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EV Multi-Battery Swapping Model Incorporating Strategic Discounts and Solar Power Integration

Aandal.R[1], Muthu Ganesh.A[2], Joel.I[3], Saravana lingam.B[4], HariHaran.V[5]

Assistant Professor, Department of EEE, Francis Xavier Engineering College,Tirunelveli, India[1]

UG Students, Department of EEE, Francis Xavier Engineering College,Tirunelveli, India[2,3,4,5].

ABSTRACT: The successful roll-out of electric vehicles (EVs) in the market requires adequate charging infrastructure to mitigate concerns regarding their range and long charging delays. With this motivation, a business model is proposed in this paper for the modelling of multi-battery swapping stations for EVs with some strategic discounts. The proposed model generates profits for their owners while providing an efficient alternative to charging EV batteries. This model also utilizes solar energy for charging these batteries, with the provision to supply excess power back to the grid. The proposed model considers two different types of batteries along with discounts during solar peak hours. The results show its feasibility and effectiveness in providing the required services

KEYWORDS: Electricity vehicle, Battery Swapping Station (BSS), energy storage, optimal scheduling, solar generation variability, mixed-integer programming, PV Array.

I. INTRODUCTION

Electric vehicles (EVs) are being widely concerned as an environmentally friendly transportation compared to internal-combustion-engine vehicles. The government of China introduced related policies to promote the popularization of EV. Now the popular mode com plementary energy for EV is by charging. But EV need towait in queue if the chargers are not enough when they arrive at the charging station. It usually takes less than half an hour for fast charging or 4~8 hour for a normal charging. Battery swapping is much more flexible compared to the battery charging, especially for Taxi and other public transportations.

As for the power system, EV BSS can charge the bat teries in advance, even during the valley period, to fulfill swapping peak demand which is highly consistent with peak demand

of power system theoretically. In theory, the more battery reserves makes BSS much more flexible load to consume clean energy at specific period. BSS can be regard as one kind of demand response resources to bring benefits to both power system and environment. Now in China, relevant practices of battery swapping mode have been carried out in many areas. For example, city launched a pilot project for taxi fleets and placed battery swapping stations into operation on the high way from city center to airport, Sichuan provincnce and Chongqing city which together called Cheng Yu area are building the first inter provincial travel channel for new energy vehicle in China on the basis of battery swapping mode, trying to set up a green travel demonstration zone. Due to energy storage feature, BSS is able to act as supplementary automatic generation control and black-start resource. In spite of that, the most popular and fundamental contribution of BSS is to reducing carbon emissions, facilitate renewable integration. Optimal strategies and schedules for BSS operation have been wide reported in literatures. A charging strategy considering service availability and self consumption of PV energy is proposed in [7], which proves the performance of PV-based BSS is better for both economic and environment. In [8], a detailed operation model of BSS is presented considering many differ ent energy transfer mode like G2B, B2G, or B2B. A new optimal dispatching strategy for microgrid containing BSS is given in [9], which indicates that BSS is also able to be a kind of controllable resource to support power system. A short-term battery management and market strategy are proposed and a dynamic operation model of BSS in electricity market is built . Recent studies such as have identified the need for combined facility configuration problem and operation strategy of BSS. The investment return of BSS is closely related to the operation strategy and schedule for daily swapping service. Therefore, it is necessary to take into account the operation strategy simulation when study on optimal configuration scheme of BSS. Swapping demand, the cost for battery, other facilities and the cost for charging should be considered synthetically while allocating the number of batteries for BSS .. Previous works used

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queuing theory to solve the EVs' swapping facilities configuration problem, while the expectation result is not applicable for some extreme cases. A multi-objective optimization problem for component capacity of PV based battery swapping station is solved in [13], aiming at maximizing the bene fits of economy and environment. A capacity optimization method for PV-based BSS considering second-use of EV batteries is studied in [14]. The EV battery pack quantity planning problem under mode of centralized charging and unified distribution is researched and a comprehensive planning model is pro posed in [15]. The power network reinforcement should be taken into consideration during the battery charging or swap station configuration process, and the battery charging/swap station model are developed in [18]. In the particular case of BSS regarded as one kind of de mand response resources, various references have demon strated that BSS has its unique advantages to handle adverse effects on distribution network with high penetra tion of EVs and distributed renewable resources benefit ting both power system and environment [5, 6, 9, 11]. A new supplementary automatic generation control strategy using energy storage in BSSs is proposed in [5], and the optimization model for power system restoration with support from EVs under battery swapping mode is ana lyzed. Research results testify it is feasible to include BSS into AGC market and power system restoration process. BSS has its own batteries to buffer the transferring of power from grid to EVs and to balance supply and de mand [11], this should be commonly concerned by the system operators and load aggregators in electricity market.

