A Unified Power System Model to Analyze the Benefits of Electric Vehicles in Power Grid

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***Abstract*—Electric vehicles (EVs) can serve as generators, supplying power during blackouts to mitigate potential damage and losses. However, current power system models prevent a comprehensive analysis of EVs' role in power grid operations since EVs are located at the residential level, and large-scale power system studies use separate models for generation, transmission, and distribution. To analyze how EVs can improve the power grid operations under contingencies, it is necessary to construct the power grid model considering three aspects.**

This paper presents an undergraduate senior design study that introduces an end-to-end model of the electric grid that includes generation, transmission, distribution and customer. Based on the proposed model, the authors build a synthetic grid for Bryan/College Station (BCS) area to analyze the benefits of EVs in power grids. The proposed model not only presents a more complete model of EVs and distributed generation but also provides different scenarios for EVs' benefits studies.

***Index Terms*—Electric Vehicle, Unified Power System Model, Power System Restoration, Peak Load Shaving**

I. Introduction

The world today depends on power. From essential life support to business communications, power is a necessity. Daily life slows without it due to the interruptions it causes. Minor blackouts can be recovered quickly, however, large scale blackouts lasting more than a few hours can be detrimental, costing billions of dollars in irreparable damage [1]. The cost of the 2003 Northeast blackout ranges from $4 billion to $10 billion dollars [2]. Mortality rates increased two to eightfold during the blackout from respiratory, cardiovascular, and renal diseases [3]. Blackouts can cause delay of emergency services and damage the equipment and its function that rely on continuous power supply. In power systems, it is an important task to ensure the reliability of power supply and restore blackouts timely.

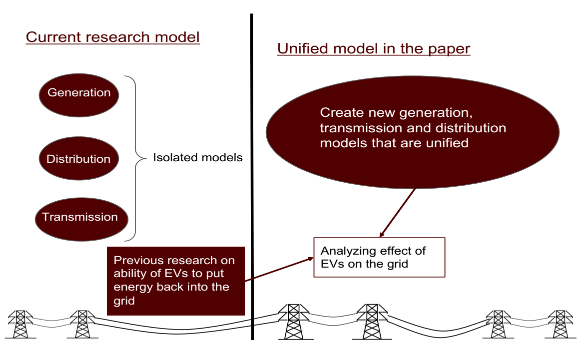

Figure 1. Block Diagram for Power System Models: Current research has separated models for different systems and the target of this paper is to connect all subsystems together to study EVs

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For critical infrastructure in distribution system, blackout restoration service is rather important since it directly affects customers. In [4]–[6], several control and management schemes of microgrids and distributed energy resources (DERs) have been proposed for reliable and efficient distribution system restoration. However, the required investment of new microgrids and DERs are huge, and actual construction can also take a long time. On the other side, our daily activities rely much on vehicles. The price of electric vehicles (EVs) is dropping rapidly [7], which make them competitive to traditional gasoline vehicles in the market. The replacement of traditional gasoline vehicles with EVs is not only environmentally friendly but also can be utilized for energy management. In [8], it presents a review of vehicles-to-grid technologies and shows their benefits with different strategies. Since EVs are a source of power generation, they help improve the robustness of the grid under contingencies [9]. Batteries from electric vehicles can help synchronize and sectionalize the power grid, aiding quicker restoration that puts less strain on the overall system. In the event of a blackout, all loads with EVs could be isolated and then energized using the Electric Storage Unit (ESU) from EVs. After these sectionalized components are synchronized, they assist in reenergizing the rest of the circuit [10]. In [11], Gouveia et al. discuss the application of EVs in microgrid for restoration service and develop a self-healing strategy for microgrid with the help of EVs. In [12], Sun et al. propose an optimal power system restoration model with the support from EVs battery to efficiently restore a power system without black-start generators or insufficient cranking path from black-start generators.

