Determining the Ability of Distributed Generation to Relieve Stress Placed on the Grid by Electric Vehicle Charging

A Thesis

Presented in Partial Fulfillment of the Requirements for Graduation with Research Distinction from the College of Engineering

By

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2016

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Abstract

The increased penetration of Electric Vehicles (EVs) within the market presents the challenge of how to best integrate and charge these vehicles without causing undue stress to the grid. Public charging, in particular, fast DC charging technologies can cause stress to the grid, including voltage deviations, increased loading, and power losses, leading municipal utilities to hesitate on approval. Distributed Generation (DG) provides a generation source closer to the load, which can offset these stresses. These DG units can be coupled with the installation of charging stations, providing on-site electricity supply; multiple DGs can be used in situations where on-site DG is not feasible. While the goal of EVs is to obtain a more environmentally friendly way of transportation, the electricity used to charge them must have a quick ramp up speed and, thus, is generated by coal plants. However, DG, generating locally, from renewable sources and with cleaner technology, has great potential to relieve stress to the grid as an alternative to conventional power plants, while also helping reach the goal of "green" transportation. The purpose of this project is to determine DG's capability of relieving EV induced stress onto the grid and to investigate strategies maximizing this benefit. Through the use of Ladder Iterative Power flow techniques, an accepted methodology, and simulations of a standard IEEE-37 bus system via MATLAB and GridLAB-D, DG units are proven to reduce voltage deviations and power losses and counter increased loading caused by EV charging stations in a way that is more beneficial that simply increasing the capacity generated on the generation side of the grid.

Though many have studied the effects of both DG installation and EV charging station installation, no studies have paired these losses with EV charging station installation, DG's ability to alleviate issues, or the correlation between decreased losses and a reduction in pollution. Pollution calculations based upon the power losses within various cases of a distribution system also prove that DG can reduce losses and other stresses, while also reducing the pollution caused by increasing the capacity of the grid to meet the demand of EV charging. Through optimizing generating capacity and location of various DG units, a helpful model is provided for utilities to more readily accept the increased demand for EV charging facilities by utilizing DG. These findings can help increase the adoption rate of EVs, thus reducing non-renewable fuel consumption, while also ensuring minimal stress to the electric grid and adding more renewable generation to the electric generation portfolio.

Dedication

Dedicated to my family, friends and co-researchers for their endless support and motivation

Acknowledgements

This research project would not have been possible without the endless support from my advisor, Dr. JK Wang, and her support and mentorship throughout three years of my undergraduate education. Thank you to the College of Engineering for supporting my research efforts and providing the opportunity to conduct research in an important field and The Ohio State University for being a leading research institution.

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D. Meyer, JongChan Choi and Jiankang Wang, "Increasing EV public charging with distributed generation in the electric grid," *Transportation Electrification Conference and Expo (ITEC), 2015 IEEE*, Dearborn, MI, 2015, pp. 1-6.

Fields of Study

Major Field: Electrical and Computer Engineering

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Introduction

The urgent need of expanding public electric vehicle (EV) charging is raised by increasing sales of EVs; Nissan has sold more Leafs each month of 2014 than that month's total in 2013 for twenty consecutive months [1], [2]. With more EV being driven, public charging, in particular, fast charging services, will be indispensible to facilitate future city operation, improve EV owner experience, promoting the replacement of of traditional vehicles by EVs. The importance of public charging facilities to EV sales is demonstrated by California, which, in 2013, had the third highest percentage EV registrations and the highest number of public charging stations, 1,958 [3], [4]. California, Washington and Oregon, the states with the 3rd, 1st, and 5th highest percentage of EV registrations in 2013, respectively, paired to create the "West Coast Electric Highway," just one of many public charging projects, which provides a network of charging stations every 25 to 50 miles along major roadways in the region [5].

The installation of these charging stations necessary to encourage the adoption of EVs, however, faces many hurdles. To most benefit vehicle users, public charging should ideally be located in the center of commercial areas and in the direct path of main transportation ways, much like the West Coast Electric Highway. This need to be in areas of high commercial concentration introduces an extra hurdle in the necessity of approval procedures including meeting zoning requirements, permitting, and most importantly an electrical source and metering. The municipal utility must be consulted to determine the PEV rate structure, availability of power, total load management, and type of charging [6]. Current electrical infrastructure can prove a hurdle to the installation of EV charging stations, depending on the level of charging desired. EV charging can be completed in one of 3 ways, as shown in Table 1. DC fast chargers, such as the Eaton DC Quick Charger, provide the fastest charge for EV users and can pull up to 50 kW [7], while the average household load in 2012 was 903 kWh per month [8].

TABLE I
STANDARD EV CHARGING TYPES

Specification	AC Level 1	AC Level 2	DC Fast
Voltage	120 V	208/240 V	≤ 500 V
Typical Output	1.4 kW	3.6/7.2 kW	50 kW
Maximum Output	1.9 kW	19.2 kW	50 kW

Due to the fact that EV charging can add more load to the distribution side of the grid than the average household load, many utilities and power systems researchers have investigated the various stresses that charging can cause, including voltage deviations, load profile disruptions, and power losses. This increase in load must also be met be an increase in generation capacity; however, building new power plants and other large scale generation facilities is costly and can lead to more losses and the electricity is transmitted.

Distributed Generation (DG), which are installed within the distribution side of the grid near homes, provides a possible solution to address these problems. DG can be owned and operated by consumers or by third parties, and can be used for emergency backup or to supply power to groups of buildings [9]. Renewable energy generation technologies are widely available for use within DGs' deployment; for example, in the first six months of 2014, solar plants constituted more than a quarter of U.S. power plant capacity additions, while wind plants contributed one sixth [10]. Renewable energy has increasingly become an important part of the grid and solar photovoltaics have become more cost competitive. Thus, renewables are an important and growing part of the electricity sector and distributed generation provides an attractive and efficient outlet for their use. DG provides an economical alternative to running expensive transmission lines to remote areas, increases grid security, and can provide higher power quality [11]. All of these benefits are desirable to both utilities and customers, making them an attractive way to utilize renewables, while providing support to the grid to help counteract the stress caused by EVs.

