Framework for Evaluating Grid Readiness for Integrating Electric Vehicles and Utility Scale Storage in India

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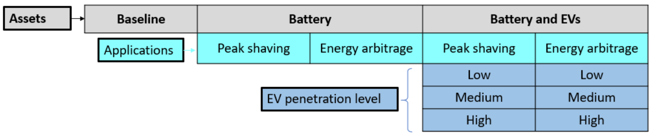
***Abstract*—Electric vehicles (EVs) and distributed solar are poised to grow substantially in India in the coming years following ambitious Government of India targets. The localized impact of these changes, both in terms of infrastructure investments and demand patterns, are not well understood, nor are tools for this type of analysis readily available. This paper describes the development of a framework that can analyze network readiness in terms of feeder impacts for distributed energy resources (DERs) including growing EV penetration, and the potential solutions introduced by utility-scale battery energy storage systems (BESSs).**

The building blocks of the feeder analysis require multiple data sets to be compiled into a usable network model. The work is driven by feeder head and distribution transformer (DT) loading data along with all the technical specifications and schematics of distribution feeders. These measured datasets are conditioned to remove any afflictions, and the cleaned load profiles are used to perform multi-year quasi-static time-series power flow analyses on detailed three-phase feeder models. EVs translated to grid-tied loads are represented with aggregated EV demand profile estimates based on possible charging scenarios in residential sector, and in workplace and/or public charging stations. Finally, BESSs are evaluated for their cost-effectiveness in the framework through an initial screening that includes the benefits of grid service applications to mitigate present and future overloading scenarios. The outcomes from this framework are expected to help utilities gauge the readiness of their distribution grid for integrating an increasing number of EVs as well as load growth during a projected multi-year time horizon, where BESSs can contribute in making the grid more reliable.

I. Introduction

Emerging technologies such as solar PV, battery energy storage systems (BESS), and electric vehicles (EV) present both opportunities and challenges to distribution utilities. However, when optimally utilized and planned for, these technologies can provide added value to the grid, both economically and technically. This paper presents an overview of a framework under a research collaboration between National Renewable Energy Laboratory (NREL) and BSES Rajdhani Power Limited (BRPL) that addresses key research questions about the integration of these emerging technologies onto BRPLs distribution grid. This framework is designed to analyze the economic and technical benefits/challenges of EV and BESS integration, and to help optimize infrastructure development costs for utilities. In this on-going effort, cost-benefit analyses will be performed on a few selected feeders (within the BRPL service territory) to understand the system-wide impacts of EVs and BESSs. Storage technologies have the potential to provide multiple services to the grid. Value streams of utility-scale grid-interactive BESS will be identified under this framework, across diverse use cases such as peak shaving and energy arbitrage for local grid-support services. Along with BESS, models of various EV technologies such as E-rickshaws and plug-in EVs will be deployed at various penetration levels for public, private and commercial vehicles. These models will translate the EV fleet on the streets into grid-connected temporal load curves. Additionally, a suite of grid readiness metrics will be computed for techno-economic assessments of the network operations impacts under different use cases and scenarios.



Assets	Baseline	Battery		Battery and EVs	
Applications		Peak shaving	Energy arbitrage	Peak shaving	Energy arbitrage
EV penetration level				Low	Low
				Medium	Medium
				High	High

Fig. 1. Different use cases and scenarios to consider for the EV/BESS pilot study

Interactions between BESS and EV technologies across diverse use cases and penetration levels can be analyzed within the framework being developed, as shown in Fig. 1. NREL's high performance computing (HPC) system is used to generate relevant scenarios for this integration study and perform multi-year simulations which helps in reducing the total runtime, within the contexts of a planning phase study [1]. In order to obtain all combinations of these technologies, we will perform the study under three major use cases as listed below:

A. *Baseline*

The baseline scenario uses the existing network architecture and feeder loading, which helps in differentiating the changes caused by new technologies on the local grid in the subsequent simulation scenarios.

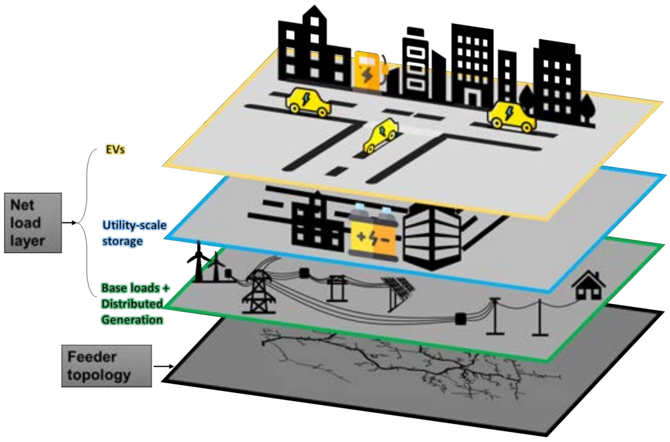


Fig. 2. Various layers for modeling loads, EVs, and other DERs for centralized charging concept