With the increasing popularity of EVs, they can also be utilized to improve the reliability and security of power systems. In [13], Clement et al. propose a coordinated charging profile of EV to minimize the power loss and maximize the main grid load factor. They also implement a voltage constraint for coordinated charging and discharging to support the grids with voltage control and congestion management in [14]. In [15], Falahi et al. analyze how the EVs can improve the power quality in distribution systems. Khodayar et al. formulate a stochastic security-constrained unit commitment model to integrate aggregated plug-in EVs in power grids to mitigate the variability of renewable energy sources and reduce grid operation cost [16]. In [17], Talebizadeh et al. bridge the unit commitment problem with plug-in EV and show the EVs can significantly reduce operation cost and share load from expensive generation units. Even though the above researches demonstrate the great potential and benefits of utilizing EVs in power systems, they are focus on distribution side analysis and lack of consideration from transmission side.

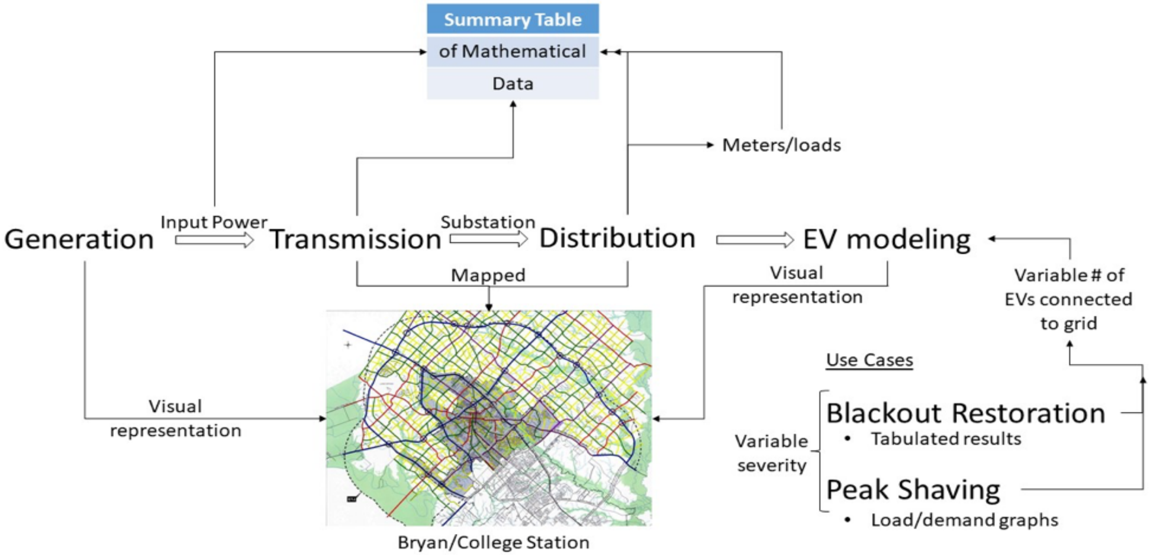


Figure 2. Overview of the Proposed Unified Model: The unified power grid model for EV studies, including generation, transmission, distribution, and EV modeling, with detailed visualization of BSC area. Two use cases for EV studies: Blackout Restoration and Peak Shaving. All data are collected to *MATLAB* for mathematical analyses within *MATPOWER*.

As shown in Figure 1., there are typically segmented models of transmission and distribution in power systems for specific studies. There are powerful transmission network models available that researchers and utilities may use to analyze the power grid [18], [19]. The situation is similar for distribution systems [20]. There are also different models being proposed, i.e. [21]–[23], to analyze EVs' effect on power systems. However, these models focus on the distribution networks instead of a complete view from the whole grid. EVs and other loads can affect the entire system. To understand the impact and schedule EVs, it is necessary to create a model that allows us to view the entire power grid at once. Thus, this paper presents a senior undergraduate design project that creates a unified model for power system studies, connecting generation, transmission and distribution down to a residential level with an EV model. This model can help people analyze how EVs connected in a residential level could affect the operation of the whole grid under different contingencies, such as blackout restoration and peak load shaving.