As applied to EVs, DG provides a way for utilities to reduce peak loads and keep the supply of power to all consumers reliable, while also making the use of EVs more “green” by utilizing renewables to supply the electricity used to charge them. To discern just how effective DG can be in offsetting EV charging to relieve system stress in the form of voltage deviations, load profile disruptions, and power losses, further study is required. This thesis presents a quantitative approach to determining the ideal size and location of DG within a distribution system, which has the highest stress minimizing qualities. This model of pairing EV charging station installation with the installation of DG elsewhere in the grid to alleviate voltage deviation, increased loading, and power losses can decrease utility resistance to charging stations and increase EV sales through greater availability of charging stations. Additional investigation of pollution reduction through the study of losses further validates the appeal of renewable DG installation, as it counters stress and maximizes the “green” potential of EVs. Established models for power flow will be used to model the stress charging stations place on the grid and the ability of combinations of DG to lessen them through optimized placement within the distribution system. Though many have investigated both DG and charging stations, this thesis provides an original contribution in the form of alleviating stress and pollution via DG.

Literature Review

Many researchers and industry professionals have conducted studies and published results, which present the issues that can be caused by EV charging station installation. Optimization of station installation is a much researched topic; however, these studies focus on driver behavior, optimal scheduling, and behavioral characterizations [12], [13], [14]. Though these studies do not directly impact the results of this research, they are helpful in furthering the assertion that EV drivers do use public charging stations and find them to be essential [15]. When creating statistical models for EV charging station choice, those stations which are within a direct travel path or near commercial areas are frequently given higher attractiveness scores [16]. A study conducted in Australia found that drivers were willing to pay more than a dollar more for electricity if it resulted in a 10-minute reduction in charging time, which suggests that drivers are more likely to use DC Fast charging stations when available [17]. Though DC Fast charging stations are more appealing to consumers, they can also cause large load increases while in use. Many found that charging behavior is less than optimal, especially in the first weeks of ownership, as users charge more than necessary, adding undue stress to the grid [15], [18], [19]. Providing incentives to users for charging overnight is an often discussed way to lessen stress to the grid; however, as adoption rates reach the projected and desired levels, simply charging at night will not completely eliminate mal-effects [15].

The many stresses placed on the grid by increased EV penetration have also been well studied. Of critical importance to the degree EV charging stations affect the grid is related to when users are most likely to charge. If users charge during peak hours, the grid can struggle to adjust. In the Netherlands, researchers found distinct peaks in charging as users arrived at and charged while working and also around 6pm, as drivers plugged in once they returned from work [20]. This increase in charging during a time at which the grid is likely already operating near peak can exacerbate stress to the grid. The impacts of PHEVs on load flow on residential systems was modeled and a forecasting model was created in [21]; however, the results of a purely EV fleet could alter the results. Residential areas of varying size were used to determine incremental energy losses due to EV in [22] and the effect on utility equipment is presented in [23]. While analyzing various DG types, many papers favor PV and wind turbine based systems, as they exemplify commonly installed systems [24], [25].

Voltage deviation and power flow studies are often coupled [26]. However, these studies often use Newton Raphson based techniques, which have been shown to be inefficient when analyzing distribution systems due to the high $\frac{R}{X}$ ratio within distribution systems [27]. Load flow methods for distribution systems, such as backward and forward sweep [28], have been employed and offer better solutions [29]. A modified Z-bus approach has been presented; however, the authors only considered the optimal size and location of DG within a balanced system, which is unlikely to happen in a real world setting [30]. Vector analysis has been employed to describe the effects of DG placement, but no full mathematical model was provided to justify claims, though DG capacity was proven to have an effect on voltage deviation [31]. Many studies have been conducted on the ability of DG to reduce power losses within the distribution system, yet none have paired these losses with EV charging station installation or correlated them to a reduction in pollution [32], [33], [34]. Though pure loss reduction is of high interest, pairing the overall "green" goal of EVs with DG necessitates an investigation of pollution reduction benefits. An analytical approach for DG allocation in a distribution network based on loss sensitivity analysis was proposed in [35]. This approach to optimizing a distribution system is often used with capacitor allocation to reduce losses and the authors have modified the computational procedure in a way which allows its application to DG optimization. This approach is utilized within this research to conduct analysis of power losses resulting from various cases of increased generation capacity needed to meet demand caused by public EV charging. Though this study will be largely used during this research, it does not address the importance of EVs or pollution. The environmental effects of EV use in China have been studied, largely due to the majority of China's portfolio being based on coal fired generation [36]. This lack of renewable sources can increase various types of pollution within the country. To analyze the pollution created by electricity generation, a fixed heat efficiency approach is sometimes used to determine pollution caused by both generation and use [37]. The environmental life-cycle emissions caused by electric vehicles in both the United States and Europe have been widely studied, but these results have not considered pollution reduction that could occur via renewable DG sources and the increase in pollution that could occur due to the necessity of increased generation capacity to meet EV charging demand [38], [39]. Many organizations have conducted analysis to determine the grams of CO_2 created per kWh generated by various generation sources [40] and these estimates will be used in conjunction with loss calculations to determine pollution via various sources used to increase generation capacity in the following section.

Analyzing Stress to the Electric Grid Caused by Public EV Charging

A. Ladder Iterative Techniques

Two major types of stress on the electric grid are increased loading of power equipment and voltage deviation. These stresses are well-documented within the literature. Load voltage curves have been created through stochastic modeling to show the deviations caused by charging stations [41] and the effect of an EV load on voltages has been investigated using steady-state models [42].

We analyze these two phenomena with modified *Ladder Iterative* techniques [43], which are extensively used within literature for power flow analysis on radial systems, as in [44]. This technique is suitable for power flow analysis in electric distribution systems, which is the last stage of power delivery and operates, as opposed to high voltage transmission systems, at a lower voltage (from $2\ kV$ to $69\ kV$). EV charging stations are connected to the grid at the distribution systems.

