Comprehensive Design of a Microgrid Energy Storage with Guaranteed Optimality

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***Abstract*—Improving reliability of a microgrid by incorporating Battery Energy Storage (BES) can be a cost-effective solution. This study proposes a Comprehensive Microgrid Energy Storage (CMES) solution that improves both reliability and cost performance of a microgrid. The solution is implemented on different case studies and the corresponding reliability and cost analysis results are presented.**

***Index Terms*—Battery energy storage, degradation cost, life-cycle cost, optimization, reliability**

I. Introduction

Energy systems are transitioning from traditional towards low-carbon sustainable systems. A modernized system with both renewable energy and traditional sources is widely referred to as a ”smart grid” [1]. Microgrids are a key component in the modernized electricity grid with the potential to manage energy supply and demand in a reliable, economical and sustainable way [2]. Increasing presence of renewable sources and energy storage systems in microgrids necessitate reliability assessments to ensure stability and security [3].

Several U.S. states have taken a keen interest in Energy Storage (ES). Massachusetts has set a goal for 1,000 MWh of ES by the end of 2025. California’s three largest electric cooperatives have been mandated to develop a combined ES capacity of 1,825 MW by the end of 2024 [4].

Liang et al. [5] evaluates the reliability of an islanded microgrid. Monte Carlo simulation is used to sample the fault conditions of equipment to reflect the possible states of microgrid operation. Chen et al. [6] considers energy exchange and dispatch strategy between several microgrids to assess reliability of a multi-microgrid system. Critical and non-critical loads for related reliability indices for connected and islanded modes are evaluated. Escalera et al. [7] assesses the contribution of energy storage towards reliability by considering three influential factors: energy storage size, initial State Of Charge (SoC) and renewable distributed generators’ penetration level during a fault. In [8], energy storage supply part of the load in low voltage distribution networks but the influence of energy storage size was not evaluated. Xu and Singh [9] evaluate the reliability of a distribution network for different energy storage sizes and renewable distributed generator penetrations. However, the impact of initial stored energy when a fault occurs is not addressed and recommendations on energy storage sizing to fulfill specific reliability targets are not provided.

This paper develops a method for optimal design and operation of a low-cost rechargeable battery for minimizing the Life-Cycle Cost (LCC) and maximizing microgrid reliability. An optimization is performed on the battery and inverter sizes as well as their operation throughout the year. Potential electricity market participation is assessed based on the optimum size of battery.

The remainder of this paper is organized as follows. The problem statement is defined in Section II. Section III illustrates reliability assessment and establishes the optimization method. Proposed solution is defined in Section IV. Simulation results are shown in section V. The potential market participation is explained in Section VI and the conclusions are shown in Section VII.

II. Problem Statement

The main purpose of this study is to find a low-cost reliable battery design with low LCC. The reliability

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analysis of expected load loss and maximum power loss establishes a lower limit for the battery and inverter sizes. This guarantees 100% and 130% reliability for critical loads. To ensure efficient long-term operation of batteries, maximum allowable Depth of Discharge (DoD) is 40%, or in other words, the minimum allowable SoC is 60%.

The total cost of a CMES system is a function of several variables like the battery size (S_b), inverter size (S_{inv}), power output ($P_b(t)$) at every hour, and the cost models of both the electricity tariff (C_{tariff}) and battery degradation (C_{deg}). The initial investment cost C_I depends on S_b, S_{inv}, unit cost of the battery (C_{bu}) in \$/kWh and unit cost of the inverter (C_{iu}) in \$/kW as shown in Eq. 1. The operational costs (C_{tariff} & C_{deg}) are determined by all the variables together.

$$C_I = (S_b \times C_{bu}) + (S_{inv} \times C_{iu}) \tag{1}$$

The optimization aims to reduce the LCC (C_{LCC}) by taking into account the initial investment and operational costs as shown in Eq. 2. C_{tariff} and C_{deg} are calculated over 20 years whereas C_I is a one-time cost.

