the operators of a municipal parking deck.

The EV users can charge their vehicles either at the home or public decks. At homes, the EVs would be charged with a low charging level overnight. In contrast, at public parking decks, fast chargers can be installed and the EVs can be charged more rapidly [9]. On the other hand, at any time, there are a large number of EVs parked at a parking deck which can be translated to a considerable storage capacity. Therefore, municipal parking decks have been introduced as some proper candidate places to provide required infrastructure for charging/discharging programs of EVs [10]. These entities can effectively play the role of EVs fleet aggregators. During emergency conditions, a remarkable amount of power can be injected from the batteries of EVs parked in parking decks into the grid and thus the reliability level of distribution systems would be improved. However, only after running a systematical investigation on the reliability benefits of V2G-capable vehicles at parking decks, one can expect to get the most out of the EVs capabilities and all their merits. This seems to be missing in the previous published works and is the main concern of this paper. The general structure of the proposed method is illustrated in Fig. 1. As the first step of the proposed method, an analytical probabilistic model for the available energy in batteries of EVs parked in the parking deck is presented. This model is derived taking into account different driving behaviors of users, plugging and departure times of vehicles, characteristics of the EVs batteries and also operating policy of V2G programs. The pertinent data are collected from National Home Traveling Survey (NHTS) [11].

It is evident that due to non-uniform temporal behavior of EV users, the number of vehicles as well as the energy stored in the batteries of the EVs parked in parking decks would not be uniform during the period of studies. On the other hand, the load that is expected to be supplied though stored energy in parking deck in case of occurrence of a contingency does not have a uniform pattern either. Therefore, the period of studies must be divided into

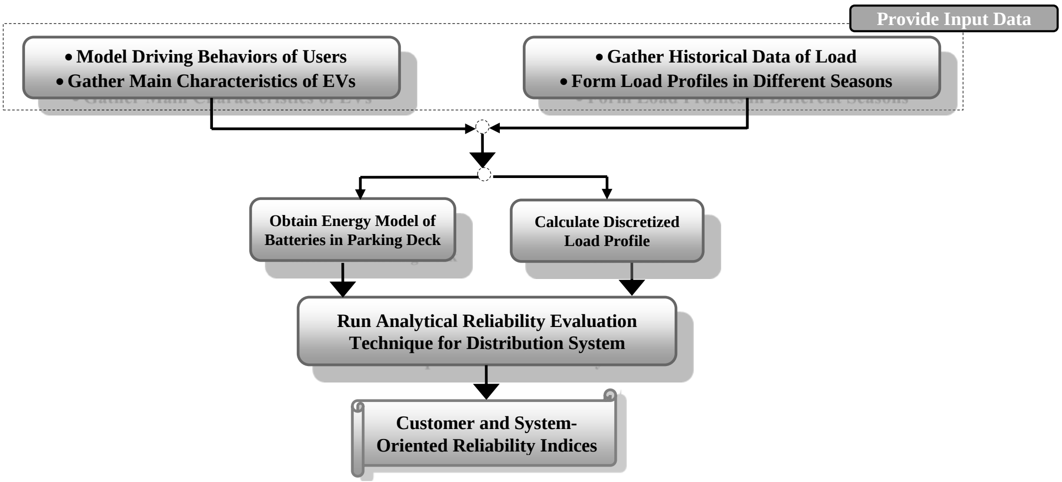

Fig. 1. General structure of the proposed framework.

shorter intervals and reliability studies should be carried out for each interval. Subsequently, the results of all the intervals can be aggregated to obtain the long-term reliability indices. It is noteworthy to say that these intervals should be sufficiently short such that the variations in the amounts of energy stored in EV's batteries and distribution system load can be ignored. Therefore, as the next step, load profile of distribution system at different times should be discretized into some levels. Convolving the extracted probabilistic model of available energy in batteries of EVs and discretized model of system load, different reliability indices can be calculated.

