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Active/Reactive Power Losses Minimization Based on Optimal Location of Battery Energy Storage System

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***Abstract*— The fast development in battery energy storage (BESS) technology gave rise to utilizing it in ancillary services at optimal cost. The paper addresses an optimization tool of the BESS placement in a given network so as to reduce both active/reactive power losses. The strategy is tested based on real-data-based network and loss sensitivity factor approach is used to make best-selected bus to accommodate the BESS such that the associated parameters are maintained optimally. It has been observed that the grid performance improves in terms of power losses because of the local generation of the BESS at the selected bus, which is possesses the highest index of loss sensitivity factor that quantify the severity of a bus performance.**

***Index Terms*— Active power losses; battery energy storage; loss sensitivity factor; power networks**

I. INTRODUCTION

The increasing power demand urged conventional electric networks to shift to new schemes through which efficient utilization is achieved. Energy storage systems are candidates to support traditional power systems to meet the rising demand efficiently. Battery energy storage system (BESS) is widely used in microgrid concept and can be employed for this application. Saudi Arabia has been experiencing a steady increase in energy demand, which compels Saudi Arabia adopt expensive new power substations. However, existing substations can still meet the new demand with the support of BESS. In this paper, active power losses minimization is the main goal, provided that the BESS is optimally located in a given power network. It is important to select the location to which the BESS is placed; otherwise the main goal might backfire. In fact, a suboptimal placement might lead to degraded power losses, so a careful place selection is vital. Literature is full of optimization techniques that are applicable only to special cases, as they do not consider all parameters, which restrict their generality. Loss Sensitivity Factor (LSF) is a technique used to place generating units, and it is used here for the BESS purpose whereby the network buses are arranged in a descending order to make the selection. In order to prove this technique effective, a trial-and-error technique, where all buses are simulated with the BESS to enumerate all possibilities for a comparison purpose. This paper studies the BESS effect on the selected network for active power loss minimization. An optimal placement of BESS is the key for reducing such losses, or the outcomes would be more losses if not placed properly. Hence, this paper offers a procedure to optimally place BESS in the network. Generally, literature considers a single load type for the power losses minimization studies (residential) and that is not a good reflection of the diverse load types, and hence this paper takes four different load categories: residential, commercial, hospital, and industrial. The data for these load types were collected from Saudi Electricity Company (SEC) in the eastern province of Saudi Arabia, and a MATLAB simulation was held to obtain power losses results as a result of adopting the BESS. The remainder of the paper is organized as follows. Section II discusses related work. The problem statement is described in Section III. The proposed methodology is presented in Section IV. Results and discussion are addressed in Section V.

II. RELATED WORK

BESS was introduced to micorgrid for different applications like load leveling of renewable energy sources, peak shaving during peak hours, frequency regulation due to uncertainty of generation resources, voltage profile and power quality issues enhancements [1, 2, 3, 4, 5, 6, 7]. Peak loading occurs often for a short time in a given load profile, but these peaks must be met by generation units [8]. Traditionally, a generating unit is brought to operation to fulfill additional capacity requirements, but this approach is expensive and inefficient. Thus, peak shaving is a potential solution to the conventional approach [9]. The peak shaving application has many benefits to grids, including power quality, system efficiency, and cost effectiveness [10]. The system efficiency is related to line loss reduction due to freeing generating units from additional power production, which impacts voltage profile positively [11]. BESS is integrated into grids for

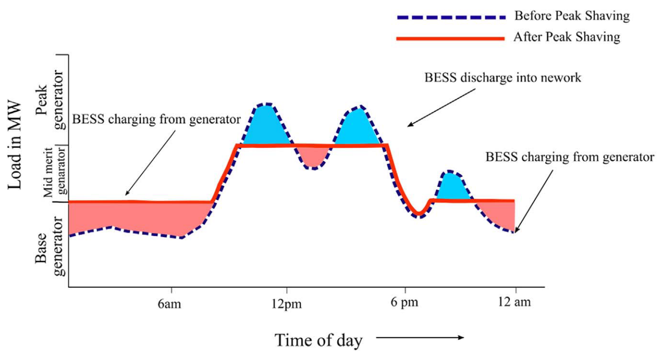

Fig. 1. Peak load shaving using BESS [22].