$$\min_{P_b, S_b, S_{inv}} C_{LCC} = C_I + \sum_{k=1}^{20} (C_{tariff}(k) + C_{deg}(k)) \tag{2}$$

$$\text{subject to} \begin{cases} -S_{inv} \leq P_b(t) \leq \beta_{ch} \times S_{inv} \\ SoC_{min} \leq SoC(t) \leq SoC_{max} \\ SoC(t+\Delta t) = SoC(t) + \eta \times \frac{P_b(t)}{S_b} \times \Delta t \end{cases} \tag{3}$$

$$\text{where} \begin{cases} k \equiv \text{Current year} \\ \beta_{ch} \equiv \text{Discharge-charge power ratio} \\ \eta \equiv \text{Battery efficiency} \end{cases} \tag{4}$$

Eq. 3 shows the three constraints of the optimization problem. The first one limits the power input/output of the battery to the maximum inverter capacity. The second constraint defines the SoC limits within which the battery is allowed to operate. The third constraint defines the relation between the SoC and the power output. For example, if the battery is being charged, $P_b(t)$ is positive, and $SoC(t + \Delta t)$ depends on the total energy supplied to the battery for over a time period Δt.

Experimental results give information about the number of charge-discharge cycles a battery can undergo if its discharged from full capacity to a specific DoD and charged back (Fig. 4). Using this, we have developed a degradation "loss" (L_{deg}) associated with each such cycle as a function of SoC (Eq.5). The monetary cost (C_{deg}) can then be calculated with respect to the overall battery cost as shown in Eq. 6. Thus, when a battery starts discharging at time t, we can calculate the cost incurred between time t and $t + \Delta t$ by subtracting the values of C_{deg} at those times (Eq. 7).

$$L_{deg}(SoC) = -0.0064 \times SoC + 0.0066 \tag{5}$$

$$C_{deg}(SoC) = L_{deg}(SoC) \times C_{bu} \times S_b \tag{6}$$

$$C_{deg}(t, t+\Delta t) = C_{deg}(SoC(t)) - C_{deg}(SoC(t+1)) \quad \text{subject to } SOC(t) > SOC(t+1) \tag{7}$$

III. Optimization Method

A multi-level offline optimization is performed on the battery and inverter sizes at the upper level, and the hourly battery power output at the lower level. Both levels together aim to reduce the total cost incurred, which includes the battery and inverter installation costs, the annual electricity bill, and battery degradation cost.

In this study, reliability analysis is done for a backup system with parallel generators using likelihood of survival and expected lost load. The likelihood of survival is the expected survival rate for a specific duration of outage. Probability of generators being available after an outage is calculated using the number of available generators, likelihood of Fail-to-Start and Fail-to-Run probability. To meet critical load, the minimum number of generators required is obtained by dividing critical load with the generator capacity and rounding up the result. The backup system survives the outage if the available capacity for each outage hour is greater than the critical load for that hour.

The expected lost load is a measurement of the insufficient energy if only diesel generators are used during the outage and can be shown as a curve. The maximum value of this curve shows the desired battery capacity to make the site 100% secured for a given duration of outage. Furthermore, based on the "expected lost load" analysis, the "maximum power loss" for an outage duration can also calculated. The physical meaning of this value is the minimum inverter size needed to bring survival rate to 100% given a battery at the size of "expected lost load". The optimum size of battery and inverter are defined by reliability analysis.

For reliability assessment, equal probability for an outage throughout a year is considered. The assumptions present in the reliability analysis are summarized in Table.I.

TABLE I: Assumptions used in the reliability analysis

Availability	Failure to start	Mean time between failure (hours)	Diesel fuel conversion factor (BTU/gallon)
99 %	0.2 %	1700 hrs	137,381

The optimization is performed over the entire year, and thus the number of decision variables is high (above 8000). Due to this, the objective function is modeled as a convex function (Eq. 2). GUROBI [10], a commercial optimization solver, is used. Fig. 1 illustrates the optimization approach.

Some assumptions made in the model and the optimization process are as follows:

1) The hourly load for the full year is assumed to be known beforehand.