The contributions of this paper are as follow:

1) This paper presents a unified model for a complete view of power grids and it can be updated to different areas with corresponding data.
2) Based on the map of Bryan/College station (BCS) area and the data of connected transmission networks, this paper presents a detailed synthetic grid beginning at generation all the way down to a residential level.
3) The proposed model can provide conclusive numerical evidence that demonstrates the effect of EVs on the grid for power system restoration and peak load shaving.

The rest of paper is organized as follow. Section II presents the architecture of the proposed unified model with specific use cases for EV studies. In Section III, with the required data, we build a synthetic grid for BCS area. Section IV shows the application of the unified power grid to analyze how EVs can contribute to power system restoration and peak shaving. More discussions of EVs' benefits are in Section V.

II. A Unified Model for Power Systems

MATPOWER [24] is an open source package that can simulate the power grid in detail and provide a platform to analyze the output data. The proposed model is built in *MATLAB* [25] and can be exported into an application that can be utilized on any computer. The application allows the user to have a complete view of power grids under different circumstances and modify the number of EVs on the grid at a time to study the benefits of utilizing EVs. Figure. 2 shows the unified model with generation, transmission, distribution, and EVs in BCS area. As shown in the figure, the unified model collects data from all segments for mathematical analyses within *MATPOWER*. There are two use cases for EV studies with this model: blackout restoration and peak load shaving. The contingency for each use case can be created in *MATPOWER* by modifying the initial state of the grid. Through modifying the number of EV connected in the grid, the contribution of EV for each contingency can be analyzed. Each segment of power systems has been modeled as follow:

1) **Generation**: a mathematical model that demonstrates the power being delivered to the system.
2) **Transmission**: a detailed visual presentation and mathematical model that shows the power flow.
3) **Distribution**: a detailed synthetic grid model based on the local mapbook parcel data to present the residential information.
4) **EV Model**: a 3.3 kW bi-directional inverter that can transfer energy with the grid simulation [26]. The total power output from EVs is as follow:

$$P_{output} = N \times 0.0033 \times d\% \quad (1)$$

where N is the number of EVs connected in the grid and d is the deviation from daily human activity and an average load.

The unified model has a map of the distribution, transmission and parcels of the area modeled, which includes a visual representation of the generators, transmission lines, distribution lines and residential areas. There is also a detailed tabular representation of the output from the grid, load and EVs. The tabulated results allow the user to view and compare the results with different amounts of EVs on the grid at a time.

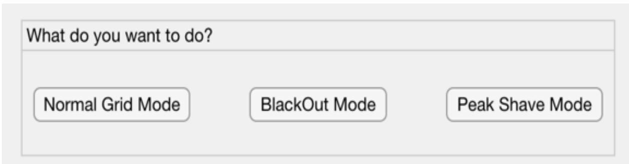
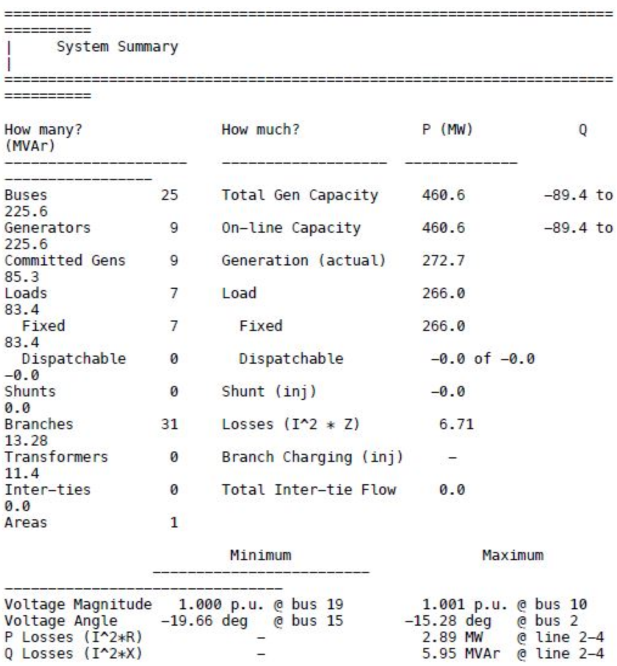


Figure 3. User Interface for Selecting Analysis Mode: **Normal Grid Mode**, **BlackOut Mode**, and **Peak Shave Mode**.



