Electric Vehicle Transportation Center

Techno-Economic Analyses of Large-Scale Electric Vehicle Systems

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The objective of the Techno-Economic Analyses of Large-Scale Electric Vehicle Systems was to develop a computer model to evaluate the techno-economic implications of a large-scale electrified transportation sector. The model factors included the developing and interacting with a network of electric vehicles and the electric grid, the infrastructure for electric vehicle charging, the integrating of the transportation and power systems into the urban setting, the studying of the impact of distributed energy storage and the determining of the economic impact of increased renewable energy and EVs on the electricity grid. The work was conducted by Dr. Zhihua Qu, Principle Investigator, his graduate students and postdoctoral researchers (who are first authors of resulting publications) in the College of Engineering and Computer Science at the University of Central Florida.

Final Research Project Report

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1.0 Abstract

This project developed the process, methodology and algorithms for computer models to evaluate the techno-economic implications of a large-scale electrified transportation sector. The model factors include developing and interacting with a network of electric vehicles and the electric grid, the infrastructure for electric vehicle charging, integrating the transportation and power systems into the urban setting, studying the impact of distributed energy storage and determining the economic impact of increased renewable energy and EVs on the electricity grid and its stability. The modeling related project results are presented in five journal articles and two conference papers. In this final report, the project results are presented in four sections; (1) EV Capacity for Distributed Generation and Stochastic Optimization Using V2G Capacity Forecast; (2) Multivariate Predictive Analytics for Control of Energy Storage; (3) Modularized Design for Cooperative Control and Plug-And-Play Operation; and (4) EVs and Smart Grid Control and Generation Methods for Integrating Distributed Generators.

2.0 Background

In the future, transportation systems policy and planning will see the need for close coordination and the combining of efforts with the policies and planning for electrical power systems. Mathematically, a techno-economic model of EV integration would be constructed as a constrained economic dispatch problem that includes an optimization framework of conventional and renewable electricity generation, residential, commercial and industrial energy loads, and a transportation sector with EVs and their charging loads.

For a typical EV owner, EVs are used when needed (and hence the transportation need is of highest priority), but EV usage, on average, is a small fraction of the use time. Accordingly, EVs need to be charged by the grid, called G2V, but not necessarily each time used or during an optimized grid time period. Thus, for the majority of time EVs can provide ancillary services or grid storage, called vehicle to grid (V2G). This optimization problem is subject to the constraints of EV-usage time, capacity limits (for each battery set), charging/discharging rate, power transfer limits (of charging stations, substations, and transmission lines), and load/generation profiles. If the optimization problem is solved for different penetration levels of EVs, a fully quantified model of the techno-economic impacts of EV adoption would result.

Figure 1. Electric vehicle charger on UCF campus with PV power assist. Photo: Enrico Sacchetti

The fundamental challenge to solving the optimization problem is threefold. First, transportation system needs must be prioritized. There are traffic flow forecasts pertaining to specific cities/municipalities studied, but there is a lack of modeling that is transferrable for performing systematic studies, nor is there any quantitative data on EVs and their usage differences from conventional internal combustion vehicles. Second, G2V and V2G services require charging/parking infrastructures that are currently in their initial utilization stages and, hence, difficult to evaluate since there is no reliable large-scale model at this time. Third, consumer/commercial loads, dispatchable generation, and renewable power generation resources (solar and wind) are variable, but their combination can balance vehicles' charging needs over time. For example, daily electricity usage patterns change as more EVs are integrated, and scheduling of other adjustable loads can be changed accordingly to minimize the need of increasing the peak load. Such data collection and behavior modeling at the consumer and aggregator levels are required to perform meaningful, techno-economic studies.

Finally, storage technologies (including batteries) have been shown to be very effective in improving both economic operation and resilience of electric grids due to several reasons [1]. First, storage devices can release active power when grid prices are high and store excessive energy when grid prices are low (and even negative), which gives the primary reason for improvements in economic operation of electric grids [2, 3]. Second, active power can be controlled transiently to help stabilizing the frequency of the overall power system [4]. Third, storage devices such as battery banks are equipped with power converters/inverters, and these power electronic devices are capable of supplying reactive power with or without supplying active power [5]. Reactive power compensation is essential to maintain voltage stability within the power grid [6, 7]. Frequency control and reactive power compensation are ancillary services traditionally supplied by spinning reserves (i.e., generators running partially idle), and costs associated with keeping these reserves online can be alleviated by real time control of battery storage [8]. Finally, renewable energy sources are inherently variable and intermittent, and battery storage can smooth out renewable energy output and, in turn, provide a level of resilience [9]. All these aspects of energy storage are directly related to EVs and their use in the transportation system network.