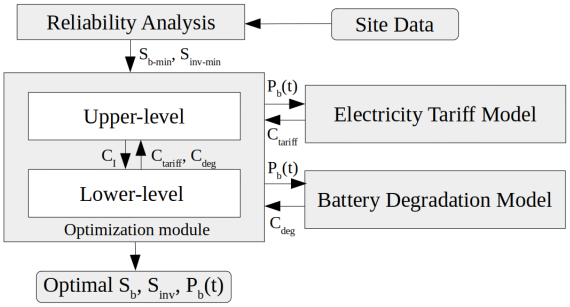


Fig. 1: Optimization Procedure

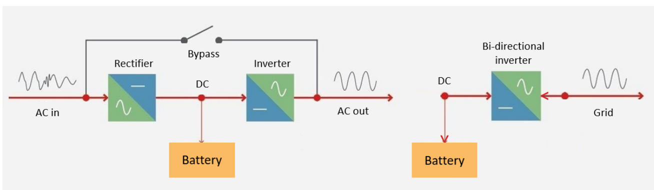


Fig. 2: Different connections of battery to grid

2) Load distribution is assumed to be same as 2018 for the next 20 years.
3) Battery is fully charged at the beginning and end of each day.
4) Battery efficiency (η) is assumed to be 98%. It represents the energy loss during charging/discharging.
5) Loss of charge in the battery due to multiple charge-discharge cycles is not considered.

IV. Discussion

A. CMES Solution

The model of microgrid components and BES are utilized to simulate various operational scenarios in microgrid. There are two BES systems topologies that can be used to provide backup power and participate in the market which are shown in Fig.2. Power backup can also be used to reduce demand by regulating the current to the rectifier. These systems can only power loads connected to the inverter, but they are active at all times, including when grid power is lost. Another topology is called grid-tied system because the inverter used is bidirectional. Grid-tied systems are required by UL 1741 to sense a valid frequency in operation mode or supplying power to all the loads on the grid in islanded mode.

B. Tariff Model

The term tariff in this paper refers to the energy bill policies of utility companies. In order to analyze the economic impact, analytical tariff models for the optimization process need to be built. The sources used to construct the model are energy contracts, which include the energy price, demand charge, demand-response incentives, etc. Fig.3 shows Time of Usage (ToU) energy price. A charge

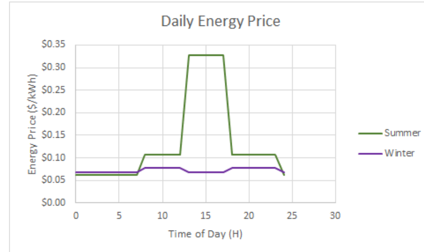


Fig. 3: Simplified TOU energy price for microgrid

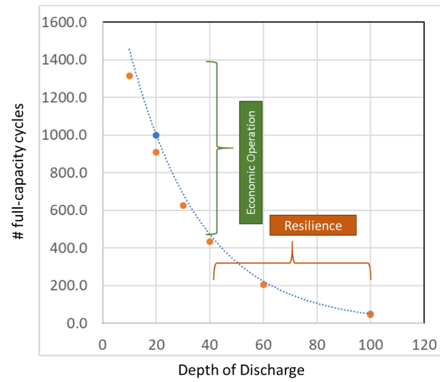


Fig. 4: Relationship between DoD and the number of cycles for each cell

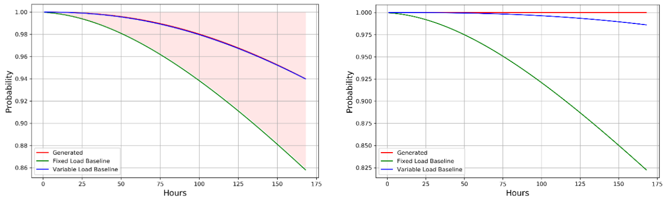
for monthly peak power demand is also usually present in the tariff model.