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==========================================================================
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|     System Summary
|
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How many?                How much?              P (MW)            Q
(MVAr)
---------------------    -------------------  -------------
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Buses               25    Total Gen Capacity     460.6         -89.4 to
225.6
Generators           9    On-line Capacity       460.6         -89.4 to
225.6
Committed Gens       9    Generation (actual)    272.7
85.3
Loads                7    Load                   266.0
83.4
  Fixed              7      Fixed                266.0
83.4
  Dispatchable       0      Dispatchable          -0.0 of -0.0
-0.0
Shunts               0    Shunt (inj)             -0.0
0.0
Branches            31    Losses (I^2 * Z)         6.71
13.28
Transformers         0    Branch Charging (inj)    -
11.4
Inter-ties           0    Total Inter-tie Flow     0.0
0.0
Areas                1

                           Minimum                      Maximum
                 -------------------------
--------------------------------
Voltage Magnitude   1.000 p.u. @ bus 19        1.001 p.u. @ bus 10
Voltage Angle     -19.66 deg   @ bus 15      -15.28 deg   @ bus 2
P Losses (I^2*R)             -                 2.89 MW    @ line 2-4
Q Losses (I^2*X)             -                 5.95 MVAr  @ line 2-4
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Figure 4. System Overview Output From **Normal Grid Mode**

Figure 3. shows the three modes in the unified model to study EVs in power systems, **Normal Grid Mode**, **Blackout Mode**, and **Peak Shave Mode**. For specific purpose, users can select corresponding mode. The user is able to view the entire grid under normal load conditions in **Normal Grid Mode**, which shows the basic power system information of the grid, such as the total generation, total load, bus status, etc., in a tabular form with summarized results, as seen in Figure 4. To analyze EVs' benefits for power grid operations, the user can use **Blackout Mode** and **Peak Shave Mode**, where the user can modify the number of EVs in the grid, change the status of generation plant, and observe the improvement with the model's analyses and output.

In **BlackOut Mode**, there are different levels of blackout severity that users can choose from and users can vary the number of EVs on the grid, which can be seen in Figure 5. When the program runs, it provides the usual tabular output of the grid and a blackout restoration analysis with how long restoration takes, how much the time is improved and how the strain is reduced on local generators with the help of EVs. Moreover, it also provides a visualization of transmission and distribution system during the blackout.

In **Peak Shave Mode**, there is an interactive table that demonstrates the load in a 24-hour period in the BCS area and how it changes as the number of EVs connected to the grid change. The output of this mode is two plots showing the demand versus the generated power before and after EVs are added to the grid as shown in Figure 9. More applications and analyses regarding to EV's contribution with these two modes are in Section IV with BCS grid's data.

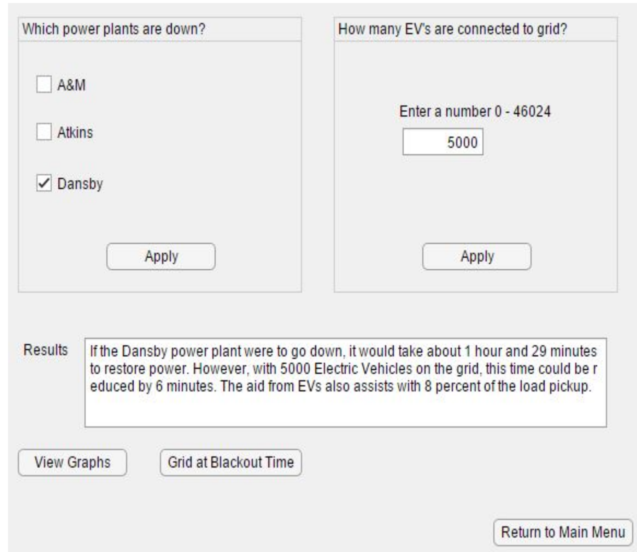


Figure 5. User Interface for **BlackOut Mode**. Users can select the power plant(s) down and input the number of EV that connect to the grid.