Based on this structure, the remainder of this paper is organized as follows: in the first, the modelling outlines of parking decks as energy storage systems is delineated. Consequently, the proposed reliability assessment technique is provided. Several case studies are offered and the results are put under discussion and finally, conclusions are drawn.

MODELLING OUTLINES

In adequacy studies of distribution systems, the load modeling procedure can significantly affect the accuracy of calculated reliability indices. Dealing with the variations in system load in analytical studies, calls for an appropriate approximation technique to create a trade-off between the desired accuracy and the imposed computational burden. In this paper, we have divided a day based on the load level into three time intervals of peak-load, mid-load and light-load and as previously mentioned, reliability studies are conducted for each period and finally are aggregated. Load profile during each interval is assumed to be constant.

After discretization of the load profile, a proper probabilistic model for the energy stored in batteries of available EVs should be extracted. In doing so, PHEVs characteristics as well as driving behavior of the users should be taken into consideration.

The battery of a PHEV can be described in terms of its storage size and also the charging level. A wide range of battery sizes, from 7.8 kWh to 27.6 kWh, has been randomly assigned to the vehicles taking into account the market share of various PHEVs [12]. The charging level of a battery is usually specified by a factor of the battery capacity (C) [13].

In this paper, it has been assumed that a certain portion of PHEV users charge their vehicles in the parking deck and participate in the V2G programs intended to supply loads during distribution system outages. Therefore, a number of $V^k = \pi V^{Tot}$ vehicles are considered for this purpose where π is the participation ratio and V^k, V^{tot} respectively denote the number of vehicles participating in the program and the total number of vehicles in the system under study. evaluating the impact of this program on the reliability level of the system, the charging pattern and availability of these vehicles must be determined.

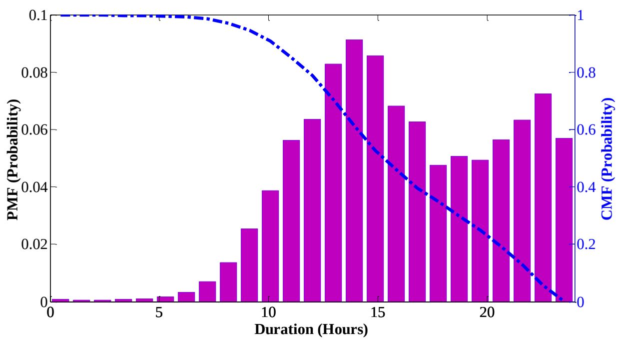

Fig. 2. Distribution of parking durations according to NHTS data.

In this regard, some parameters for each of these vehicles must be simulated during the period of studies. These parameters include arrival time, battery capacity, state of charge (SOC) at the beginning of the charging process, and most importantly the duration for which the vehicle is plugged-into the grid. These data are obtained from National Home Traveling Survey 2009 (NHTS), which contains a comprehensive record of household travels from US [11]. For example, probability distribution of parking durations for the vehicles is depicted in Fig. 2. As can be observed, a high percentage of cars are parked for more than 10 hours in the parking location and therefore can be considered as an appropriate backup resource during system outages.

Once these patterns are extracted, different characteristics of each vehicle can be randomly assigned using random sampling. i.e., by generating uniform random numbers and comparing them with cumulative mass functions (CMF) of each parameter [14]. After setting all the necessary parameters for each vehicle, their charging schedules are obtained and the profile of stored energy in PHEV batteries at each time can be calculated.

In order to investigate the impact of V2G programs on the reliability level, as previously mentioned, apart from having the correct information about behaviour and characteristics of PHEVs, discharging strategy of the batteries during contingencies should also be specified. Discharging strategy determines that in different situations, how much energy can be extracted from available batteries. In this paper, we have assumed that upon the occurrence of a contingency, the operator collects the data on available energy in PHEV batteries in the parking deck and based on these information, assigns loads to each battery. For example, loads with higher priorities are supplied by batteries with higher energy contents. It should be notified that discharging strategy depends on the contract between system operator and PHEV owners, and when obtaining the probabilistic model of available energy, should be taken as the reference.