Accordingly, the project research focused upon developing the system-level modeling and optimization methodology for techno-economic analysis of EV energy systems. At the system level, the most critical issue was to formulate an appropriate optimization problem that consists of the constraints, the uncertainties in loads, the power generation, and G2V/V2G interactions. There are two basic ways to handle uncertainties.

One is the so-called robust optimization which is a deterministic set-based method to model uncertainties. Advantages of this method are that it requires only moderate amounts of information, such as the support and moments of the underlying uncertainties and that it yields a robust solution against all possibilities of uncertainties within their sets [10]. The robustness property is consistent with the reliability requirement of power systems operation, but the methodology of robust optimization can give the optimal worst-case solution and, hence, the resulting cost is usually higher.

The better alternative is stochastic optimization which is modeling uncertainties as random variables and using available data to further quantify these random variables through estimating their probabilistic distributions. Upon having joint distributions of random variables, the constraints involving the random variables can be converted into deterministic constraints by imposing a risk-tolerant level. This chance-constrained stochastic optimization framework is applied to the techno-economic analysis of EV energy systems.

3.0 Research Results

With the above modeling comments made, the project results are presented in five journal articles and two conference papers that are listed in the Project References section. The results from these publications are presented in four topic areas as follows.

3.1 EV Capacity for Distributed Generation and Stochastic Optimization Using V2G Capacity Forecast

The interaction of EVs and grid through distribution networks can lead to an increased power demand and less responsive voltage profiles. This paper [11] investigates a way of quantifying the economic benefits of V2G technology as an effective means of buffering active and reactive power fluctuations, thus providing voltage and frequency control. Forecasts of V2G capacity that are based on the average availability of vehicles expected to be available from clusters of EV chargers are used to build stochastic measures of uncertainty such as density forecasts. This contrasts with point forecast that provides only a single value for the considered time resolution. Thus, the projected mean values of the V2G capacity can offer distributions of V2G capacity for different future times. This ability of predicting probabilities associated with different V2G power levels in the future is critical for a successful integration and control of the EV charging stations in usage and in maximizing their economic benefits.

To account for uncertainty of point forecasts, ensemble predictions are used to study different models for characterization or estimation of uncertainty. The uncertainty is reflected either in the point forecasts or in the data variations. Prediction ensembles are a set of quantiles that represent the empirical cumulative distribution function that can be calculated from a full probability distribution function by using a set of kernel functions and their smoothing. Paper [12] estimates the true underlying error distribution in forecasting that can be provided by either a parametric or a non-parametric representation. Non-parametric or empirical representation is a way of modeling the ensembles because these representations can reflect on how real EVs behave and future prediction errors can be estimated from past predictions using historical data. On the other hand, most probabilistic forecasts are provided for consecutive future times independently, which results in two time series: one for forecasted data, and the other for prediction errors. Hence, they lack any information on the characteristics that drive the temporal evolution of V2G capacity and error data. In fact, the cross-correlations and dependencies between the forecasting error series over the considered time horizon are valuable characteristics, particularly, for power system problems that have time-dependent memory such as EV charging levels.

In the paper [13], ensembles of V2G capacity are estimated and calculated. The paper objectives are: i) schedule charging as demand response, whose solution follows the chanced-constrained optimization of energy economic dispatch problem; ii) using the remaining capacity of V2G to generate reactive power and cooperatively perform voltage control.

The first objective can be met by a control center. While important, computational algorithms are available for solving this centralized optimization problem. As such, the paper focuses upon the second objective and, since it requires real-time solution and implementation, a new algorithm was developed. This project developed a cooperative distributed optimization technique to optimally dispatch the reactive power generation of distributed generation in a micro-grid [11]. In particular, the technique consists of a consensus algorithm and a sub-gradient algorithm. The former makes decentralized network optimization algorithms converge to the global optimal solution with respect to a sum of objective functions (that represents the optimal voltage profile) at different nodes, while the latter minimizes each component function that is known only to a particular node of a distributed network. By combining this distributed algorithm with ensemble predictions of V2G capacity, variations across time and availability of EVs are now taken into account to yield a more suitable optimization algorithm for V2G-enabled reactive power control. The proposed algorithm is robust to variations and offer a certain level of optimality with respect to several-hours-ahead traffic grid and electric grid management techniques.