III. BCS Grid Model

This section shows the data of each subsystem in BCS area.

a) Generation Data: The generation model is based on power generated from the Dansby and Atkins natural gas power plants and Texas AM University Central Utility plant located in the BCS area. The total energy provided by the three plants is 272 MW, which are capable of solely supporting the area. Afterwards, the power is transmitted to the step up substation to 138 kV and sent through transmission lines. To estimate the restoration time, each generator's start time, ramp rate, stabilization time, and drive time are also considered.

b) Transmission Data: The transmission model is based on the transmission line mapping of the BCS area. The transmission system receives data from generation. In this case, it is from three power plants in the BCS area. The lines traveling away from the plants are 138-kV or 69-kV, 60 Hz three phase power. This level of voltage will remain until the lines reach a substation.

c) Distribution Data: Figure 6. represents the distribution system in BCS area based on the parcel map [27]. Each parcel is assigned to a substation through the corresponding feeder. In each parcel, there are specific labels of residential area and commercial area and we assume the energy consumption of commercial area is twice as residential area. In this way, we can determine the weight for each parcel in the same feeder and calculate the energy consumption for each parcel based on the total load supply from the substation.

d) EV Model: EVs' parameters follow the battery in Tesla Model 3 whose parameters are 75 kWh, 350 V. The simulation is able to show both the effects of EVs pulling

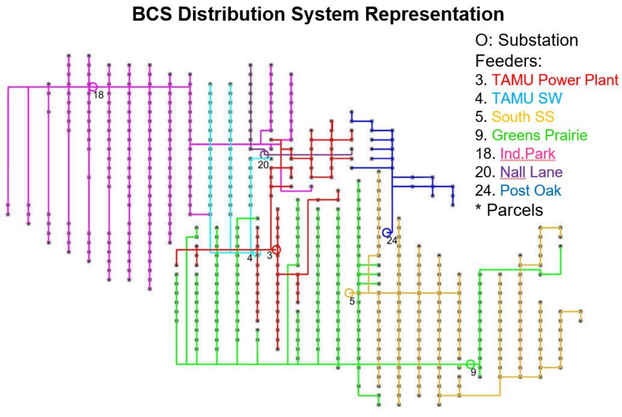


Figure 6. BCS Area Distribution System with Parcel Assignment

power from the grid as well as the distributed generation resources to inject power into the grid [26].

When the system is turned on, $MATPOWER$ [24] analyzes the input data for generation and transmission, that is calculated based on information from power plants, the BCS transmission map and Texas synthetic grid [28]. From this data, the system calculates information about every bus and branch in the transmission system as well as information about the overall load and generation. Data used is calculated in our transmission system to determine which substations are active in distribution and how much demand is on each of them. With this information, load demand is calculated for every parcel.

IV. Case Studies

As mentioned before, EVs are usually used to provide more robustness to power systems during contingencies, like blackout and peak load. In this section, based on the unified power grid model of BCS area, it analyzes EVs contribution to power system restoration and peak load shaving.

A. Power System Restoration

With the unified model of BCS area, we analyze how EVs can contribute to the restoration regarding to restoration time and how much load relies on generators. As shown in Figure. 5, the **BlackOut Mode** allows users: (1) to simulate varying severity blackout scenarios in BCS area by selecting different power plants down and (2) to input the number of EVs as an additional generation source in the model. The grid simulation provides the power flow and losses information of the system and the user interface provides the results of the improvement of power system restoration with the help of EVs.