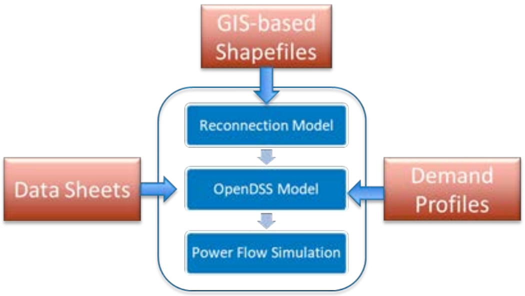


Fig. 3. GIS-based dataset translation to OpenDSS model

B. *BESS with control applications*

This use case will consider utility-scale BESSs, sized as recommended by common utility practices, on the baseline model. The intent is to analyze and evaluate the achievable value streams from the integrated energy storage asset. Control applications such as load leveling will be considered under this use case under load growth. Additional EVs will be not be included in this use case.

C. *BESS and EVs*

Growing levels of EV penetration will be analyzed under this use case. Two sub-categories of this use case are: i) with BESSs (similar applications as mentioned in Battery use cases), and ii) without BESSs. Each use case will consider a couple of scenarios representing three levels of EV penetration- low, medium and high. High penetration levels will represent centralized charging scenarios where the EVs mostly use public/commercial charging stations to charge. Net load layer modeling for such concept is depicted in Fig. 2. Medium and low levels of EV penetration will have more distributed or residential charging cases, as compared to centralized ones.

II. FEEDER MODEL DEVELOPMENT

Using the topological and network configuration data provided by BRPL, the network is modeled in OpenDSS - an open-source software for simulating electric distribution systems [2]. This model provides a platform for a quasi-static steady state timeseries simulation that can integrate varying scenarios involving EVs and BESS use cases.

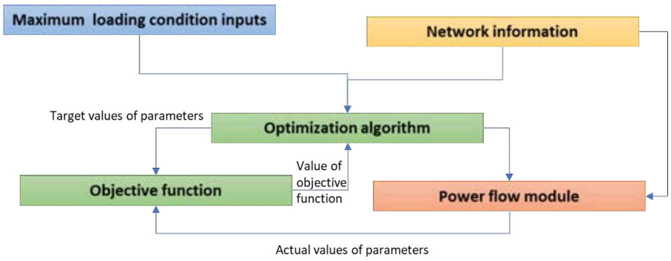


Fig. 4. Flow chart of load allocation using optimization algorithm

Fig. 3 presents a flow chart for model creation in OpenDSS and conducting power flow simulations using the same. First, the GIS database that manages the network assets, need to be converted into network segments. This process involves aligning all adjacent network assets so that their starting/ending cooordinates are representative of a connected electrical system (containing nodes and edges). For example, some line segments are represented with polylines in the GIS data which are resolved to a single line with a set of source and end coordinates.

Once the topology is defined from the GIS-based shapefiles using node coordinates with corresponding attribute table, edges are formed to represent all the various line layers of the feeder. Some of the considered parameters for these lines include capacitance, continuous line ratings, positive, negative, and zero sequence impedances. Also, in this class are distribution transformers for connecting nodes, whose parameters are defined such as the connection types, windings, maximum and minimum taps, and percentage load and no-load losses.

After the static feeder topology is built in OpenDSS for the primary circuit (to the point of connections of the distribution transformers), the next step is to define the secondary loads for a more accurate power flow simulation for the feeder. A load allocation method was applied to obtain these peak load values for all secondary customers downstream of each distribution transformer, as seen in Fig. 4. In this approach each transformer was allocated optimal loads separately. Load kW and power factor values act as inputs for maximum loading condition block in this flow chart. Network information contains the topology and component specifications as defined by the OpenDSS feeder model. At the heart of the load allocation process is the optimization algorithm that has an objective function of minimizing the differences between the actual voltage (measurement data) and target voltage (outputs from the power flow module for load and pf values generated from the optimization algorithm). This optimization algorithm for load allocation helps in capturing the peak loading conditions, power factors, phase imbalances and tap positions of all the transformers, while considering the available SCADA data and by suitably filling in any gaps in the data.