In the planning future, economic benefits of ancillary services (reactive power control and frequency control) will be monitored and optimized through the electricity market. The proposed algorithms provide the basis for utilities and independent system operators to quantify the gain of real-time inverter controls and to determine the appropriate incentives (real-time prices) for such services.

3.2 Multivariate Predictive Analytics for Control of Energy Storage

This paper [13] studies the combination of wind power generation and energy storage. The goal is to better forecast wind generation and then use storage to minimize variability of the total dispatchable energy over the next few hours. This problem is mathematically similar to the problem of forecasting the EV charging needs and then scheduling EVs for charging over the next few hours.

The paper presents a stochastic spatio-temporal multivariate methodology for data analytics, forecasting and data-driven modeling. The proposed multivariate model is composed of three elements: copula function, kernel function, and marginal distributions. Although a copula function is simply defined as the joint distribution of two or more random vectors each transformed as uniform random variables, the use of copulas allows for the decomposing of any joint distribution into a dependency structure (copula function) and individual marginal distributions. As such, each variable can be described by a different distribution (e.g., Gaussian, Weibull, or even empirical distributions), and copula functions capture the nonlinear dependence structure used to estimate ensembles.

In the proposed approach [13], the forecasting uncertainty and their prediction intervals are expressed in the form of ensembles: a set of quantiles or intervals, mean, variance, or probability density functions. In particular, the proposed method aims to capture the following nonlinear non-parametric characteristics together:

- Temporal dependence of forecasting error time series that is the dependence between forecasting error distributions at each time index.
- Temporal dependence of wind power outputs' time series.
- Interdependence or cross-correlation between wind power times and the corresponding error series.
- Empirical distributions of forecasting error and wind power data at each time index as well as the considered time horizon.

The calculated final distributions, ensembles, or predicted intervals are conditional on previous observations. The proposed algorithm uses the copula-based model to fit to the historical data. Once the fitting is done off-line, the conditional forecast error ensembles at each future time or predicted intervals can be calculated in real-time. That is, the proposed method is an adaptive probabilistic forecasting for different future time periods. Algorithm effectiveness was successfully demonstrated.

It is well known that wind power generation is stochastic but hard to predict and there is a large set of performance data available. On the other hand, EV usage and charging are also stochastic, and there is little data on a large number of EVs. Both problems exhibit temporal and spatial dependence in their data sets. Hence, the proposed modeling technique can be applied to EV charging.

3.3 Modularized Design for Cooperative Control and Plug-And-Play Operation

The preceding discussions and papers have dealt with forecasting, optimization and control algorithms. While each of the algorithms are well developed, their combinational and real-time implementation makes the overall system dynamic (due to their adaptive nature). As such, stability of the overall system with various dynamics (including conventional generators, recursive/adaptive algorithms, etc.) must be considered.

Paper [14] presents an answer to the fundamental question of how a network of heterogeneous dynamical systems can be operated in a stable and cooperative manner. To this end, the concept of passivity short systems is defined, and dynamic behaviors of individual heterogeneous systems are captured using the simple parameter (called impact coefficient) of a constant value. It is shown that, as long as the impact coefficients are upper bounded by a threshold value, a cooperative network of heterogeneous systems will always be stable.

3.4 EVs and Smart Grid Control and Generation Methods for Integrating Distributed Generators

Utility companies measure real-time total net load and generation at the utility side of the meter and have access to customer meter data approximately every 5 minutes. However, utilities have no control of generation on the customer side of the meters. With high penetration of EVs and renewables, it is important for utilities to get real-time estimates of net load/generation along distribution lines. This paper [15] presents a distributed control and generation estimation approach which can dispatch multiple distributed generations in the distribution network.

The approach works with the existing supervisory control and data acquisition (SCADA) system at the substation level and accepts aggregated power dispatch signals. Moreover, it enables dynamics estimation of the aggregated generation capacity of distributed generation and guarantees that each distributed generator can adjust its power output coherently. In particular, all of distributed generators operate in the same utilization ratio while the aggregated power output can meet the power dispatch command from the SCADA.