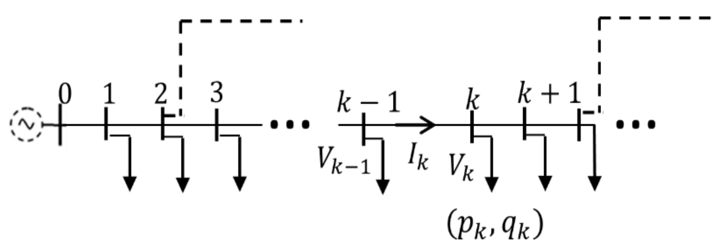


Figure 1. Power delivery in a radial distribution system.

I. Voltage Deviation Analysis:

Consider a distribution system shown in Fig. 1. The three-phase voltage difference between Bus $k-1$ and Bus k is given by (1). This result is normalized by a voltage base of V_0 in the *per unit* system.

$$\begin{bmatrix} \Delta V_k^+ \\ \Delta V_k^- \\ \Delta V_k^0 \end{bmatrix} = \begin{bmatrix} R_k^+ & 0 & 0 \\ 0 & R_k^- & 0 \\ 0 & 0 & R_k^0 \end{bmatrix} \begin{bmatrix} P_k^+ \\ P_k^- \\ P_k^0 \end{bmatrix} + \begin{bmatrix} X_k^+ & 0 & 0 \\ 0 & X_k^- & 0 \\ 0 & 0 & X_k^0 \end{bmatrix} \begin{bmatrix} Q_k^+ \\ Q_k^- \\ Q_k^0 \end{bmatrix} \tag{1}$$

From (1), we observe that the voltage drop on the kth feeder section depends on two factors: the per phase power flow on the feeder P_k and Q_k, and the impedance of the feeder R_k of each phase and X_k. The X_k matrix above, as discussed in [20], excludes coupling inductance due to the distance between phases. Real and reactive power flow P_k and Q_k are the total power consumption at the downstream of Bus k, shown in (2).

$$\begin{bmatrix} P_k^+ \\ P_k^- \\ P_k^0 \end{bmatrix} = \begin{bmatrix} \sum_k^n p_k^+ \\ \sum_k^n p_k^- \\ \sum_k^n p_k^0 \end{bmatrix}, \begin{bmatrix} Q_k^+ \\ Q_k^- \\ Q_k^0 \end{bmatrix} = \begin{bmatrix} \sum_k^n q_k^+ \\ \sum_k^n q_k^- \\ \sum_k^n q_k^0 \end{bmatrix} \tag{2}$$

Finally, the voltage at Bus k is the accumulative voltage drop along the feeder. Defining the voltage at the substation of the distribution system as *primary voltage* V_0, the voltage profile of the feeder is:

$$V_k^{\emptyset} = V_0^{\emptyset} - \sum_k \Delta V_k^{\emptyset} = V_0^{\emptyset} - \sum_1^k \sum_k^n R_k^{\emptyset} p_k^{\emptyset} - X_k^{\emptyset} q_k^{\emptyset} \tag{3}$$

where ø corresponds to each phase. After placing an EV charging station at Bus k, the electric load is increased by P_k^{EV}, causing voltage deviation across the feeder as:

$$V_h^{\Delta} = P_k^{EV} \sum_1^h R_i \quad for\ h \leq k\ (Bus\ h\ located\ upstream\ of\ Bus\ k);$$

$$V_h^{\Delta} = P_k^{EV} \sum_{1}^{k} R_i \quad for\ h > k\ (Bus\ h\ located\ downstream\ of\ Bus\ k); \qquad (4)$$

In (4) only real power is considered, as an electric vehicle charging with a DC fast charger receives real power from the grid after it passes through an inverter, transforming AC into DC. If the inverter is assumed to control the power factor, an analysis can be developed, which includes reactive power in EV charging. This analysis would allow for the inclusion of bi-directional charging capabilities, through which the EV could serve as some DG units, which provide reactive power to the grid, often referred to as Vehicle-to-Grid (V2G) capabilities.

II. Feeder Loading Analysis:

A feeder's loading level is evaluated by its carried current. For feeder section k in Fig. 1, the magnitude of its carried current I_k is composed of real current $I_{p,k}$ and reactive current $I_{q,k}$. Similar to power flow calculation, current I_k is the total current drawn together by its downstream electric loads. Based on the power and current relationship, an EV charging station at Bus k will increase the feeder's loading by

$$I_k = i_{p,k} = \frac{P_k^{EV}}{V_k} \qquad (5)$$

B. Using Distributed Generation to Relieve EV Charging Stress

Distributed generation (DG) are small scale generators, of capacities varying from 1 kW to tens of MW, which are connected to the grid at distribution systems [21]. DGs typically use renewable energy sources and provide a promising solution to utility resistance. In addition to "being green," research shows that DG may effectively relieve stress caused by EV charging on the distribution grid.

I. On-Site DG

From (3) and (5), we observe that power flow on the feeder determines the voltage deviation and feeder loading stress. Placing DG on the same feeder which hosts an EV charging station can offset the EV-induced power flow, and therefore relieve the stress on the distribution system. Equation (4) and (5) show that grid stress can be completely relieved if an on-site DG is placed at the EV charging station. Thus, for an EV charging station at bus k, its on-site DG should have a capacity S_k^{DG}:

$$S_k^{DG} \cos(\theta - \alpha) = P_k^{EV} \cos \alpha \tag{6}$$

where, θ is the DG's power factor angle; α is the impedance characteristic angle of the feeder section k, $\alpha = \operatorname{atan} {R_k}/{X_k}$.

There are, of course, limitations of on-site integration, including space requirements and the feasibility of DG integration at that specific site. However, an alternative solution can be reached by pairing a large EV charging installation with the installation of DG elsewhere in the grid to offset stress or the use of contracts with existing DG units to increase capacity.