many purposes, such as peak shaving. This is achieved by charging BESS during valley hours and discharging them in peak times as shown in Fig. 1. It provides economical and technical benefits since the need for additional capacity generating units is reduced and the associated power loss is improved [12]. It is essential to select optimal location of BESS in a grid; otherwise, anticipated effects might render ineffective [13]. In fact, the quality of power losses is significantly impacted as a function of the BESS relative location to load centers [14]. A general review of BESS placement was introduced in [15]. Authors in [5] utilized multi-objective particle swarm optimization and genetic algorithm on an IEEE-30 wind power distribution system to obtain optimal BESS location for power cost and voltage profile improvements. Also, the multi-objective BESS allocation along with neural networks were used in [16] to optimize the BESS location in transmission and distribution networks. Mixed-integer programming was employed in [17] to optimize the BESS location, which was extended in [18] through the usage of linear programming for the same purpose. Two main drivers of optimal BESS placement: energy loss minimization and deferral of networks upgrading [18]. The authors in [19] investigated the BESS location impact on LV feeder for power loss and voltage profile. Optimal AC power flow technique utilization in presence of BESS in a power system was analyzed in terms of many indices: voltage deviations, power quality, load shedding, and energy cost improvements. Loss sensitivity factor (LSF) is a wll-known tool for optimally place DG units [20, 21]. Likewise, LSF is employed to find optimal placement of BESS, as BESS resembles DG operation in discharging mode.

III. Problem Statement

There is different applications related to BESS including load leveling, peak shaving, frequency regulation, etc. Peak shaving is one of the applications of BESS whereby it stores energy during off-peak hours and release energy in peak times. The peak shaving depends on load forecasting, but this study is not for forecasting, so this part is omitted. Instead, off-peak times and peak times are already known for one year span. The load peaks pushes the power system to its limit, resulting in more losses and bad voltage profiles, so it is prudent to spare generating units during peak times to mitigate these effects. Therefore, an optimal placement of BESS is essential in this scheme so as to achieve desired outcomes. LSF is an effective tool employed in placement of DG units, and since BESS has a similar functionality to the DGs during its discharging mode, it is justifiable to adopt it.

IV. Proposed Methodology

A. BESS Placement Based on LFS

LSF is a parameter that specifies the sensitivity of each bus in a power network to injected active/reactive power [20, 23]. It is modeled for active/reactive power injection as follows:

$$\frac{\partial P_{line_loss}}{\partial P} = 2 * \frac{P(q) * R(k)}{V(q)^2} \tag{1}$$

$$\frac{\partial P_{line_loss}}{\partial Q} = 2 * \frac{Q(q) * X(k)}{V(q)^2} \tag{2}$$

The active part of LSF is only considered, so the reactive LSF is ignored for assessing the reactive power loss. The mechanism of the LSF tool is to arrange network buses in a descending order such that the bus whose LSF index is the highest is the candidate for BESS installment. A complete simulation of all possible locations of BESS in network buses is achieved to confirm the attained earlier results.

B. Control Strategy

Peak shaving is the prime function of the BESS in this paper. BESS can function as a load (during charging period) or as a generator (during discharging period). Thus, BESS has the capability to perform peak shaving. Traditionally, peak shaving is based on load forecasting so that valleys in load profile are utilized to mitigate peak times. The total output power of DGs in a network is given below

$$P_{DG,peak} = \sum_{i=1}^{N} P_{DGi} \tag{3}$$

Where N is the number of all DGs running during peak periods. The total output power $P_{DG,peak}$ has to be higher than the desired load level P_{Level} in order to meet the demand load in the peak times. The BESS reduces the load level to the base level P_{Level}. That being said, the load in the next day is forecasted with a good accuracy, so the predicted demand P_D is used to estimate the BESS required energy in the peak times as seen in 7

$$E_{Peak} = \int_{t_{a,peak}}^{t_{b,peak}} (P_{D(t)} - P_{Level})dt \tag{4}$$

After that, it is vital to ensure that the BESS stores enough energy for peak times, which boils down to anticipating the reserved SOC for such peak times. Let E_{rated} denotes the rated capacity for the BESS, SOC_{res} is the reserved SOC for peak periods, and SOC_{min} is the minimum SOC for the BESS, then the following formula holds

$$(SOC_{res} - SOC_{min}).E_{rated} = E_{peak} \tag{5}$$

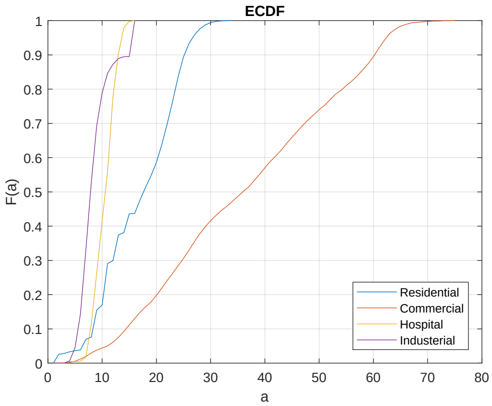

Fig. 2. Empirical Cumulative Distribution Function.