Since there are three generation plants in BCS area, this paper considers all scenarios of plants are down and analyzes EVs' contribution to power system restoration with different number of EVs connected in the system. For each scenario, there is a scheme and order of restoration that chooses which generator is re-energized first followed the guideline set by the industry [29]. With the simulation, the amount of power delivered to assist in generation pickup is calculated which can decrease the power needed to ramp up and therefore decreasing the time. In addition to time reduction, the **Black-Out Mode** also analyzes the percentage of load pickup that is reduced with the addition of EVs. Different scenarios of generators down correspond to different amounts of load that is shed to keep the power balance. The amount of load needs to be restored can strain the generator. Increased generation sources from EVs reduces some of this strain, which is equivalent to the load percentage on generators.

Figure 7. shows the contribution of EVs during the restoration when all power plants in BCS area are down, which is the most severe situation. From the figure, it can be clearly seen that EVs have positive impact to power system restoration in a distribution network. The total restoration time and reliance on generator is reducing with more EVs connected. In this way, EVs can be managed to assure the restoration of some critical load, such as hospitals, in a timely manner. Figure 8(a). and Figure 8(b). show the time needed for restoration and the load percentage on generations for all blackout situations with EVs' help in BCS area respectively. The results keep the same pattern, especially when there is one power plant down, with enough EVs, some load can completely rely on EVs. However, the restoration time reduction is not much improved when A&M power plant is down. Since the unified model considers the transmission network from outside, electricity can also be supplied from outside. A further economic analysis between the power plant generation cost and EVs scheduling cost need to be conducted to better assess EVs' benefits in the long run.

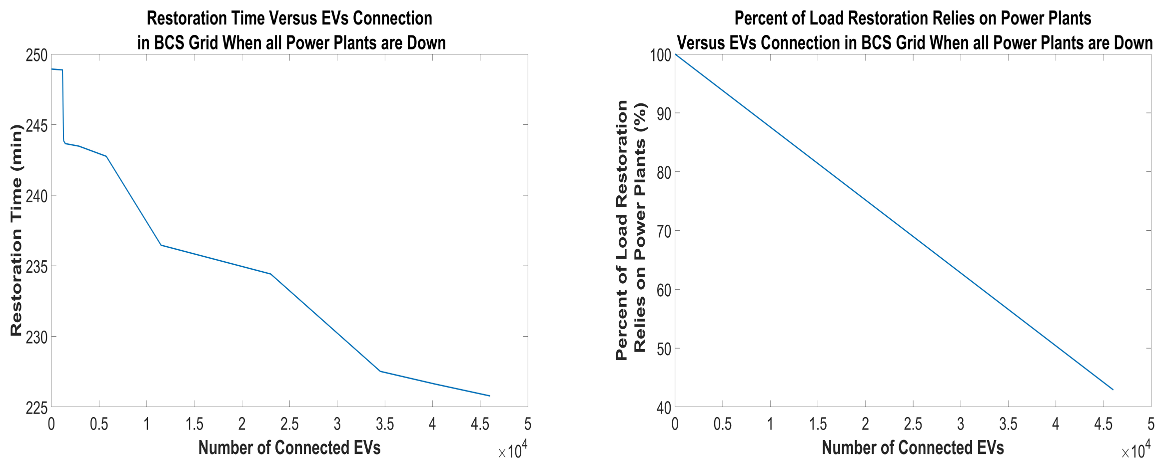
B. Peak Load Shaving

Besides power system restoration, the flexibility of EVs' charging and discharging allows them to be used to shave peak load to release the burden from generators. In certain situations where the load gets too close to the available power, the utilities may have to intentionally put customers out of power in order to keep the rest of the system stable. EVs can help reduce the load demand or keep residences online while they are being shed. To analyze EVs' contribution, the **Peak Shave Mode** models the load of the grid in BCS area for a typical spring day over a 24-hour period, which is based on an average of human activity reported from the Electric Reliability Council of Texas (ERCOT) [30]. EV's output is 3.3kW and the total impact is based on the number of EVs in the network. The **Peak Shave Mode** allows users to simulate the load vs. time demand in the BCS area and see how EVs impact the grid in terms of load profile. This analysis works on the premise that electric vehicles have the ability to put energy into the grid during the day and take energy at night.