II. Multiple-DG

Based on (3) and (5), the condition for m DG units, their dispersion of location and capacity to offset EV charging stress is:

$$\sum_{h}^{m} S_h^{DG} \cos(\theta_h\text{-}\alpha) L_h = P_k^{EV} \cos\alpha \, L_k \tag{7}$$

where L_h and L_k are the distance of DG units at node h and the EV charging station at node k to the primary bus. The above equation for DG's dispersion on feeder becomes more intuitive when considering a special case of all DG operating at unit power factor. Then (7) is rewritten as

$$\frac{\sum_h^m P_h^{DG} L_h}{L_k} = P_k^{EV} \tag{8}$$

Equation (8) shows that *on a feeder where EV charging induces least stress, the charging station is placed in the* ***(electric) center of weight*** *of all the DG units*.

Theorem 1

On a feeder where EV charging induces least stress, the charging station is placed in the ***(electric) center of weight*** *of all the DG units*.

If multiple EV charging stations are present and multiple DGs are used to balance these stations, the importance of the electric center of weight described in (8) holds. In the case of multiple EV charging stations and multiple DGs, the electric center of weight is equal, shown in (9)

$$\sum_h^m P_h^{DG} L_h = \sum_k^n P_k^{EV} L_k \tag{9}$$

Corollary 1

When multiple EV stations and DG's are present, a feeder is subject to least stress, if the electric centers of weight are overlapped for that is induced from DG installment and that is induced from EV charging stations.

C. Power Losses

Distributions systems, along with the electric grid as whole, experience losses while transmitting power to loads. When optimum DG placement within a system is a key goal, the strategy employed can be the optimal active power consumption. As explained within the literature review, many studies have considered optimal DG allocation; however, many strategies are computationally demanding. One study, however, applies a modified loss sensitivity factor approach, which is less demanding and has been expanded here to function with multiple DG units within a distribution system [34].

Real power losses within a system are often represented by an exact loss formula, as in (10).

$$P_L = \sum_{i=1}^{N}\sum_{j=1}^{N}\left[\alpha_{ij}\left(P_iP_j + Q_iQ_j\right) + \beta_{ij}\left(Q_iP_j + P_iQ_j\right)\right] \tag{10}$$

In (10), α_{ij} and β_{ij}, defined in (11) and (12) are dependent on the line resistance, r_{ij}, between ith and jth bus, where $r_{ij} + x_{ij} = Z_{ij}$ are the ijth elements of the Z_{bus} matrix, and the voltage and angle at bus i, V_i and δ_i, respectively.

$$\alpha_{ij} = \frac{r_{ij}}{|V_i||V_j|}\cos(\delta_i - \delta_j) \tag{11}$$

$$\beta_{ij} = \frac{r_{ij}}{|V_i||V_j|}\sin\left(\delta_i - \delta_j\right) \tag{12}$$

Though the original system introduces nonlinear equations, the sensitivity analysis is employed to linearize the original equation around an initial operating point. This method also helps to reduce the size of the solution space. Though this method has been heavily employed within capacitor allocation problems, it has been previously applied to DG allocation [34]. To determine the sensitivity factor of real power losses with respect to real power injection, (10) is differentiated with respect to the real power injection at bus i, P_i, as shown in (12).

$$\alpha_i = \frac{dP_L}{dP_i} = 2\sum_{j=1}^{N}(\alpha_{ij}P_j - \beta_{ij}Q_i) \tag{13}$$

To conduct complete analysis, sensitivity factors need to be completed at each bus. Initially, the values determined from base load flows are used. Sensitivity factor values are obtained for each bus and these buses are then sorted from highest to lowest to determine a priority list. The bus that has the lowest sensitivity factor is the best location for a DG unit [34]. Total losses plotted against injected power creates a parabolic function, which is at minimum when the rate of change for the losses becomes zero (14). (15) and (16) follow from (14),

$$\frac{dP_L}{dP_i} = 2\sum_{j=1}^{N}\left(\alpha_{ij}P_j - \beta_{ij}Q_i\right) = 0 \tag{14}$$

$$\alpha_{ii}P_i - \beta_{ii}Q_i + \textstyle\sum_{j=1,j\neq i}^{N}\left(\alpha_{ij}P_j - \beta_{ij}Q_j\right) = 0 \tag{15}$$

$$P_i = \frac{1}{\alpha_{ij}}\left[\beta_{ii}Q_i + \sum_{j=1,j\neq i}^{N}(\alpha_{ij}P_j - \beta_{ij}Q_j)\right] \tag{16}$$

where, P_i is the real power injection at i, which is the difference between the real power injected by DG, P_{DGi}, and load demand at that node, P_{Di} .

$$P_i = P_{DGi} - P_{Di} \tag{17}$$

By combining (16) and (17), (18) is created and shows the optimum size of a DG unit at each bus i within a given system to create minimum losses. If a size larger than P_{DGi} is chosen, higher losses will occur [x] and these losses are a function of the loss coefficients of the system, α and β.

$$P_{DGi} = P_{Di} + \frac{1}{\alpha_{ij}}\left[\beta_{ii}Q_i - \sum_{j=1,j\neq i}^{N}(\alpha_{ij}P_j - \beta_{ij}Q_j)\right] \tag{18}$$

Loss coefficient values will change as DG are added to the system and new load flow calculations are completed. However, analysis within [34] and analysis conducted for this research show that the effect of updating loss coefficient values is negligible and, thus, optimum DG size was completed from the base load flow case.

Once the optimum size of the DG unit has been determined, the optimum location must be obtained. This is done utilizing an algorithm in which the base case load flow is completed and (18) is used to determine the optimum size of DG for each bus. (10) is then used to determine the losses for each bus if a DG of a size determined via (18) is added. The bus at which losses are at a minimum is then chosen for DG addition and the load flow is then rerun [34]. In the case of multiple DG, as occurs within later case studies, this process is repeated after each DG addition until the desired increase in generation capacity is reached.

D. Pollution Related to Power Losses

After conducting power loss analysis, the losses experienced by the system can be translated into an approximation of pollution resulting from the transmission of electricity within the distribution system. Though this analysis has not been widely done within the literature, estimates of this pollution exist and can be applied to a system. The French Environment &

Energy Management Agency has compiled a list of estimates, which state grams of CO_2 created by kWh delivered for various generation methods [40]. Generation methods of interest are detail in Table II, below.

