Optimal Battery Locations for Shiftable Loads in Distribution Systems

Nicolas Martins, Qingyu Dai, Gesler Herrera, Zongjie Wang
Department of Electrical and Computer Engineering
University of Connecticut
Storrs, CT, USA

Abstract—The integration of Battery Energy Storage Systems (BESS) into power grids is crucial for enhancing grid stability, efficiency, and the integration of renewable energy sources. This study investigates the optimal placement of BESS within an IEEE 33-bus system to minimize power losses, improve voltage stability, and minimize costs. Simulation scenarios utilize power loss minimization with different pricing schemes, such as real-time pricing and time-of-use pricing, to evaluate the impact of Price Based Demand Response (PBDR) on optimal BESS placement. The results demonstrate that strategically placing BESS not only reduces power losses and enhances grid reliability, but also offers significant cost savings. This study highlights the synergistic benefits of combining PBDR with optimal BESS placement, providing a comprehensive approach to modern power system management that ensures a sustainable and resilient energy infrastructure.

I. Introduction

To ensure maximal stability of the power grid, BESS become vital in reducing the overall demand from the grid and distributing energy to consumers in a secure manner. The power grid is a series of components transmitting electricity to millions of consumers, and such errors in a system could lead to severe economic losses as well as major health and safety risks [1]. By connecting all types of power generation including wind, solar, and non-renewable, a secure way to store and distribute this energy is necessary for optimal efficiency and stability of the grid. Optimal BESS placement working in conjunction with shiftable loads offer a solution to this problem as they involve adjusting electricity consumption timing to improve grid efficiency, while reducing power losses. This is achieved by charging batteries during off-peak hours earlier in the day, thus reducing electricity generation and transmission distance during high-demand periods [2]. Moreover, focusing on minimization of the cost, shiftable loads can strategically power up BESS during low-demand times to help mitigate the impact prices of peak-hour electricity. Transferring these loads to earlier in the day reduces demand on the grid, in effect improving stability and reducing the cost of generation. To optimize this process, focusing on the locations of BESS on an IEEE 33-bus system will be vital to ensure maximal energy efficiency and voltage stability of the system.

All authors are with the Department of Electrical and Computer Engineering at the University of Connecticut, Storrs, Connecticut, USA 06268. (Corresponding author: Dr. Zongjie Wang, zongjie.wang@uconn.edu).

An aim of picking BESS locations is to assist the system in relation to demand response (DR) which can cause instabilities in the system if not addressed. DR expresses the change in electric usage from the predicted consumption based on previous data in response to variation in the price of electricity over time [3]. A main cause of fluctuations in DR is due to rapid change in demand levels, which can be resolved through revision of the locations of BESS in unison with shiftable loads. This will offer significant benefits by enhancing the security and resilience of the system through reducing the overall demand.

A further goal is to refine the flexibility of such a system. Due to the variance and the unpredictable nature of renewable energy generation, this can cause major instabilities in energy distribution leading to unreliable operation of the power grid [4]. To counteract this, BESS serve as a way to store this generated energy in a flexible manner. With sufficient power available in the battery at all times, especially during peak hours, flexibility in the grid will be achieved.

In addition, the world of renewable energy integration possesses a significant challenge in effectively integrating Battery Management Systems (BMS) with Grid Management Systems (GMS) to ensure the seamless coordination of energy storage systems with grid operations. This integration necessitates the harmonious alignment of stored energy utilization with the dynamic fluctuations in grid demand, the variability of renewable energy generation, and the overarching requirements for grid stability. However, a promising solution emerges through the convergence of BMS with GMS, facilitating real-time communication and control between energy storage assets and the grid. By harnessing advanced communication protocols and control algorithms, these integrated systems can dynamically respond to grid conditions, offering essential ancillary services such as frequency regulation, peak shaving, and grid balancing. This collaborative integration not only enhances grid reliability but also fosters increased integration of renewable energy sources, ultimately driving improvements in overall system efficiency. The potential of grid-scale energy storage to catalyze the transition towards a more sustainable and resilient energy infrastructure is underscored by the transformative capabilities of this integrated approach.