Figure 9. shows the load profile under different numbers of EVs connected in the grid. The red line is the load profile for 24 hours. When there is no EV in the grid, the peak load can be as high as 275 MW, which is over the total output from local generators. When there is no support from outside through transmission networks, some customers have to be cut off electricity. With EVs' help, the load profile can be re-shaped to ensure there is enough local generation for the load. However, with too many EVs in the grid, since EVs are the consuming energy at night with the assumption, the peak load hour is completely shift to the night, which may still cause some issues. Therefore, how to reasonably schedule EVs' charging and discharging modes is an important task for future studies and development.

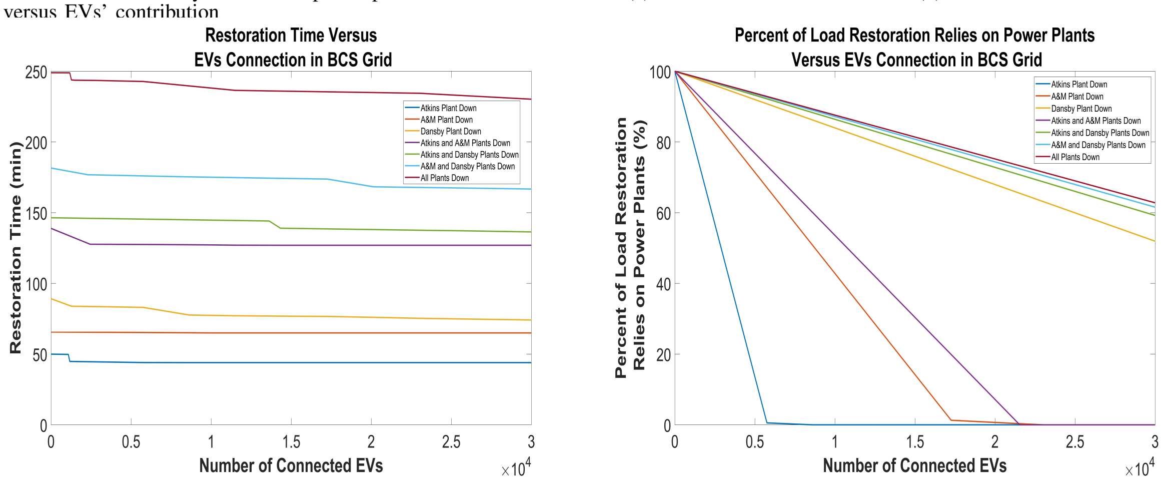
V. Discussion of EVs' Benefits from Case Studies

With the power system restoration study, it can be seen that EVs, which has the bidirectional capability to transfer energy with grids, can be used for blackout restoration with some adjustments to power utility operation. However, to observe



(a) (b)

Figure 7. **BlackOut Mode** Analysis when all power plants are down in BCS area:(a) Restoration time versus EVs' (b) Percent of load relies on power plants to pick up versus EVs' contribution



(a) (b)

Figure 8. **BlackOut Mode** Analysis for all scenarios of power plant outages in BCS area:(a) Restoration time versus EVs' (b) Percent of load relies on power plants to pick up versus EVs' contribution

a significant improvement with the current data, it requires a large number of EVs in the grid. They still have the potential to reduce restoration time and the strain on generators from picking up load. With their flexibility, the EVs can be better managed for critical infrastructure' restoration.