II. PROBLEM DESCRIPTION

Business mode for BSS :Battery swap service is available to EVs in BSS. The BSS could charge batteries by consuming PV power from PV electricity suppliers or power from the main grid during off peak time and offer swapping service by charging for fee to make profit and maintain its business. Considering TOU and the energy of PV electricity supplier can provide, BSS optimizes char ging schedule in the case of satisfying customer satis faction and PV consumption task. BSS is incentive to charge batteries during the lower price period as much as possible and consume enough PV energy to meet PV consumption requirement. This strategy can both save the electricity bills for BSS and utilize more clean energy, bringing economic benefits and increas ing the efficiency of environmental reduction of EVs simultaneously. It is worth noting that the ability BSS can serve at one time interval is influenced by both the number of EV batteries fully charged and the number of swapping ro bots. During high swapping demand period, EVs should wait in the queue for a short time if BSS can't provide swapping service at once. The structure of BSS is displayed in Fig. 1 and main facilities are such as follows: 1) EV battery: the key equipment for BSS to serve EVs with swapping serve. 2) EV battery charger: the terminal to charge EV batteries in BSS. 3) Swapping robot: the machine help to swap EV batteries. 4) Control unit for optimization: the key unit for EV BSS, which is responsible for coordinate and control the equipment in BSS to optimize the operation.

KEY PROBLEMS FOR BUSSINESS OF BSS:

The profit level of Battery Swapping Stations (BSS) is influenced by several key factors:

1. Swapping Demand: The amount and distribution characteristics of swapping demand significantly impact BSS income. Larger swapping demand generally leads to higher income under normal conditions. The distribution pattern of swapping demand affects both income and the flexibility of demand response for BSS. However, this aspect is not covered in our current study.
2. Service Fee for Battery Swapping: BSS charges a fee for swapping batteries in electric vehicles (EVs). The service fee is a critical factor influencing BSS income. While income typically increases with higher fees (assuming unchanged demand), it's essential to consider the price elasticity of demand, which is not zero in reality.
3. Electricity Price Level: The cost of electricity significantly affects BSS income due to the large power consumption required for charging. Generally, lower electricity prices lead to stronger profitability for BSS. Additionally, using renewable energy sources (which are usually cheaper than conventional ones) can further reduce electricity costs and enhance BSS profits.
4. Facility Costs: BSS relies on three main facilities: EV batteries, battery chargers, and swapping robots. Each of these components is essential, and none can be omitted. Lower facility costs allow BSS to allocate more resources for absorbing cheaper electricity during off-peak hours.

III. PROPOSED WORK AND DESCRIPTION

BSS Players

The main idea of introducing the BSS into the EV industry is that an EV owner can quickly swap an empty or a near- empty battery with a fully-charged one in a short time. To implement this innovative idea, at least three main

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players, including the EV owner, the BSS owner, and the power system, should take part. In what follows, the BSS will be investigated from each player's perspective.

From the EV owner's perspective, the BSS deployment has several benefits. The first and foremost advantage is that the sticker price of the EV is significantly reduced, as the battery is owned by the BSS instead of the EV owner. The battery replacement is processed faster than refuelling a gasoline- powered vehicle. By properly placing the BSS, the EV owner could easily plan for longer distance trips, and accordingly the range anxiety could be alleviated. Moreover, the EV owner is no longer concerned about the battery lifetime. As the BSS owner is in charge of upgrading charging facilities, such as high-power battery chargers, the relevant cost for upgrading household infrastructure is also entirely eliminated.

Power system operators are always looking for viable approaches to reduce network congestion and the peak load, for adding economic and reliability value to the grid by better utilizing available resources. However, the unpredictable behavior of EV owners for charging the batteries in plug-in mode could negatively impact power system operation in terms of increasing peak load and network congestion. The BSS approach could potentially turn this challenge into an opportunity by providing a scheduled charging/discharging strategy. By considering the aggregated batteries inside the BSS as a large shiftable load, the battery charging schedule could be shifted to the night time or off-peak hours in order to tackle the potential peak demand or overloading, caused by growing penetration of EVs. Nevertheless, the BSS can serve as a viable source of energy storage in the system to capture solar generation variability, as discussed in this paper.

The BSS owner could potentially achieve the largest benefits among players. Compared to the BCS, the BSS could minimize its electricity cost for battery charging/discharging by operating at a least-cost schedule based on hourly electricity prices. Furthermore, the BSS owner could make a profit via participating in electricity market and offering ancillary and reserve services to the grid. In terms of the cost of real estate, as the BSS owner does not need access to spacious parking lots, as compared to the BCS, substantial cost savings would be guaranteed. Eventually, since all batteries are unified and follow a consistent standard, as assumed in this paper, the battery charging/discharging process is convenient for the BSS owner.