Moreover, flexible loads in conjunction with optimal BESS placement offer inherent benefits to a system. Deferrable loads offer time-shiftable tasks that provides scheduling flexibility for demand response. Some examples include: charging electric vehicles or operating home appliances, all of which can be time flexible for a demand response [5]. Deferrable loads offer potential to be shifted later in the day during off-peak hours due to their non-urgent nature. This allows sufficient time for BESS to charge and deliver power during peak hours. Meanwhile, for tasks that lack the flexibility of deferrable loads, shiftable loads can be utilized to enhance grid flexibility by allowing for better management of renewable energy sources, such as wind and solar. By aligning electricity consumption with the availability of renewable energy, it becomes possible to reduce reliance on traditional power plants and decrease carbon emissions through the use of storing renewable energy in BESS to later be distributed when demanded by time-dependent loads.

Crucially, addressing voltage deviation is necessary for maintaining grid stability and reliability. Voltage deviation refers to the fluctuation of voltage levels at various bus nodes from their nominal values. Excessive deviation can lead to under-voltage or over-voltage conditions, causing equipment damage, inefficiencies, and instability within the power system [6]. The strategic placement of BESS can significantly mitigate voltage deviations by providing localized support to maintain voltage within the desired range. For instance, integrating BESS with distributed generation resources can effectively mitigate voltage deviations and improve power quality. A coordinated voltage control algorithm can distribute the voltage control burden among all available resources in the grid, resolving voltage violations more efficiently than local control strategies alone. This approach not only addresses voltage deviation but also enhances the hosting capacity of distribution grids, particularly those with high penetration of renewable energy sources [7].

The main contributions of the paper are shown as follows:

(i) Create a model that is able to optimize the best location of BESS placement, which gives minimal power loss.

(ii) Add flexible load constrains to bring demand respond to the system, which is beneficial with increase of microgrids.

(iii) Simulation results displaying power losses for each bus and their respective costs.

II. Problem Formulation

A. Objective Function

By selecting optimal locations for BESS, this involves minimizing the cost caused by power losses in a system as shown by the following equation:

$$min \sum_{i \in I} B_i (C_C + C_D)(P_{i,t} * P_{i,t}^{loss\%}) - (B_i - 1)(C_G(P_{i,t} * P_{i,t}^{loss\%}) \quad (1)$$

Where B_i is a binary indicator of whether a BESS is present on bus i, which allows the minimization of a conditional statement to intelligently determine optimal locations. If a BESS is present, the first half of the equation will be summed and disregard the second half, and vice versa if a BESS is not present.

The C_C and C_D coefficients are the cost of charging and discharging respectively, disregarding the aging effects of BESS for simulation purposes, while the C_G coefficient represents the cost of power transmission directly from the generator.

$P_{i,t} * P_{i,t}^{loss\%}$ are the bus load and percent loss respectively at time t. Their product derives the power loss at bus i due to line loss, while taking distance to BESS or generator into account. Losses due to transmission lines can result in increased costs, therefore, minimizing this will reveal the optimal BESS placements through various simulations.

B. Power Flow

$$\sum P_i^G + \sum P_i^B - \sum P_i^L - \sum P_i^{loss} = 0 \quad (2)$$

In this simulation, all real power will be accounted for, meaning that the total power from the generator (P_i^G) and BESS (P_i^B) will be equal to the sum of the bus loads (P_i^L) and their respective losses (P_i^{loss}).

C. Flexible Load Modeling

PBDR allows consumers to adjust their usage through time-of-use pricing structures, based around thermostatically controlled, deferrable, and elastic loads. This plays a crucial role on optimizing our model for BESS placement by allowing batteries closer to larger loads to charge during off-peak hours. Thus lowering the pricing structure and power losses, by allowing loads to receive power from the charged battery rather than directly from the generator during peak hours. This can be shown through the following load methods:

(1) Thermostatically Controlled Load:

Heating, Ventilation, and Air Conditioning or HVAC systems with TCL features can be adjusted to operate at slightly higher temperatures during peak times, reducing the load on the grid [8]. The battery storage brings flexibility to the time-varying thermal energy storage. Once the desired temperature is reached, TCL can turn off the HVAC system until the temperature deviates from the set point again.

(2) Deferrable Load:

Deferrable Load is load that can be delayed or shifted to operate during off-peak hours or times when electricity demand is lower. By shifting these activities, the demand is reduced or flattened thus causing less strain in the power grid during peak times [9]. Adjusting deferrable load strategies to the power grid can improve stability and efficiency.

$$\sum_{t=1}^{t_b} L_t^d + P_{dl}^B \leq \sum_{t=1}^{t_b} L_t^{db}, \quad \forall t_b \geq 1 \quad (3)$$

$$L_t^d \geq 0, \quad \forall t \quad (4)$$

$$P_{dl}^{B} + P_{tcl}^{B} \leq \sum_{i=1}^{33} SOC_{i,t} \tag{5}$$

P_{dl}^{B} and P_{tcl}^{B} are the amount of battery power due to the deferrable load and thermostatically controlled load respectively. L_t^d and L_t^{db} represent the deferrable load and deferrable battery load at time t respectively.