TABLE II
GRAMS OF CO_2 PER kWh BY GENERATION METHOD [40]

Generation Method	Grams of CO_2 per kWh delivered
Coal	800
Natural Gas	430
Nuclear	6
Solar/PV	60
Wind	3

When electricity is generated it is sent to the loads where it is needed; however, this transmission is not purely efficient. According to the Energy Information Administration (EIA), transmission and distribution losses account for 7.5% of electricity generated in 2012 [45]. Translating this statistic to a meaningful figure leads to an estimate of 1 kWh delivered to a load actually corresponds to 1.075 kWh produced. This disconnect between the amount of electricity generated and the amount of electricity actually consumed by loads leads to an increase in the amount of pollution generated within a system. To conduct analysis on test systems, the losses are first calculated and then translated into kWh per year, as in (19).

$$Pollution = P_L * \frac{6000\ hours}{1\ year} * F_{CO_2} \tag{19}$$

where, P_L is the system losses calculated previously and F_{CO_2} is the coefficient corresponding to pounds of CO_2 created per kWh delivered from Table II. Though this analysis of pollution is not exact, it can provide a glimpse into the capability of DG to reduce pollution through not only reducing power losses, but also utilizing renewable generation methods.

Case Studies

A. *Voltage Deviation and Increased Loading*

To demonstrate the efficacy of DG to counter EV charging station stress, a standard IEEE-37 node test feeder system was used. This system is shown in Fig. 2, below, with the charging station and added DG locations for Cases 1 and 2.

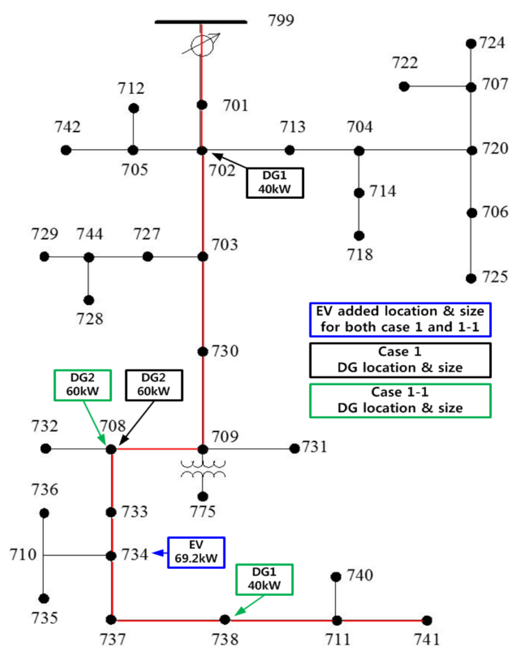


Figure 2. An IEEE-37 node test feeder showing the aggregated locations of DG and EV charging stations for Cases 1 and 2.

Table III shows the initial conditions for each phase within the system and illustrates the initial unbalance present. Within analysis, DG units added to the system were modeled as diesel generators within GridLab-D, a power system analysis software.

TABLE III
INITITAL REAL AND REACTIVE LOADS FOR AN IEEE-37 NODE TEST FEEDER

	Phase A	Phase B	Phase C
Real Power (kW)	727	639	1091
Reactive Power (kVA)	357	314	530

Throughout analysis, loads at their optimum locations were chosen according to (8) and (9). Regardless of the location of these optimal loads, they can be aggregated to the closest node along the main feeder, as shown in Fig. 2. Using (8), Fig. 3 shown the voltage deviation that would result at each possible location if 40kW and 60kW DG units were added.

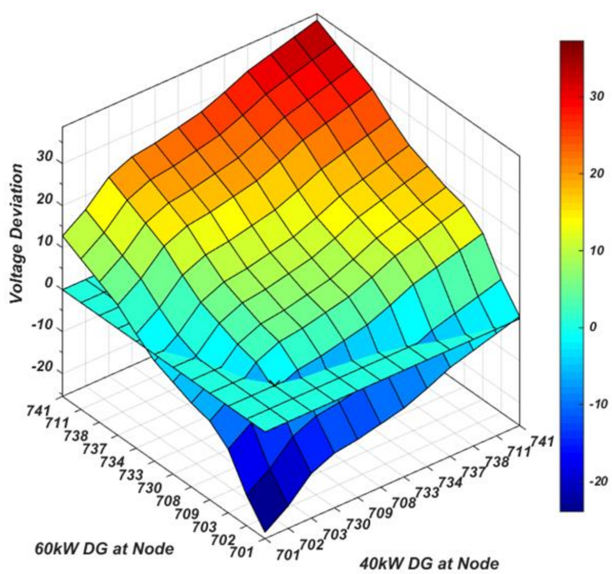


Figure 3. Voltage deviation resulting from DG unit addition at each possible location.

The positive and negative values of the voltage deviation represent that the voltage would be excessively or insufficiently increased by placing the DGs at each corresponding location. The optimal locations of DG units are indicated by voltage deviation of zero to completely offset the EV-induced power flow and the chosen locations are indicated by black arrows.

Several possible solutions of the location and capacity of DGs can be chosen with zero voltage deviation. Fig. 3. shows the optimal DG location at 40kW at node 702 and 60kW at 708. Fig. 4 illustrates the results of Case 1 in all three phases. The voltage and current profiles are negatively affected by the addition of an EV charging station. The addition of two DG units counters this stress in all phases, bringing the profiles close to those of the original feeder load.

To demonstrate the importance of DG unit location on voltage profiles and feeder loading, Case 2 utilizes the same DG capacities as Case 1, but changes their location. It is assumed that there were two AC level 2 chargers at 19.2kW at each installed at node 734. An additional AC level 2 unit and a DC fast unit at 50 kW were added to the same node, increasing the total load to 69.2 kW. The range of DG capacity available was chosen to be from 40 to 60kW, simulating a planning case where available DG capacities are pre-specified and available for system planning. To compare the zero value and positive voltage deviation to the locations selected within the first study, the altered DG locations are moved to 40kW at node 738 and 60kW at 708, which has positive value of voltage deviation. Fig. 5 shows the results of this case in phase A.