Optimal Scheduling Model:

Consider a distribution network in which a BSS and several consumers with the ability of electricity generation, i.e., prosumers, are connected to a distribution feeder. The prosumers own distributed rooftop solar PV, where accordingly bring variability to the power required to be supplied by the utility grid. In addition, the behavior of prosumers for buying/selling electricity to/from the utility grid is uncontrolled, as they aim at maximizing benefits subject to their financial objectives (i.e., the minimum electricity payment). The BSS which is deployed at the distribution network not only aims at providing fully-charged batteries to EV owners, but also can capture the variability in solar PV generation associated with the prosumers. By doing this, the power needed to be injected to the feeder by the utility grid can be controlled to some extent. Fig. 1 shows the BSS-based model architecture for capturing distribution grid-integrated variability

PROBLEM FORMULATION :

The BSS owner's objective is to minimize its operation cost, i.e., the cost of exchanging power with the utility grid, as in (1). The quantity of power exchange with the utility grid is determined by subtracting the accumulated battery charging power from the discharging power as in (2). This quantity can be positive or negative as for power import or export, respectively. min [ ] M t t t P ρτ ∑ (1) ch dch ( ) M t bt bt b P P P t = − ∀ ∑ (2) Based on the forecasted hourly electricity price ρ, the operation cost is calculated. As the power exchange with the utility grid can be positive or negative, the objective function can be positive or negative which means the BSS owner not only is able to minimize its cost, but can also make revenue through exporting power to the utility grid. τ denotes time period, which can be set according to the BSS owner's discretion. By considering shorter time periods, the BSS can more accurately capture the rapid variability of solar generation. However, the proper choice of the time period is a tradeoff between the accuracy and the computation time. The objective function of the proposed model is subject to the following constraints. A. Grid Constraints The sum of transferred power for charging/discharging batteries in each time period is limited by the flow limits of the line connecting the BSS to the utility grid, as represented in (3). ,max ,max M M M t P P P t − ≤ ≤ ∀ (3) B. BSS System Constraints The BSS constraints are employed to model available fully-charged batteries in order to meet the battery swapping demand in each time period, as formulated in (4)-(5). max max 1 ( ) 1 ( ) , F bt bt bt MC C x C C t b ε + − ≤ ≤ + − ∀∀ (4) (1) F t b t b D x t − = ∀ ∑ (5) To determine whether the battery is fully-charged or not, (4) is

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proposed. If Cbt is equal to Cbmax, battery b is fully charged and binary variable xbt F is set to one, which indicates battery b is ready to be swapped in the next time period. Otherwise, if Cbt less than Cbmax, the battery is not fully charged and the binary variable xbt F is forced to be 0, which means battery b is not ready for swapping. The balance equation (5) ensures that the number of the fully-charged batteries in the previous time period is equal to the current swapping demand. In other words, once a battery is fully charged, it will be swapped in the subsequent time period.

Uncertainty Consideration :

To capture variability of solar generation, the proposed model uses hourly forecasted values of solar generation. As the solar generation is affected by weather conditions which are uncontrollable, the forecasting errors are inevitable. To deal with the solar generation uncertainty, a robust optimization method will be utilized. By maximizing the minimum value of the objective (1) over a defined uncertainty set, i.e., solar generation uncertainty, the worst-case solution will be determined. The uncertain parameter, i.e., solar generation, is assumed to be within an interval around the forecasted value, i.e., a polyhedral uncertainty set. By increasing maximum number of instances that this uncertain parameter can differ from its forecasted value, which is called the budget of uncertainty, the robustness of the solution will increase, while reducing the solution optimality.

NUMERICAL SIMULATIONS :

The performance of the proposed model is analyzed with a BSS consisting of 300 batteries with the individual capacity of 100 kWh. The BSS is equipped with 300 AC-level-2 battery chargers with the maximum power of 17.2 kW for a 100-kWh configured battery [31]. It is assumed that there is no power transfer limit between the BSS and the utility grid. The time period is set to be 1 h, i.e, τ=1 h, where the proposed model for BSS optimal scheduling model is solved for a 24-h horizon. The maximum value of variability desired to be captured by the utility grid, i.e., Δu, is assumed to be 1 MW/h. It means that the BSS is used to capture the aggregated prosumers net loads variability above this value. The day-ahead forecasted values of electricity price over the 24-h horizon are given in Table I. The aggregated load data, solar generation, and consequently the net load for a sample distribution feeder are listed in Table II. The BSS demand over the 24-h horizon is tabulated in Table III. The proposed BSS optimal scheduling problem is solved using CPLEX 11.0 by a personal computer with Intel Core i5, 2.3 GHz processor, and 4 GB RAM. The computation time for each of the following cases is less than 10 min, which advocates the computational efficiency of the proposed model. The following cases are :
Case 1: BSS optimal scheduling ignoring solar variability constraints.
Case 2: BSS optimal scheduling with solar variability constraints.
Case 3: BSS optimal scheduling under solar generation uncertainty.