(3) Elastic Load:

$$\varepsilon_t = \frac{\Delta q}{\Delta p} \tag{6}$$

Equation 6 shows how the percentage change in load (Δq) is due to the percentage change in price (Δp) and the ratio, "self-elasticity", is equal to ε at time period t [2]. When prices are high, these loads decrease consumption, and when prices are low, they increase consumption. This responsiveness helps balance supply and demand, enhancing grid stability and efficiency [10].

D. Renewable energy

Wind Generation:

$$0 \leq \left(1 - W_{i,t}^{c}\right) P_i^W \leq \overline{P}_i^W, \quad \forall \in \Omega_W, t \tag{7}$$

$$0 \leq W_{i,t}^{c} \leq 1, \quad \forall \in \Omega_W, t \tag{8}$$

Equation 7 ensures that the output power of each wind generator P_i^W is within allowable bounds, adjusted by the curtailment factor $W_{i,t}^c$. This guarantees that the power output is non-negative and does not exceed the generator's rated capacity. While equation 8 represents the curtailment factor for wind generation, This allows the curtailment to between no curtailment to complete curtailment. This is denoted as 0 or 1 respectively, providing flexibility in our simulation results.

Solar generation:

$$0 \leq (1 - S_{i,t}^{c}) P_i^S \leq \overline{P}_i^S, \quad \forall \in \Omega_S, t \tag{9}$$

$$0 \leq S_{i,t}^{c} \leq 1, \quad \forall s \in \Omega_S, t \tag{10}$$

Likewise for equation 7 and 8, equation 9 and 10 are identical however, these inequalities apply for solar power used for this simulation.

E. Inequality Constraints

Node Voltages:

$$V_i, min \leq V_i \leq V_i, max \tag{11}$$

Equation 11 ensures that the voltage at each bus are within the specifies bounds where V_i, min 0.95 per unit and V_i, max 1.05 per unit. This prevents over and under-voltage conditions to appear when conducting simulation results.

State of Charge:

$$SOC_{min} * Bess_{min,t} \leq SOC_{i,t} \leq SOC_{max} * Bess_{max,t} \tag{12}$$

$$SOC_{i,t} = SOC_{i,t-1} + \alpha_i (P_{i,t}^{C} - P_{i,t}^{D}), \forall i \,\epsilon\, \Omega_{ESS,t} \tag{13}$$

Both $Bess_{min,t}$ and $Bess_{max,t}$ in equation 12 are the threshold for the battery to prevent under and over charge. These thresholds are 20% and 90% respectively. Equation 13 represents the dynamic behavior of the SOC of the BESS over time. This equation ensures that the SOC at any given time is properly updated based on the charging and discharging activities of the battery.

Line Capacity:

$$P_{i,tmin}^{W} \leq P_{i,t}^{W} \leq P_{i,tmax}^{W} \tag{14}$$

$$P_{i,tmin}^{S} \leq P_{i,t}^{S} \leq P_{i,tmax}^{S} \tag{15}$$

$$P_{i,tmin} \leq P_{i,t} \leq P_{i,tmax} \tag{16}$$

These inequalities ensures the power flow are within the specified limits of $P_i, tmin$ and $P_i, tmax$ in the grid. This maintains the stability and optimization for the grid. This utilizes equations 7-10 and equation is the main equation as it represents the total power of both wind and solar.

Generator Limit:

$$\sum_{t \epsilon T} (P_{g,t} \tau_t) \leq \sum_{t \epsilon T} (P_{g,t,max}) \tag{17}$$

This constraint ensures the total power generated by all the generators at each and not exceed the a maximum limit. Equation 17 is culmination of the generators. $P_{g,t}$ represents the power generated by the generators by a given time of t. τ_t is the duration of time period t. This prevents power exceed the maximum generation capacity where in this equation is $P_{g,t,max}$.