Under these assumptions, the probabilistic model of batteries available energy can be extracted as follows:

1) For each time interval of studies, a simulation should be run to obtain the PHEV charging schedules and determine the energy levels of batteries at different time slots.

2) Then batteries are rank based on their available energy.

3) The histogram of energy stored in the batteries is calculated as illustrated in table I. In this table, R_j, E_S, L and P_{Lj} respectively stand for j^{th} rank of PHEVs, discrete energy levels, maximum number of levels, and the occurrence probability of L^{th} energy level for j^{th} rank of PHEVs.

4) The above steps should be iterated until the values of probabilities in table I converge.

TABLE I

PHEVS RANKING BASED ON ENERGY LEVEL OF BATTERIES

		PHEVs Rank				
		R_1	R_2	R_3	$\cdots$	R_V
Energy Level of Battery	E_S	P_{11}	P_{12}	P_{13}	$\cdots$	P_{1V}
	$2\times E_S$	P_{21}	P_{22}	P_{23}	$\cdots$	P_{2V}
	$3\times E_S$	P_{31}	P_{32}	P_{33}	$\cdots$	P_{3V}
	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$
	$L\times E_S$	P_{L1}	P_{L2}	P_{L3}	$\cdots$	P_{LV}

RELIABILITY ASSESSMENT TECHNIQUE

In this section, the potential impact of V2G programs provided by municipal parking decks on commonly used distribution system reliability indices is discussed and the proposed methods for calculation of these indices is explained.

The most widely used reliability indices can be classified into two different groups of frequency-oriented, duration-oriented and energy-oriented indices [15]. Once a failure occurs in the system, the operator tries to minimize the effects on customers via the automation infrastructure. However, due to radial nature of distribution networks, in many cases, the operator is forced to disconnect the feeder from the main grid and then considering the configuration of the automation system, form islands to supply some customers via the stored energy in parking decks, if possible. Considering this fact, V2G programs would not affect the frequency indices, whereas in contrast, they are expected to significantly improve the duration and energy oriented indices of the network.

In what follows, the procedure for computing *SAIDI* and *EENS* is outlined. Before conducting the reliability assessment, reliability data of distribution network components, i.e. failure rates (λ) and repair times (r) should be gathered. Then the following steps must be taken for each load level ($k \in \{1, 2, ..., n_p\}$).

1) Select a contingency with frequency of occurrence (λ_i) and repair time (r_i).

2) If for this contingency, the parking energy cannot be used for supplying any loads in the network, the values of *SAIDI* and *EENS* can be calculated as below:

$$EENS_{k,i} = L_{k,i} \times r_i \quad (1.a)$$

$$SAIDI_{k,b} = r_i \quad (1.b)$$

where $L_{k,i}$ denotes the average of total system load during time interval k. Otherwise, they are given by:

$$EENS_{j,k,i} = \sum_{l=1}^{L}\left(\left(r_i - T_l\right) \times P_{lj} \times H\left(r_i - T_l\right) \times P_{Dis.}^{k,i}\right) \quad (2.a)$$

$$EENS_{k,i} = \sum_{j=1}^{V_k}\left(EENS_{j,k,i}\right) + \left(L_{k,i} - V_k \times P_{Dis.}^{k,i}\right) \quad (2.b)$$

$$H(\mathrm{X}) = \begin{cases} 0 & if\ X < 0 \\ 1 & if\ X \geq 1 \end{cases} \quad (2.c)$$

The share of this contingency in the amount of *SAIDI* ($SAIDI_{k,i}$) can be calculated as presented in (3). As a remark, it has been assumed that each battery is assigned to supply the load of one customer. In other words, ($N_{H,i} - V_k$) customers will remain disconnected during the outage and the other ones based on the amount of energy available in batteries, will experience lower interruption durations or even no interruptions at all.

$$SAIDI_{k,i} = \frac{\sum_{j=1}^{V_k}\sum_{l=1}^{L}\left(\left(r_i - T_l^{Dis.}\right) \times P_{lj} \times H\left(r_i - T_l\right)\right) + \sum_{l=V_k+1}^{N_{H,i}} r_i}{N_{H,i}} \quad (3)$$

where $N_{H,i}$ and T_l respectively represent the number of customers in the zones supplied during contingency *I* and discharging duration associated with energy level *l*.