C. Battery Energy Storage

In this project, low-cost, non-toxic, low maintenance ZnMnO2 batteries are used. This Battery can be used for thousands of cycles at a moderate DoD to manage energy and peak loads in the microgrid. It can also be used for more than 1500 cycles for normal discharge (DoD $<$ 40%, operation mode) and 50-100 cycles at very deep discharge (100% DoD, resilience mode) to respond to occasional emergency situations (Fig. 9). The cost of batteries ($/kWh) for a 10% utilization or 1,000 cycles are about $100/kWh. They can operate between 0°C to 50°C and therefore do not require dedicated temperature control. The battery cells can be charged in a voltage range from 1.67V to 2V and at a current of 2A to 10A.

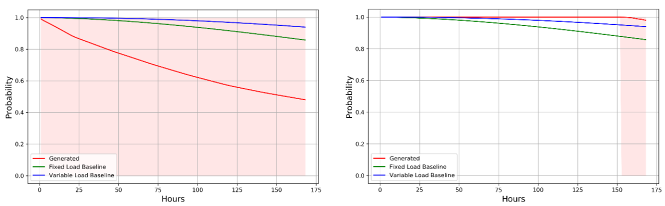
V. Simulation Results

The reliability analysis is done to meet 100% of installation critical and ride-through load with and without battery. The results for the case study are shown in Fig.5a and Fig.5b. In these figures, only the generated expected survival curve for the critical loads is not plotted, but also the distribution of survival rates in pink shaded area. Each point (for example, t=100hrs) in the generated curve is actually an average of the distribution (for example, pink shaded zone where t=100hrs). The generated results with two provided baseline curves, namely fixed load baseline



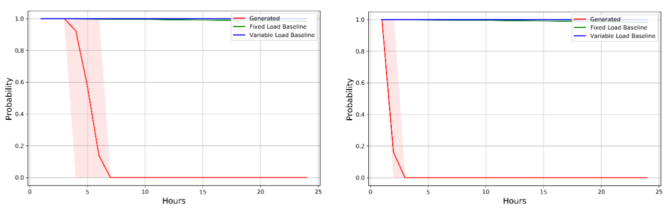
(a) 100% load without battery (b) 100% load with battery

Fig. 5: Reliability curve to meet 100% of critical load without/with Battery



(a) 130% load without battery (b) 130% load with battery

Fig. 6: Reliability curve to meet 130% of critical load without/with Battery



(a) 10% of critical load (b) 30% of critical load

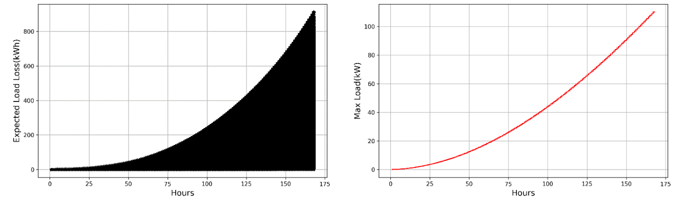
Fig. 7: Reliability curve to meet 10% and 30% of critical load with Battery

and variable load baseline are compared. The generated curve matches well with the variable baseline, which is expected. The generated curve with fixed load baseline curve are aligned very well. The results show the worst case performance using different analysis. The above results demonstrate the correctness of our simulation.

The minimum size of inverter and battery size through reliability analysis are determined. Battery size is determined with analysis of Loss of Load, and inverter size is calculated using Maximum Power Loss . The reliability assessment is done with increasing the loads to 130%. The performed simulation results are shown in Fig.6a and Fig.6b.

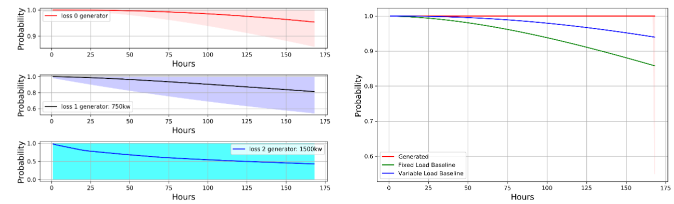
Analysis using only diesel generators to meet 10% and 30% of critical load for a duration of 24 hours is performed. The reliability curve to meet 10% and 30% of the critical load using battery optimum sizing is examined. Results from the analysis are shown in the Fig.7a and Fig.7b.