F. Power Loss Formulation

$$R_{line} = p_{line} * L_{line} / (\pi r_{line}^2) \tag{18}$$

$$P_{loss} = I^2 R_{line} \tag{19}$$

$$P_{total} = I_{gen} V_{gen} \tag{20}$$

$$P_{loss\%} = P_{loss} / P_{total} \tag{21}$$

These equations model the information to be used by our simulation where p_{line}, L_{line}, and r_{line} are the resistivity, length, and radius of the line respectively . Through calculation of the resistance of the line, the associated power loss of a load can be calculated, and in effect the total power loss for the system.

III. Simulations

A. Simulation Design

The minimization of power losses with the objective to reduce costs is explored by means of calculating power losses among all BESS-Load combinations, and selecting bus locations that minimize this quantity. This is done through the use of a modified IEEE 33-bus system with three wind and solar generators and five shiftable load locations predetermined as shown in Figure 1. From this data, we are able to calculate power losses with respect to the 33 possible battery locations and select five battery locations that minimize the losses. For simulation purposes, an arbitrary value of five was chosen for

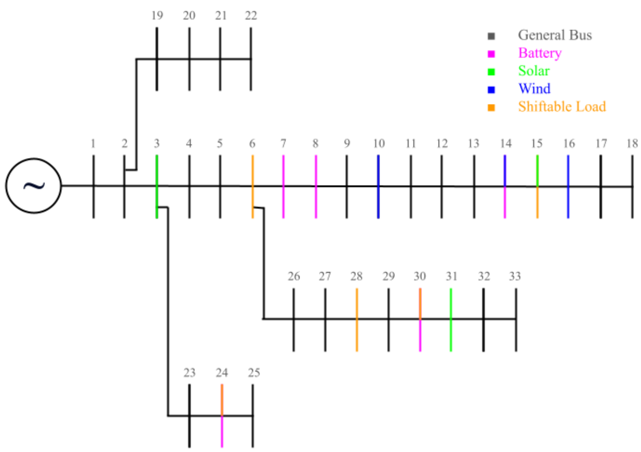

Fig. 1: A Modified IEEE 33-Bus case system.

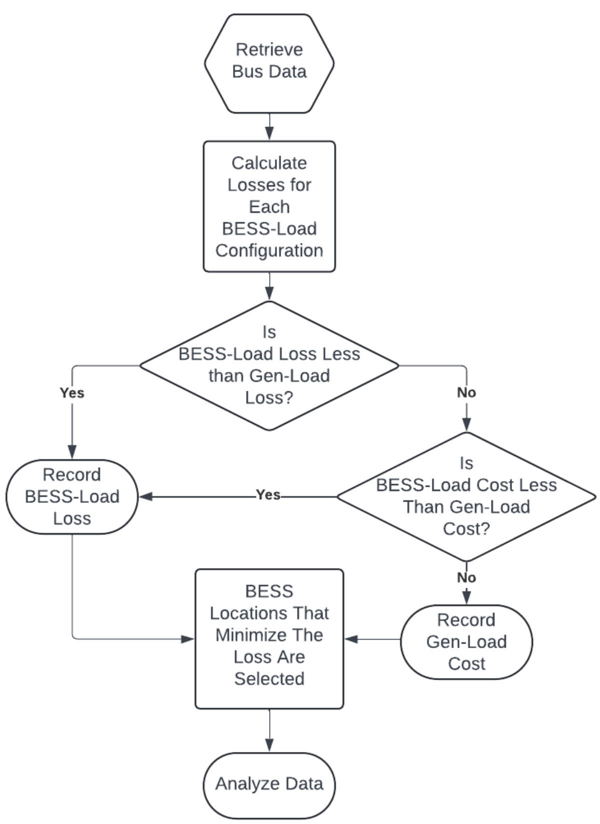

Fig. 2: Simulation Flow Chart

the number of batteries, however, it can be modified to adapt to the requirements of a given system. To most accurately isolate line losses, transmission lines consisting of a large diameter were utilized in order to consider corona losses negligible [11].

CPLEX optimization software was utilized to compute the most effective solution to the objective function while adhering to constraints as specified by the problem formulations. Figure 2 displays the process in which simulations were able to determine optimal BESS locations. Retrieving the loads of each bus allows for power losses to be calculated in relation to the load receiving power from a BESS or the generator. The values of these losses will be compared in relation to the cost, and the optimal value will be stored. Once all power loss values are generated and compared, the BESS combination resulting in power loss minimized will display the optimal locations.