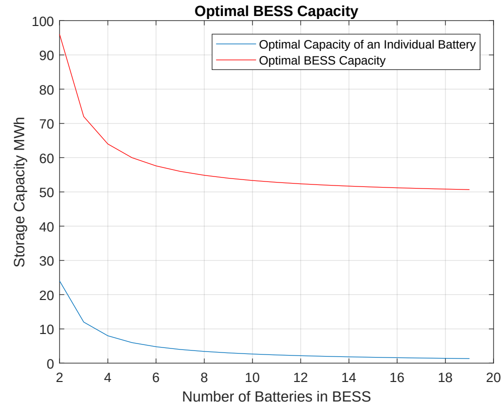

Fig. 3. Battery Energy Storage System size.

Therefore, the reserved SOC is

$$SOC_{res} = \frac{E_{peak}}{E_{rated} + SOC_{min}} \tag{6}$$

Hence, the BESS should be charging in off-peak times to at least SOC_{res} at the beginning of peak times $ta, peak$.

C. BESS Optimal Sizing

The monotonic battery sizing approach in [24] is adopted for sizing the BESS. Individual battery sizing and the overall BESS sizing are calculated such that an optimal capacity is obtained. The main concept is to dedicate batteries for charging and discharging so as to avoid cyclic charge/discharge process, thereby prolonging batteries life span. Cumulative distribution function derived empirically (ECDF) over the time span was used to find the energy variable needed to make the calculation as per as seen in Fig. 2. Seemingly, different pattern associated with different load types, so the value of a should reflect the coverage of the worst case scenario among these load types. Supposedly, the set confidence level of load coverage is 80%, then the value of should be about 52 MWh, as the commercial load type pushes it to that limit (see Fig. 3).

Next the individual battery size and the overall BESS size are evaluated in accordance with:

$$c(n) = \frac{a}{(\alpha_M - \alpha_m)(n-1)} \tag{7}$$

$$C(n) = \frac{2na}{(\alpha_M - \alpha_m)(n-1)} \tag{8}$$

V. Results and Discussions

Data representation of one full year in hourly resolution were obtained from SEC for four different load categories-namely, residential, commercial, hospital, and industrial (see Fig. 4). Also, the gathered data include transmission lines impedance values along with shunt admittance parameters. The bus number one is selected as a slack bus, whilst the rest are load buses, except in case of BESS installment, a load bus becomes a PV generation bus.

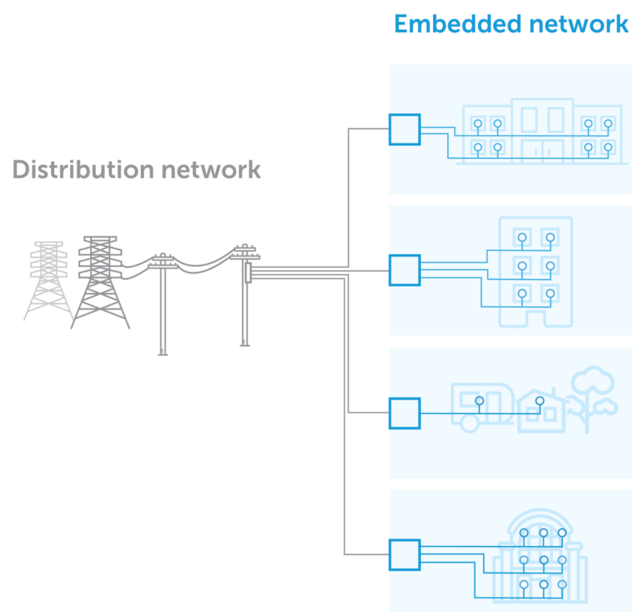

Fig. 4. System Schematic.

Load flow analysis using Newton Raphson-based technique is used to analyze the network for one year time frame in terms of load demand, line losses, voltage profile, and load peaks. The maximum load demand is about 83 MW and the average load is nearly 77 MW. It is assumed that a peak loading occurs whenever a load exceeds an average load profile (77 MW). Thus, the BESS discharges to trim a peak. The buses LSFs are shown in Fig. 5 except bus-1 since it is assumed to be the slack bus. Seemingly, bus-2 possesses the highest LSF, whilst bus-5 has the lowest LSF value. Therefore, it makes sense to discharge the BESS during peak times at bus-2 and charge it during off-peak times at bus-5, thereby reducing power line losses. However, the network configuration renders this arrangement impractical, so the charge/discharge of the BESS is held at bus-2.