The expected load loss and maximum power loss are analyzed . In the Fig.8a, the distribution of expected load loss is shown. Maximum power loss for each hour is also



(a) Expected load loss (b) Maximum load loss

Fig. 8: Expected and maximum load loss



(a) Reduced generators (b) One gen loss with battery

Fig. 9: Reliability decay due to reduced generators & with one generator loss

plotted out in Fig.8b.

The maximum load loss (the maximum point in 168 hrs) shows the battery size needed in order to operate the site with 100% reliability. Similarly, maximum power loss shows the deficiency of power. The point at 168 hrs in maximum power loss shows the inverter size needed in order to operate the site with 100% of reliability. The battery and inverter size for this case study are $912.7kWh$ and $110.1kW$. The impact of losing diesel generators in the microgrid is examined. The reliability curve for losing one and two generators are plotted in Fig.9a and Fig.9b. The equivalent power losses for losing a specific number of generators is marked.

Impact of different size of battery on the reliability curve is examined as it is shown in Fig.10. The battery size is varied to be 100%, 60% and 30% of the recommended size. As expected, the 100% size installation boost the survival rate to 100%. For a smaller installation, the battery runs out of power before the power gets restored. Currently, the

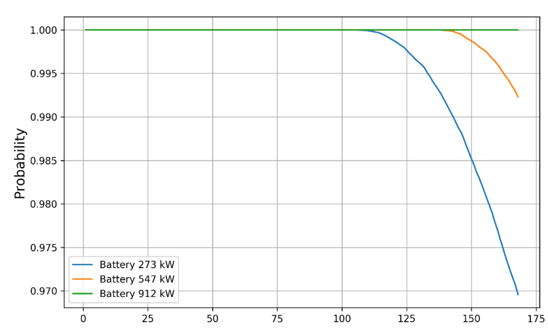


Fig. 10: Reliability vs life-cycle cost

TABLE II: Cost breakdown after optimization

Annual electricity Bill before optimization ($)	7,127,185
Battery Size after optimization (kWh)	1600
Inverter Size after optimization (kW)	600
Battery & Inverter installation Cost ($)	140,000
Annual Battery degradation cost ($)	3,575
Estimated Annual electricity bill after optimization ($)	7,051,996
Estimated annual savings ($)	71,614
Internal rate of return (%)	44
Net present value of LCC over 20 years ($)	843,204
Years to recover investment	3

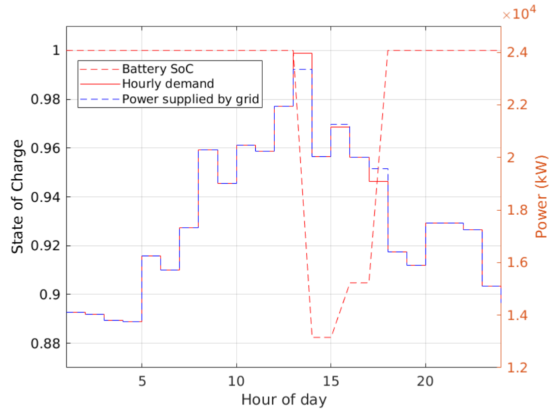


Fig. 11: Load profile for one day

microgrid meets it's energy requirements through diesel generators. Thus, the annual cost of operation involves only the electricity bill. After incorporating batteries into the system, the electricity costs change and battery degradation cost comes into play. Savings are primarily obtained through the reduction of the peak demand electricity bill when the battery is in operation. The cost breakdown obtained through the optimization is shown in Table.II. In Table II, the optimal battery and inverter size and the resulting savings are shown. The battery cost is 50$/kWh$ and the inverter cost is 100$/kW$, which is used to calculate the installation cost of the entire storage system consisting of the battery and the inverter. The annual battery degradation cost is a measure of the remaining battery life as a function of the original cost and the amount of discharging being done. When the cumulative degradation cost over multiple years of operation gets close to the original installation cost, then the battery would need to be replaced. Table.II also gives the Internal Rate of Return (IRR) and the Net Present Value (NPV) over 20 years. The annual inflation and discount rates are considered 2.2% and 6% respectively. Since the load profile is assumed to be the same over the investment horizon of 20 years, the annual savings for the first year is used to calculate the NPV. The initial investment is the battery and inverter installation cost.