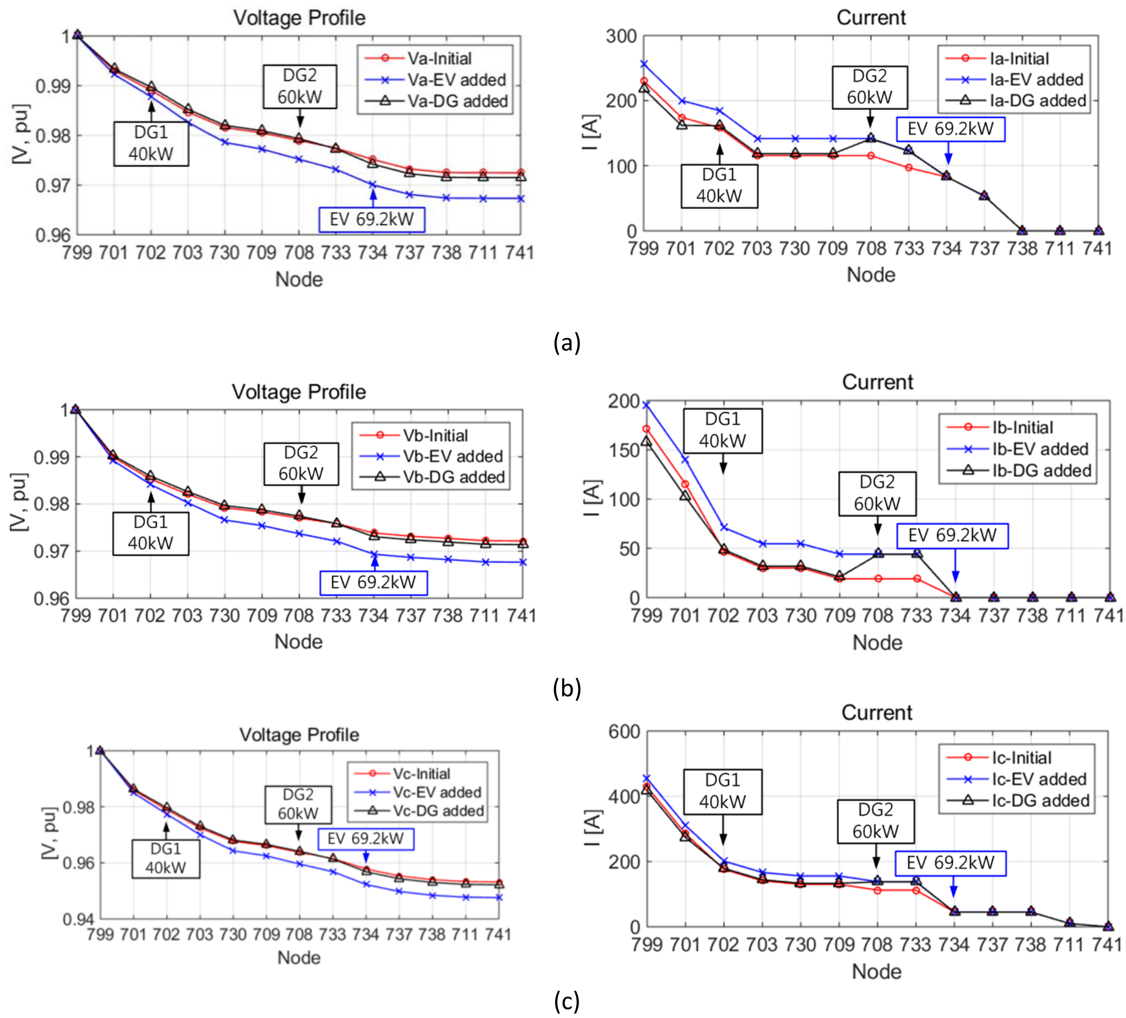


Figure 4. Voltage and current curves of phase A, B, and C with 40kW of DG at 702 and 60kW of DG at node 708

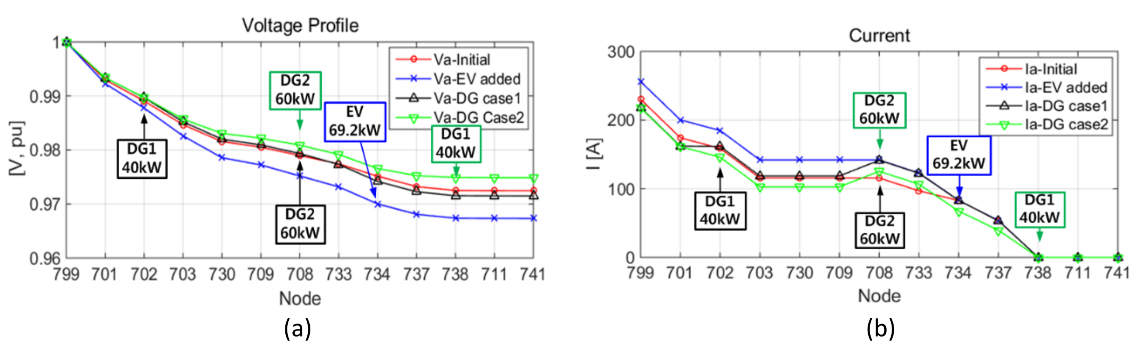
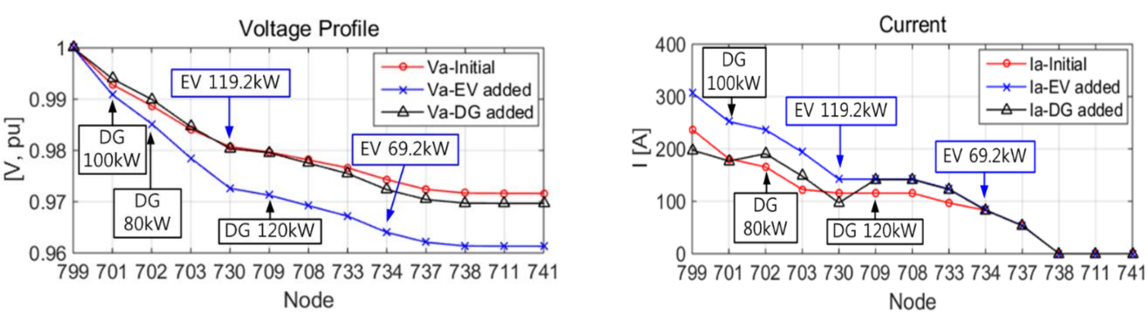


Figure 5. Voltage (a) and load (b) curves in phase A with 40kW of DG at 702 and 60kW of DG at node 708.