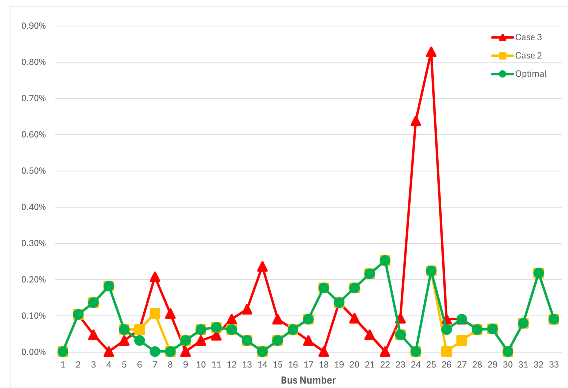

Fig. 3: Power Loss Percentage per Bus

Optimal	Case 2	Case 3
7	26	4
8	8	9
14	14	18
24	24	22
30	30	31

TABLE I: BESS Locations

B. Simulation Analysis

Using the collected results, we consider the effect BESS locations have on power losses in the system, and the costs associated with these losses. The simulations shown describe three different cases shown in Table I. The first case shows the associated power losses with all five bus locations fully optimized. Case 2 represents altering the location of one bus in the optimal case. Lastly, case 3 displays the results of randomly selecting bus locations. As shown in Figure 3 the optimal case and case 2 are incredibly similar due to there being only one difference in the bus locations, however, from totalling the power losses, the optimal case results in less power loss, supporting the optimal locations for BESS. Case 3 reveals major peaks in power losses, such as for bus 25 due to the magnitude of loads differing for each bus. Meaning that optimal locations for batteries would be closer to loads of a greater magnitude, allowing for a shorter transmission distance, reducing line loss. Random selection can not compensate for this, and it can be depicted in the simulations. Overall, through precise calculations and data analysis, proper BESS locations can be determined to effectively distribute power with minimal losses.

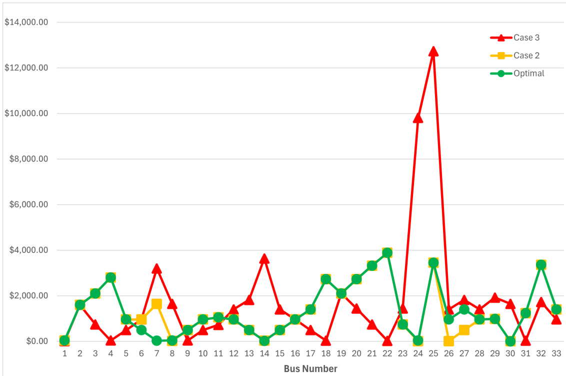

Fig. 4: Cost per Bus

In addition to the power losses, the associated costs per bus can be analyzed as shown in Figure 4. Results will look similar due to greater amounts of power loss being directly related with an increase in costs. Cost is determined when selecting the path of loss minimization. If the path to the battery minimizes loss, the battery cost will be applied, while

Bus	**Optimal**	**Case 2**	**Case 3**
1	0.0020%	0.0020%	0.0020%
2	0.1041%	0.1041%	0.1041%
3	0.1368%	0.1368%	0.0481%
4	0.1824%	0.1824%	0.0020%
5	0.0624%	0.0624%	0.0321%
6	0.0321%	0.0624%	0.0624%
7	0.0020%	0.1069%	0.2081%
8	0.0020%	0.0020%	0.1069%
9	0.0321%	0.0321%	0.0020%
10	0.0624%	0.0624%	0.0321%
11	0.0684%	0.0684%	0.0468%
12	0.0624%	0.0624%	0.0912%
13	0.0321%	0.0321%	0.1184%
14	0.0020%	0.0020%	0.2368%
15	0.0321%	0.0321%	0.0912%
16	0.0624%	0.0624%	0.0624%
17	0.0912%	0.0912%	0.0321%
18	0.1776%	0.1776%	0.0020%
19	0.1368%	0.1368%	0.1368%
20	0.1776%	0.1776%	0.0937%
21	0.2162%	0.2162%	0.0481%
22	0.2527%	0.2527%	0.0020%
23	0.0481%	0.0481%	0.0937%
24	0.0020%	0.0020%	0.6382%
25	0.2245%	0.2245%	0.8287%
26	0.0624%	0.0020%	0.0912%
27	0.0912%	0.0321%	0.0912%
28	0.0624%	0.0624%	0.0624%
29	0.0642%	0.0642%	0.0642%
30	0.0020%	0.0020%	0.0020%
31	0.0802%	0.0802%	0.0802%
32	0.2185%	0.2185%	0.2185%
33	0.0912%	0.0912%	0.0912%
Total:	**2.8764%**	**2.8922%**	**3.8226%**