3) Aggregate the obtained values for all different types of contingencies occurring in the system (denoted by C) and all the periods.

$$EENS = \sum_{k=1}^{n_P} \sum_{i=1}^{C} \frac{T_k}{8760} \times \lambda_i \times EENS_{k,i} \qquad (4.a)$$

$$SAIDI = \sum_{k=1}^{n_P} \sum_{i=1}^{C} \frac{T_k}{8760} \times \lambda_i \times SAIDI_{k,i} \qquad (4.b)$$

where T_k stands for the duration of k^{th} period of studies in a calendar year.

CASE STUDIES

The proposed approach is implemented on the modified IEEE 34-node test system whose single line diagram is depicted in Fig. 3.

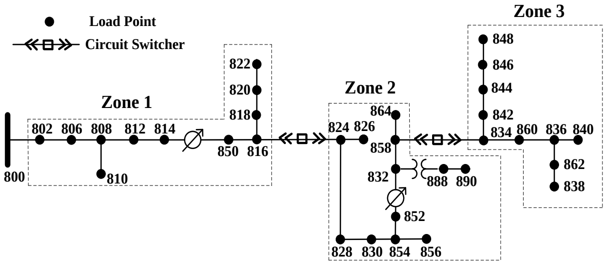

Fig. 3. Single line diagram of the modified IEEE 34-node test feeder.

All the data associated with this test system can be accessed in [16]. To more effectively investigate the abilities of V2G programs on reliability level of a distribution feeder, this feeder has been divided into three zones applying two circuit switchers as shown in Fig. 3. Reliability data of elements were taken from [17]. Two houses are assigned to each phase of load points and one parking deck is considered for this feeder. Based on the location of charging station, three cases have been defined:

- ***Case I***: Original system without parking deck (PD).
- ***Case II***: PD is placed at node 828, Zone 2.
- ***Case III***: PD is placed at node 860, Zone 3.

The probabilistic model of available energy of PD in mid-peak period of summer days is shown in fig. 4. As can be observed, PHEVs have a wide range of energy levels and adopting a discharging strategy based on the energy level can help the operator to effectively manage different loads with diverse requirements during outages. The values of reliability indices for different cases are calculated and summarized in table II. Notice that in these cases, participation ratio of EVs in V2G program is set to 10% and charging rate at parking deck is assumed to be 0.2C. Furthermore, no charging control is considered, i.e. vehicles are charged as soon as returning to the PD.

Despite low participation ratio of vehicles, the reliability indices have been significantly improved in cases II and III compared to base case of I. It is interesting to note that the PD location is an important factor in prosperity of the V2G programs from reliability point of view. This was quite expectable since as long as the PD is located in zone 3, it is feasible to utilize the stored energy for contingencies occurring in zones 1 and 2, while in case II, this is only possible for faults of zone 1.

In order to examine the effect of participation ratio, the value of AENS is computed for different participation ratios in case III and the results are illustrated in Fig. 5. It is clear that as participation ratio increases up to 0.2, drastic improvement in the value of AENS is made. However, further increase of this factor cannot reduce AENS. This is because it is not possible to apply V2G program of PD for all the faults in this radial test network and thus, raising the participation ratio cannot affect the value of AENS resulted from these contingencies.