III. DATASET RECONSTRUCTION

Feeder model, as developed in OpenDSS, requires loading profiles for each spot load included in the network. These

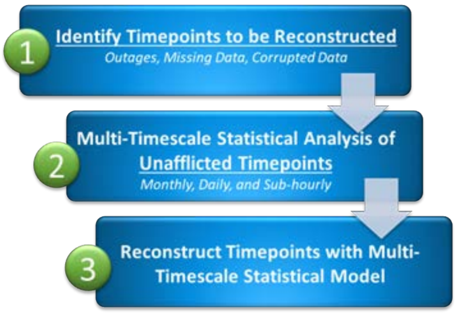


Fig. 5. Flow chart of reconstructing datasets for power flow module

profiles are constructed based on three datasets (shared by BRPL) - i) Three-phase three-wire two-watt-metered data obtained at feeder head location(s), ii) three-phase three-wire three-watt-metered data obtained at all distribution transformers, iii) and monthly customer billing data. Feeder head dataset include voltage readings (kV), current readings (amp), demand (kW), power factor, and the time stamp, and was sampled at a time resolution of 15-minutes. Each distribution transformer comes with an individual dataset comprised of active power, reactive power, and voltage on each of the three phases of the secondaries spanning the same year as the feeder head time series data. A time series which indicated outages was also included. Raw transformer datasets can be afflicted with several types of inconsistencies, such as, inaccurate representation of outages in the feeder, missing data, instances of phases not being energized or drawing no load, and meter data having sustained levels of low values which can be atypical. These various afflictions can be observed sporadically throughout the year for each distribution transformer.

Fig. 5 describes the process flow to reconstruct the dataset after removing the afflictions. The first of the primary processes here is to identify and remove the afflicted data. Next, statistical analyses are performed on the remaining data, and finally, the missing data is filled with an algorithm which is informed by the preceding analysis.

IV. EV INTEGRATION

Impacts of EV loads are being evaluated on Delhi feeder(s) for this ongoing effort. Methodologies have been developed in literature to convert EV charger demand curves applicable to power flow simulations and other steady state analyses [3] [4]. EV loads are modeled within this framework following an object-oriented approach, i.e. an individual EV, charging station, and single charger are treated as separate objects with corresponding static properties. Leveraging earlier work at NREL, the nunmber of required chargers can be calculated for varying levels of EV penetration [5]. Charging scenarios are formulated based on the types of chargers as commonly used across the territory. Bharat AC chargers are assumed to be the most prevalent models since this provides the most inexpensive charging options. Besides these AC ones, level 1 DC chargers are assumed to be available in public or workplace/commercial stations. However, level 2 DC chargers are not considered within the initial assumptions. The charger specifications are illustrated in Fig. 6.

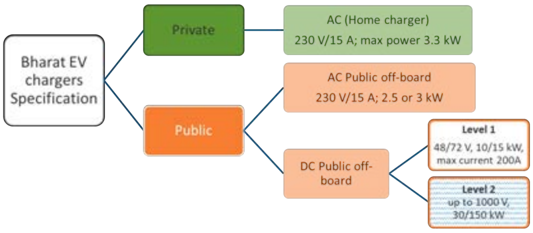


Fig. 6. Bharat EV chargers types and their specifications

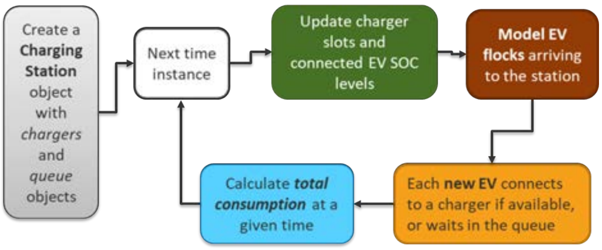


Fig. 7. Work flow of building a charging station model

In a residential-dominant charging scenario, single AC charger is assumed to fully charge a single vehicle overnight. In a low EV penetration scenario, these chargers are assumed to be scattered throughout the network (mostly residential applications). As their charging rates are slow, these chargers will be used by consumers in public or workplace-dominant modes mostly to top-off. Also, the numbers of fast chargers is assumed to grow as the EV penetration increases, compared to the number of slow chargers in a charging station infrastructure. The demand profile for such a charging station is calculated based on the chargers (fast and slow) under the infrastructure. Fig. 7 shows the flow chart to calculate these station demand profiles.

V. BESS APPLICATIONS

There are different modes of operations for the grid-connected battery energy storage system (BESS), which includes peak shaving, capacity firming and voltage support modes. However, to address the major concerns of overloading and reliable supply, this work focuses on the peak shaving control application to help alleviate the possible transformer overloading condition with load growth and rapid adoption of EVs in the modelled distribution feeder(s). A simplified control architecture for the BESS controller can be seen in Fig. 8. The peak shaving mode requires the trigger values which defines how much load or peak will be shaved off and how much the valley will be filled. This way these trigger values would guide how flat the load profile would be after the BESS integration. BESS will discharge power into the grid if the active power demand at the measured point (DT in this case) is greater than the peak shaving upper reference limit . Conversely, the BESS will charge if the load consumption at the measured point is lower than the base loading limit.