Fig. 3 indicates that the constant (a) at 80% of the

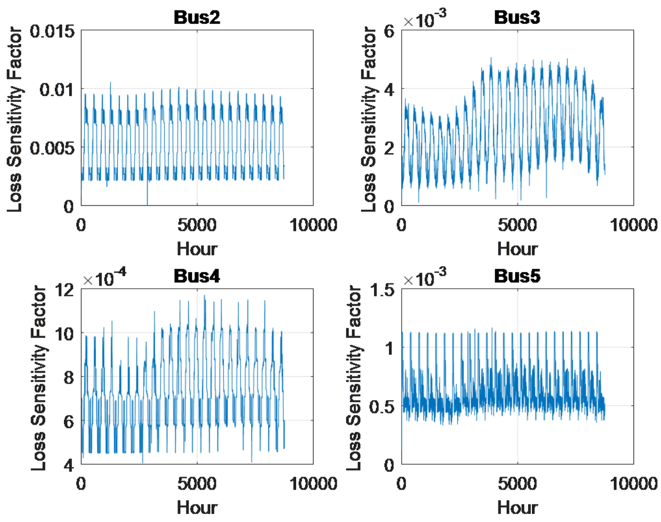

Fig. 5. Loss Sensitivity Factor.

system covered by BESS is 52 MWh, so from (7) and (8), the individual capacity and overall capacity of BESS are computed, respectively. The equations are used for different number of batteries to investigate the point beyond which an increase in number of batteries does not result in a significant capacity improvement. This can be noticed in Fig. 3 that depicts the performance of both the individual battery in BESS and the overall capacity at different battery number. These capacities are saturated beyond 12 batteries. The battery capacity is nearly 10 MWh, and it is about 220 MWh for the overall BESS. This set up is supposed to cover all the loads in the network for load leveling purpose at a confidence level of 80%. Of course, the sizing of the individual batteries as well as the overall BESS can be reduced substantially upon relaxing the confidence level, or considering critical load types only. For example, if the choice made to put the priority for the hospital bus for the BESS, the a variable would be as small as 12 MWh, resulting in nearly 3 MWh and 54 MWh for individual batteries and the BESS, respectively. The power network was simulated many times with different locations of the BESS to prove the effectiveness of the LSF tool. Table I shows the worst case scenario of power line losses and reactive power loss before $P_{Lb}\&Q_{Lb}$ and after $P_{La}\&Q_{La}$ the installment of the BESS at a particular bus. It is clear that the bus-2 is the bus contributing the most to both active and reactive power losses minimization, and therefore the LSF bus selection is correct. The BESS discharging frees the bus-1 (slack bus) from transmitting additional active/reactive power to the load buses, thereby reducing the overall power losses.Also, the reduction in the total current generated, results in an enhancement in the reactive power loss on top of the active power loss improvement. Nevertheless, the BESS involves charging process that might worsen the original power losses profile if it is located improperly. This is observed in Table I, where active/reactive power losses take

TABLE I
RESULTS OF BATTERY ENERGY STORAGE SYSTEM CONTRIBUTION.

Bus	Bus-2	Bus-3	Bus-4	Bus-5
P_{Lb} (MW)	15.1	15.1	15.1	15.1
P_{La} (MW)	13.48	18.35	18.99	33.5
Q_{Lb} (PU)	11.45	11.45	11.45	11.45
Q_{La} (PU)	9.93	12.87	11.05	12.29
P_{Loss} %	10.72	-21	-25.76	-121.85
Q_{Loss} %	13.3	-11.62	3.5	-7.34

negative percentage. This means the losses actually increased instead of decreasing as a result of improper selection of the BESS bus. Indeed, suboptimal placement of the BESS is detrimental and the process should be carefully implemented. It has to be noted that the reactive part of the LSF is not taken into consideration since the BESS does not fit in this scenario. Instead, capacitor banks or any reactive-compensation system is to be placed in this selection so as to test feasibility of reactive power LSF. However, a dual selection of BESS and capacitor banks in the same system is challenging, as the charge/discharge process needs to be in harmony in order to avoid over voltage compensation, or even a poorer power losses profile.

VI. CONCLUSION

This paper adopted the LSF approach to optimally place BESS in the five-bus system. The system active/reactive power loses at the corresponding buses were evaluated at two different scenarios-namely, normal network system and network system with the BESS. The results stated that the the BESS installed at the bus with the highest LSF yield the best performance in terms of both power losses profile as well as voltage profile. These results are supported by comparing the bus-2 performance to the rest of buses as in Table I. A reactive power compensation is to be tested in the next study to observe the dual placement of both systems in the given network.

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