A comparison of cases 1 and 2 illustrates that there is more than one solution which will decrease the negative effects of public EV charging on a given system; however, there is an optimal location to have the highest impact.

To futher investigate DG's ability to aide a given system, Case 3 introduces a case of multiple EV charging stations. The charging station created in Fig. 3 remains within the system at node 734 and an additional station consisting of one AC level 2 charger and two DC fast chargers are added to the system at node 730. The total load added to the feeder becomes 188.4 kW. Again simulating a system planning scenario, the range of possible DG capacity is prespecified at 80, 100, or 120kW. To determine the optimal location and capcity, (9) is used to analyze voltage deviation in the same procedure as case one.

Since this case includes three DGs, it leads to the creation of a 12 x 12 x 12 matrix containing possible combinations. Among the options available, a DG configuration of 80kW at node 702, 100kW at node 701, and 120kW at node 709 is chosen, as the voltage deviation is the closest to zero, indicating the most optimal choice. Fig. 6 provides the results of this case using phase A. Other phases are ignored, as the trends in phase curves remain the same as shown in Fig. 4.



(a) (b)

Figure 6. Voltage (a) and load (b) curves in phase A with 80kW of DG at 702, 100kW of DG at node 701, and 120kW of DG at node 709.

B. Power Loss and Pollution Reduction

To further analyze DG's ability to counter stress in a more thorough way, the effect of DG addition on power losses within a distribution system was studied. Using the IEEE-37 bus system previously tested, an initial case was presented, in which EV charging facilities were added. This test case involves the EV charging facilities added to the system within the previous analysis in Case 3. A charging station is present within the system at node 734 with a demand of 69.2 kW and a station consisting of one AC level 2 charger and two DC fast chargers, with a demand of 119.2 kW, are added to the system at node 730. The total load added to the feeder becomes 188.4 kW. To meet this increase in demand, the generation capacity coming from the head of the system, presumably from the power plant providing power to the system, is increased by 188.4 kW. This system state is considered the base case within this analysis. Table IV provides the results of power loss analysis within all three phases.

TABLE IV
ADDITIONAL DEMAND MET BY INCREASED SUBSTATION GENERATION

	Power Loss [kW]
Power Losses in Phase A	38.995
Power Losses in Phase B	16.8461
Power Losses in Phase C	48.6929
Total Power Losses	**104.534**

To determine the effect of DG on losses, Case 2 includes the addition of one 94.2 kW DG unit to meet half of the increased demand, while the remaining half of the demand is still supplied by the substation, as in Case 1. These results are shown in Table V, which illustrates that the losses are decrease by almost 10 kW through the addition of one DG unit in the case of maximum losses, when placed at bus 742, and by over 20 kW in the case of minimum losses, when placed at bus 740. To determine the location of DG for maximum and minimum losses, the algorithm detailed in the analysis section was implemented. This procedure is listed step wise, below [34]:

1. The base case load flow is run on the system.
2. The optimum DG size for each bus is determined using (18).
3. Using the optimum DG size found in step 2, the losses that result from placing these optimum DG sizes at each bus are found.
4. The buses at which the loss is at minimum and maximum are located.
5. In the case of the addition of multiple DG units, steps 2 through 4 are repeated after each DG unit is placed at the location of minimum loss until all DGs are placed.

TABLE V
CASE 2 - HALF OF ADDITIONAL DEMAND IS MET BY ONE DG AND HALF BY INCREASED SUBSTATION GENERATION

	Power Loss (min) [kW]	Power Loss (max) [kW]
P_loss in Phase A	29.5032	36.0007
P_loss in Phase B	14.5662	14.647
P_loss in Phase C	39.8586	44.7776
Total P_loss	**83.928**	**95.4253**

Case 3 involves meeting the total additional demand caused by the EV charging stations with one DG unit. The same computational procedure is used as in Case 2. Table VI shows that when placed at the bus that causes maximum losses, bus 742, the DG will reduce losses by 16 kW, and when placed at the bus for minimum losses, bus 711, losses are reduced by 36 kW.

TABLE VI
CASE 3 - ALL ADDITIONAL DEMAND MET BY ONE DG UNIT

	Power Loss (min) [kW]	Power Loss (max) [kW]
P_loss in Phase A	21.906	33.9029
P_loss in Phase B	13.8585	13.2403
P_loss in Phase C	33.0286	41.7001
Total P_loss	**68.7931**	**88.8433**

Finally, the computational procedure is run through step 5 to determine the optimal size and location of DG units within the system to result in minimum losses. While running the MATLAB code used to calculate the optimal location and size of DG based on the losses that would result from their insertion at each bus, Fig. 7 was created. This figure displays a graphical representation of losses the system will experience based on size and location of a DG unit.