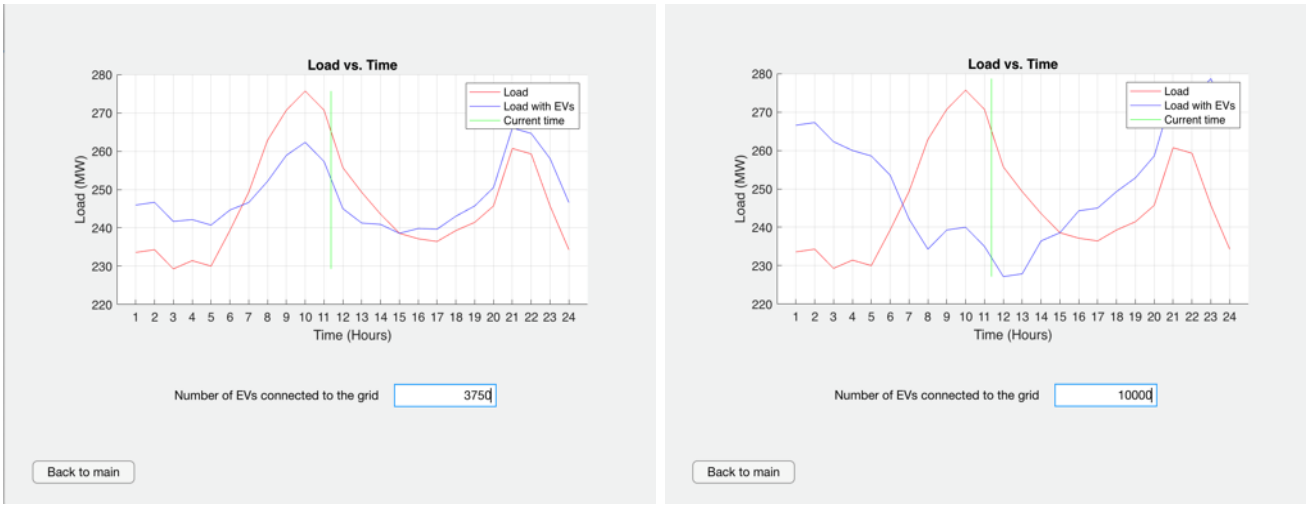
From the peak load shaving case, it can be concluded that EVs can be used in events of peak load shaving to help reduce the strain on power plants to supply load. EVs can inject power into the grid to reduce the load demand during peak hours and recharge the battery during lower demand hours. However, charging too many EVs at the same time may still cause generation deficiency. Therefore, how to reasonably schedule EVs' charging and discharging modes is an important task for future studies.

With two case studies presented, the main conclusion can be drawn from this paper is that EVs can improve the power system's robustness with more flexibility to supply power to the grid. Meanwhile, due to the limitation of EV models and real time data analysis, the conclusion from this paper requires a large number of EVs connection in the grid for an obvious benefit.

VI. Conclusion and Future Work

This paper presents a unified power grid model to analyze EVs' contribution for power system operations with a complete power system view. With the data of BCS area, the current model is marketed to researchers in the field of power systems who would like to learn more about how EVs can affect the grid in the BCS area. From case studies, even though the positive impact requires a large number of EVs, it is clear that EVs can provide more robustness during contingencies and have positive impacts for power system operations. Moreover, the unified model connects transmission, generation and distribution, which may reduce the severity of the contingency in BCS area, since it can import electricity from outside. Even though the benefits of EVs require a large number of EVs, on the other side, the studies show the great potential of this unified model to capture a complete view of power systems for EV studies.

For future work, the unified model can be developed in the following directions. First of all, it can be modified for any local area with the required data, making the model useful for different areas. Secondly, the type of EV model can be enriched, the economic information can be considered,



(a) (b)

Figure 9. User Interface for **Peak Shave Mode**: (a) 3750 EVs are connected to the grid - the peak load is shaved; (b) 10000 EVs connected to the grid - the peak load is shifted from day to night.

and the control mechanism can be embedded, which can be used for more EV studies, like the optimal charging and discharging schedule, the comparison of different EVs, the transient analysis, etc. Thirdly, the current model only provides stationary results for different scenarios. However, the model has the ability to develop a real-time simulation with incoming data from each segment. In this way, more analyses can be done, such as energy trading, online scheduling, etc.

Acknowledgment

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