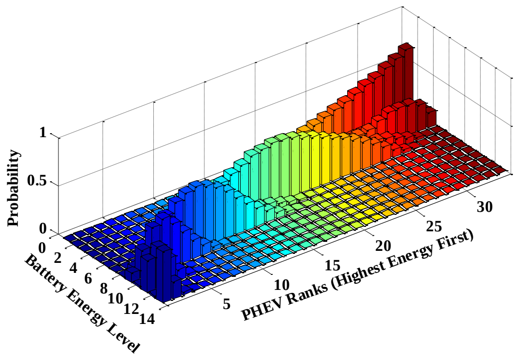

Fig. 4. Available energy probabilistic model during mid-peak period.

TABLE III
CALCULATED RELIABILITY INDICES FOR DIFFERENT CASES

	Case I		Case II		Case III	
	AENS*	SAIDI**	AENS	SAIDI	AENS	SAIDI
Zone 1	17.385	10.148	17.385	10.148	17.385	10.148
Zone 2	28.976	16.913	24.087	13.192	24.087	13.192
Zone 3	30.671	17.902	25.806	14.194	19.037	11.647
Total	26.057	15.209	22.648	12.613	20.365	11.754

*: (kWh/ Cust.yr) **: (hr/Cust.yr)

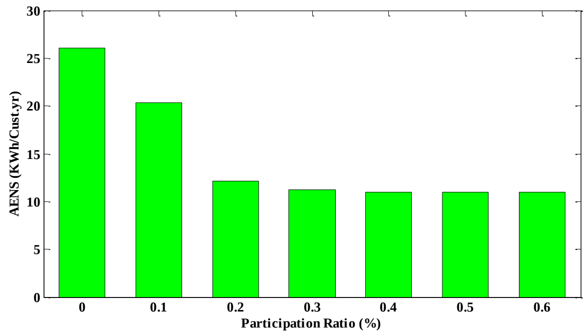

Fig. 5. AENS for case III as a function of participation ratio.

The values of mean available energy for different charging rates are reported in table III (a participation ratio of 10% is assumed). It can be inferred that charging rate does not significantly affect the amount of available energy. This is due to the diversity of arrival and departure times of vehicles to the PD. This fact is verified by plotting the amount of available energy for different hours in Fig. 6. Considering this pattern, charging the vehicles with higher rates which is available in charging stations would not dramatically improve the reliability level of distribution system through V2G programs. This problem can be overcome by employing additional energy storage systems in the distribution system. This energy storage system can be realized in the form of spare EV batteries placed in charging stations and discharged during contingencies occurring at PD's low energy hours.

TABLE III
MEAN AVAILABLE ENERGY IN PD

Charging Rate	0.2C	0.5C	1C	2C
Yearly Mean Energy (KWh)	312	325	328	330

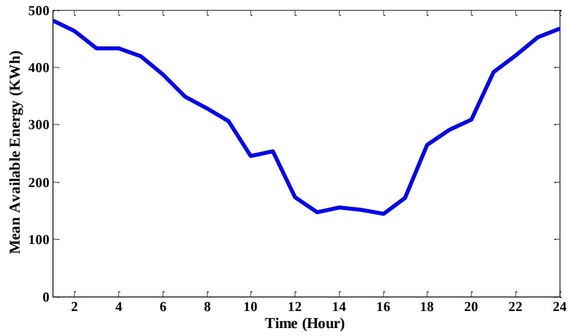

Fig. 6. Mean available energy as a function of time.

CONCLUSIONS

This paper presented an analytical approach for adequacy studies of distribution systems in presence of V2G programs proposed by public parking decks. Convolving the discretized model of system load and energy model of EVs batteries parked in parking deck, a multi-state model extracted for assistance of parking deck in contingency conditions. It was discussed that how different reliability indices of distribution systems would be affected by presence of such programs. Defining different cases, the abilities of proposed method was assessed by implementing on the modified IEEE 34-node test system. The obtained results support this claim that using parking decks as an auxiliary power source in emergency conditions can significantly improve the reliability level of distribution systems. It was also demonstrated that utilizing higher charging rates in parking decks cannot result in more improvement in reliability level of the systems. The other factors such as parking deck capacity and driving behaviours of EV users also need to be considered in this context.

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