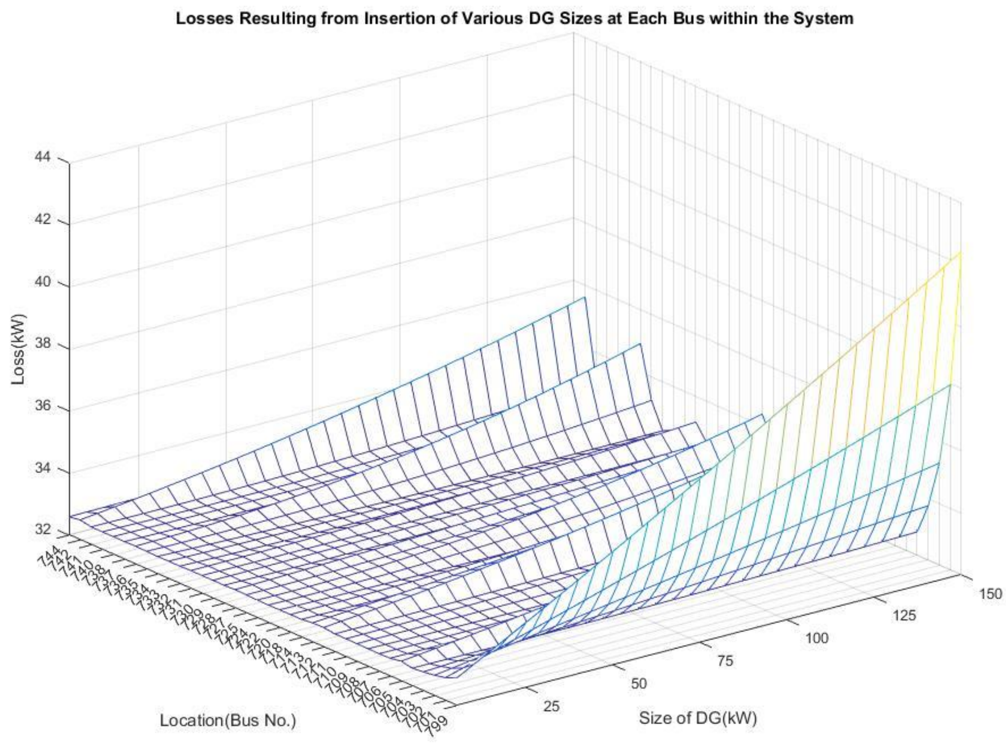


Figure 7. Simulation results display the losses experienced due to DG insertion at various locations and sizes.

Results shown in Table VII demonstrate that DG units of 127.139 kW at bus 711, 85.1032 kW at bus 710, and 75.4876 kW at bus 733 result in very low losses compared to the base case in Table IV. Through Cases 1 through 4, losses are almost halved through the addition of DG.

TABLE VII
CASE 4 - THE OPTIMAL SIZE AND LOCATION OF THREE DGS TO CAUSE MINIMUM LOSSES

	Power Loss [kW]
P_loss in Phase A	15.874
P_loss in Phase B	12.5264
P_loss in Phase C	27.0623
Total P_loss	**55.4627**

Using (19), pollution analysis was carried out to obtain an approximation of the grams of CO_2 saved through the use of DG within the distribution system to meet the increase in demand caused by EV charging stations. For the purpose of this analysis, any increased generation supplied by the substation is assumed to come from a coal powered plant, while DG generation is assumed to be from solar PV arrays. From Table II, coal results in 800 grams of CO_2 per kWh, while solar PV arrays cause 60 grams of CO_2 per kWh. It is important to note that these pollution calculations are only concerned with the grams of CO_2, which result from the additional generation capacity within the system. Thus, for each case the losses are considered with respect to which generation method contributed the increase in capacity. For example, in Case 1, only the substation increased production and all pollution caused by the losses is considered to be wholly caused by the substation. In Case 2, half of the pollution is considered to be from DG and half from the substation, as each contributed half of the overall capacity increase. In Cases 3 and 4, the substation capacity was not increased, thus only the solar PV array DG units are considered the pollution sources.

TABLE VIII

POLLUTION CAUSED BY INCREASED GENERATION CAPACITY FOR EACH OF THE FOUR CASE STUDIES

Case	Coal Pollution (g CO_2)	Solar PV Pollution (g CO_2)	Total Pollution (g CO_2)
1	501763200	0	501763200
2	201408000	15105600	216513600
3	0	24765516	24765516
4	0	19966572	19966572

The results shown above illustrate that in the simplified case simulated, the decrease in losses significantly reduces the amount of carbon dioxide pollution caused by increasing generation capacity to meet the needs to EV public charging.   From the base case, Case 1, to a system where additional demand is met by optimal placement of multiple DG units, Case 4, the pollution is reduced by one quarter of its original value. By further incorporating DG into distribution systems within the nation and around the world, system planners can work to ensure that the increased demand caused by EV does not lead to increased pollution and further the “green” goal of electric vehicles.

Conclusion

With more Electric Vehicle (EV) being driven, providing public EV charging becomes increasingly important. Public EV charging, in particular fast DC charging, will cause excessive loading of power delivery equipment and voltage deviations in the electric grid, putting a challenge on today's electrical infrastructure. This research has provided a method for quantifying the amount of voltage deviation and increased feeder loading that distribution systems can experience when public EV charging stations are installed. Analysis also shows that coupling EV charging station installation with DG can effectively offset this stress on the grid. Power losses are ever present within the electric grid and after quantifying the losses caused by the installation of charging stations, a procedure was implemented to illustrate that the use of DG to meet increased demand can lower losses within the system, even if the size and location are not optimal. Using DG as a strategy to meet increased demand also results in a lower carbon footprint within the system, as CO_2 pollution is reduced. This use of DG to offset grid stress can enable the construction of more EV charging stations, which can increase sales in an area, and also furthers the "green" goal of EVs.

Further study to reach the "green" goal of EVs will include modeling reactive power control for EVs to allow them to serve as DG units, providing reactive power or absorbing reactive power from the grid as needed. The variability in renewable generation can be incorporated with models to determine the effect of too much or too little DG output in relation to the increasing loading and voltage deviations. On-site stationary electric storage, installed at the household level, can provide a way to further power EV in the absence of high DG output, without adding more stress to the grid. Further and more complete quantitative analysis into pollution generated within each stage of the electric grid can further illustrate the “green” benefits of DG. Continuing to make generation more renewable through combinations of energy storage and generation technologies will further facilitate EV adoption and sales.

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