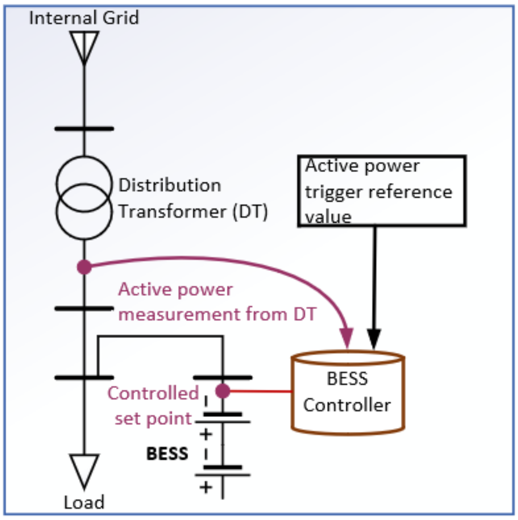


Fig. 8. Configuring peak shaving control algorithm

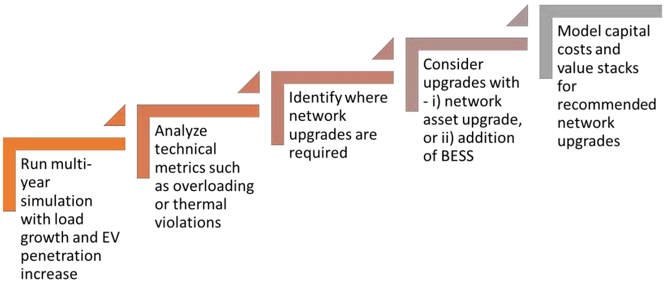


Fig. 9. Process flow for cost-benefit analyses for network upgrades

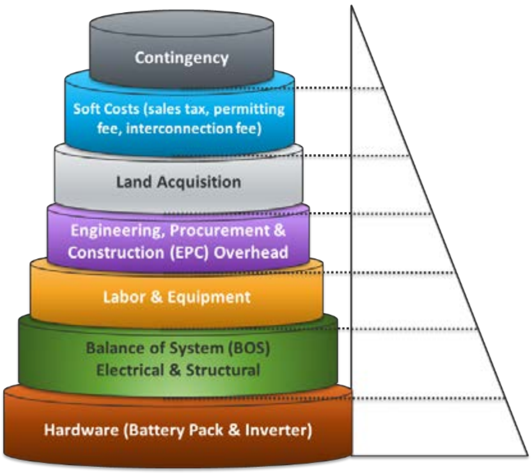


Fig. 10. Capital cost components to consider for a utility-scale BESS installation

VI. COST-BENEFIT ANALYSIS FOR NETWORK UPGRADES

Network upgrade decision points are determined based on technical analyses from the multi-year simulation performed on the OpenDSS model (flow chart in Fig. 9). These analyses reveal when and where violations of predefined suite of technical metrics occur. These technical metrics are used to localize where thermal violations, overloading, undervoltages or overall power quality issues are observed on the time axis. Since power quality is an important consideration for power system operation, these metrics would represent the grid-readiness for the expected load/EV growth [6] [7]. To ensure reliable operation, this planning phase study considers traditional and advanced upgrade options. Traditional path would consider upgrading the network asset (line or transformer) so that the overall demand growth can be fed. Advanced upgrade option would does so with the integration of BESS that can also provide added benefits on top of mitigating the violations.

The advanced upgrade path with utility-scale BESS integration requires developing a cost model using a bottom-up approach for a realistic capital cost estimate. Fig. 10 shows some itemized components (in the decreasing order of percentage of total costs, i.e. battery pack and inverter make up for the biggest cost component) to consider from a recent cost benchmarking study by NREL [8].Total system upfront capital costs are broken into hardware cost (battery cells, battery racking, storage container, and bidirectional battery inverter), electrical and structural balance of plant (BOP) costs, labor and equipment costs, engineering procurement and construction (EPC) costs, and soft costs (fees, taxes, contingencies, and developer costs). BOP includes; site preparation, mounting, wiring, containerization, and foundation. Among these components, battery pack is usually the most expensive across different power/energy sizes.

VII. SUMMARY AND FUTURE WORK

This paper briefly presents the building blocks that need to be considered for a planning study framework to integrate EVs and utility-scale BESS with cost-benefit analyses. From the raw asset and load data, the network model is built in a platform where futuristic scenarios like growth of load and EV demands can be simulated. From the technical analyses on this multi-year feeder simulation, network upgrade decisions such as adding or replacing a transformer and adding a conservatively-sized BESS are assessed. Finally, cost-benefit analyses for these upgrades are performed based on capital costs and value additions from each upgrade. This process is being applied for a few feeders in Delhi area and it can be replicated for other networks since this platform is being developed in a generic fashion.

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