IV.CONCLUSIONS

This paper introduced the BSS as an energy storage to address solar generation variability in distribution networks. A BSS optimal scheduling model was proposed from the BSS owner's perspective with the objective of capturing distribution grid-integrated solar variability. To this end, the BSS exchanged power with the utility grid was reshaped in such a way that the distributed solar generation variability was captured. Using mixed-integer linear programming, the proposed model was formulated to minimize the BSS operation cost, while taking into account the prevailing constraints associated with the utility grid power exchange, the BSS system, individual batteries, and solar variability. The proposed model was investigated through numerical simulations, where it was demonstrated that the BSS provides a viable approach in capturing the solar generation variability as well as helping the utility grids for hosting a higher penetration of solar generation.

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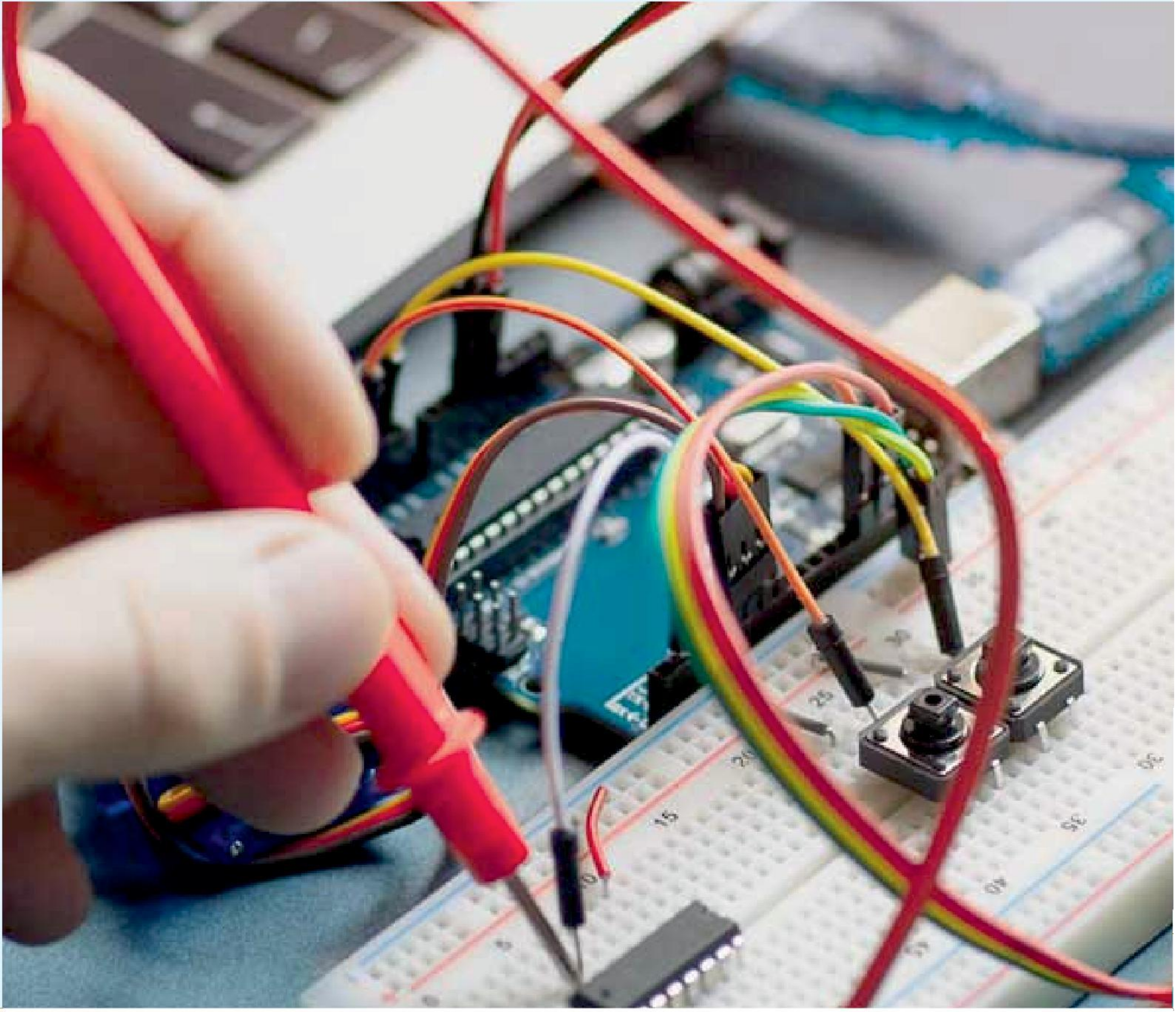

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