TABLE II: Power Loss Percentage per Bus

Optimal	Case 2	Case 3
$44,158.21	$44,349.37	$58,818.23

TABLE III: Total Costs Due to Power Loss

Bus	**Optimal**	**Case 2**	**Case 3**
1	0.0000	0.0000	0.0000
2	0.0005	0.0009	0.0009
3	0.0021	0.0041	0.0041
4	0.0043	0.0086	0.0085
5	0.0065	0.0129	0.0130
6	0.0124	0.0245	0.0248
7	0.0136	0.0270	0.0274
8	0.0145	0.0287	0.0291
9	0.0154	0.0306	0.0309
10	0.0161	0.0319	0.0324
11	0.0163	0.0323	0.0327
12	0.0165	0.0327	0.0332
13	0.0176	0.0348	0.0353
14	0.0179	0.0355	0.0360
15	0.0185	0.0366	0.0371
16	0.0190	0.0376	0.0381
17	0.0200	0.0395	0.0400
18	0.0203	0.0401	0.0406
19	0.0007	0.0014	0.0014
20	0.0025	0.0050	0.0050
21	0.0029	0.0057	0.0056
22	0.0032	0.0063	0.0062
23	0.0038	0.0079	0.0084
24	0.0070	0.0142	0.0150
25	0.0087	0.0174	0.0183
26	0.0130	0.0257	0.0261
27	0.0138	0.0274	0.0277
28	0.0178	0.0352	0.0357
29	0.0206	0.0407	0.0413
30	0.0216	0.0427	0.0433
31	0.0224	0.0441	0.0446
32	0.0230	0.0453	0.0458
33	0.0233	0.0459	0.0464

TABLE IV: Voltage Deviation in p.u.

if the generator path minimizes loss, then the generation cost will be applied. Comparing the cost data to the power loss data, there are clear similarities. Specifically, the trend involving bus 24 and 25 for case 3 remains consistent since a larger load that is not compensated for will be the source of the greatest loss, and consequently the greatest cost.

Further, through analysis of voltage deviations over a 24hr period, optimal BESS locations provide greater voltage stability. As shown in Table IV the optimal case offers minimal voltage deviation across all busses as compared to the other simulation cases.

IV. Conclusion

This study highlights the critical role of BESS in enhancing the stability and efficiency of power grids. By optimally placing BESS within an IEEE 33-bus system, we can significantly reduce power losses, improve voltage stability, and integrate renewable energy sources more effectively. The integration of PBDR into the optimization model further enhances these benefits by aligning electricity consumption with variable pricing signals, thereby reducing peak demand and operational costs.

The simulation results on the IEEE 33-bus system have demonstrated the property of power loss mitigation and have identified the effectiveness and efficiency of strategic BESS locations. This placement of BESS not only eases voltage deviations but also enhances grid reliability and provides substantial cost savings. Through the incorporation of shiftable loads in conjunction with optimal BESS placement, demand during peak hours can be managed effectively while maintaining grid stability. Voltage deviation, a crucial factor in maintaining grid stability, is effectively managed through the localized support provided by BESS, which helps regulate voltage levels within desired ranges as well as prevents under-voltage and over-voltage conditions.

Overall, this comprehensive approach to modern power system management combines optimal BESS placement with PBDR and advanced voltage control strategies. It underscores the potential of grid-scale energy storage to drive improvements in system efficiency and sustainability. The findings of this study provide a robust framework for future research and practical implementations aimed at achieving a more resilient and environmentally friendly energy infrastructure.

V. Future Work

While this study provides valuable insights into the optimal placement of BESS within a power grid and the benefits of PBDR, several areas warrant further exploration and development. Future work could expand upon this research by exploring more sophisticated optimization algorithms, such as machine learning-based approaches to yield more efficient and robust solutions for BESS placement and operation. Additionally, investigating the integration of BESS with emerging technologies such as distributed generation, microgrids, and smart grid technologies could provide a more comprehensive understanding of the potential challenges, such as blockchains. Furthermore, conducting a detailed economic analysis of different pricing schemes and their impact on both utilities and consumers would provide deeper insights into the cost-effectiveness and feasibility of various demand response strategies. Lastly, expanding the scope to include the environmental impact of BESS deployment and the potential for reducing carbon emissions would also be beneficial.

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