With high penetration of EVs, it becomes possible to have real-time control of charging/discharging storage devices in order to maximize economic benefits to both the utility company and its customers. Paper [16] proposes a multi-agent solution to solve the economic dispatch problem. It also incorporates distributed real-time optimal power flow controls at the storage/distributed generation level, and it integrates the function of the conventional hierarchical control.

By means of measuring individual power flows, system frequency and exchanging a minimum amount of information among neighboring generation unit agents, the proposed strategy can recover the nominal frequency, while minimize the generation cost of the generation units in real time under power balance, generation limit, and power flow limit constraints. The proposed strategy is economically efficient in comparison with the conventional hierarchical scheme, where load forecast inaccuracy and relatively slow updating period of tertiary control can incur higher control error. Moreover, it is robust to communication interruption and can meet the requirement of plug-and-play [16].

With high penetration of EVs, it becomes possible to restore essential electricity service when there are line outages and/or local blackouts. This paper [17] proposes a restorative method to minimize the unserved demand in a balanced and unbalanced power distribution network due to line outage. The restoration is achieved by tie-line switching and by solving a mixed-integer non-linear problem. By exploiting the information on pre-contingency solution, post-contingency topology is determined using line congestion requirements and through a modification of a greedy search algorithm. The proposed method reduces the search space of the combinatorial problem, and enables real-time automation to rapidly restore the system under line failures.

4.0 Impacts/Benefits

The proposed research shows that, by using advanced optimization/control methodologies to integrate EVs into the electricity grid, electric power systems can be operated more efficiently, reliably and resiliently.

In particular, EVs as storage devices enable a much higher level penetration of renewables by smoothing their variability and are ideal for controlling demand responses. Hence, storage can provide more reliable grid operation which is capable of providing reactive power compensation and frequency stabilization which, in turn, gives improved grid efficiency and stability and can serve as an emergency power supply for grid resiliency.

Using the proposed model and algorithms, techno-economic implications can be quantified for different levels of EV adoption supplying solutions to transportation networks and infrastructure requirements for state, region or city leaders and planners.

Also of importance is future transportation systems policy and planning programs which will require the need for close coordination and the combining of efforts with the policies and planning programs for electrical power systems.

Due to the small population of EVs in the highway system and the lack of data on the coupled EV usage within the electric grid and the transportation network, the ability to perform large scale techno-economic analysis that is verified with real data is extremely limited. However, this project has advanced the modeling tools and algorithms in the electric utility and energy industries and applied these tools to transportation systems through EV transit analysis, utility grid forecasting and distributed energy systems. These algorithm tools are:

1. A kernel-based predictive model of EV capacity for distributed voltage control and demand response;
2. A multivariate model of forecasting data for renewable (wind) generation;
3. A distributed control and generation estimation algorithm;
4. A distributed real-time optimal power flow control algorithm;
5. A restorative algorithm for resilient unbalanced power distribution networks;

6. A distributed scheduling algorithm [18];
7. A cooperative decision making algorithm [18].

These algorithms can be used to evaluate the economic implications of large-scale transportation networks. For example, the use of high-power dynamic charging systems in highway transportation networks or the wide-scale deployment of EV charging station networks.

5.0 Conclusions

The process, methodology and forecasting/optimization/control algorithms for computer modeling are developed to enhance economic benefits of a large-scale electrified transportation sector. The results have shown that vehicle to grid (V2G) can enhance power system operation and resilience and that grid to vehicle (G2V) can be optimized using stochastic forecasting, stochastic optimization and distributed control. Presented as the main results are an investigation of quantifying the economic benefits of V2G technology as an effective means of buffering active and reactive power fluctuations, a process to better forecast V2G capacity for grid ancillary services and a process to better forecast renewable generation and use storage to minimize variability of the total dispatchable energy over the next few hours. Also presented are a method to address how a network of heterogeneous dynamical systems can be operated in a stable and cooperative manner and an approach to a distributed control and generation estimation for dispatching multiple distributed generations in a distribution network. These results in aggregate provide the methodology of integrating EVs and electric grids and, due to the similarity of the underlining forecast and optimization problems, their mathematical formulation can also be used to solve the problem of forecasting EV usage and scheduling EVs for charging in a transportation system.

6.0 References

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