Fig.11 shows the energy supplied by the grid (marked in orange) and the load profile (marked in blue) over a single

TABLE III: Cost distribution during one day battery operation

Peak load cost incurred without battery	$ 288,984
Peak load cost incurred with battery	$ 281,785
Peak load savings	$ 7,199
Battery degradation cost during peak shaving	$ 507
Energy cost recharge battery to full capacity	$ 22
Overall savings	$ 6,670

day. The red dotted line represents the State of Charge (SoC) of the BES. When the battery is fully charged the SoC takes a value of 1. It decreases when the battery is discharging and vice versa. During the afternoon, a load peak occurs and thus incurs peak demand costs along with the normal generation charges. Based on the TOU of microgrid, monthly peak demand transmission and distribution charges are $5.476816 and $6.580761 per kW respectively, much higher than the energy charges. As a result of the optimization, the BES, being fully charged at this point, starts discharging when the demand gets close to the peak. Thus, the grid supplies less load than it would have without the BES. In other words, from the perspective of the grid, the peak load is partially lowered or 'shaved' by the BES. This results in savings on the peak demand charges, which is much higher than the battery degradation cost during the discharging period. The BES is charged back again when the demand drops. The cost distribution in Table.III further illustrates this point. For the studied microgrid, the NPV is very high and the number of years to recover the investment is 3 years.

VI. Potential Market Revenue

The potential revenue out of electricity market associated with utility TOU rate, charging scheme of battery, battery characteristics such as the state of charge, the degradation cost and the storage inverter which manage the rate of stored or discharged energy. In this study, the effects of energy storage ramp rate is neglected. In addition, the battery should charge back each day in order to be ready for another signal for market participation and the state of charge cannot be less than 60% every hour which limits the amount of energy available for market participation. For charging the battery, there are two options for the cost: charging with the same rate in the yearly contract with utilities or charging with the market prices whenever the price is low. The maximum net revenue is a critical calculation because it shows the performance of energy storage in the market and it could be achievable when the price for market recoup the battery storage related costs. Battery can provide real-time frequency regulation when they are not being used for peak shaving. Spinning reserves are also available with much less frequent dispatch. Revenue primarily comes from capacity rather than energy. Dual-use programs (frequency

TABLE IV: Ancillary market maximum revenue with battery participation

Responsive Reserve	$/yr 98,249
Non-spinning reserve	$/yr 15,406
Regulation Up	$/yr 38,211
Regulation down	$/yr 12,427
Battery degradation cost	$/day 385.44
Battery Minimum charge (Market)	$/day 26.15
Battery Minimum charge (Utility)	$/day 47.023

regulation and peak shaving) revenues are actually higher, because peak reduction occurs on a limited number of days during each month. The assessing of ancillary market is summarized in Table.IV.

VII. Conclusion

The studies conducted across the five sites show extremely promising results for proposed CMES solution, including UEP batteries. The key findings are CMES solution enable us to size and design a storage system that guarantees 100% of installation critical and ride-through load requirement for all the sites. We were able to demonstrate that with the addition of the sized CMES solution we are able to meet 130% of installation critical and ride-through load requirement for all the sites. We were able to demonstrate that with the addition of the sized CMES solution we are able to meet 10% and 30% of installation critical and ride-through load when no diesel fuel is available. The CMES solution is able to generate storage solution such that not only all the reliability requirements are met but the technology investment cost can be recovered in less than 20 years. The CMES solution shows that one of the generators can be replaced with the storage system without significant impact on the site's reliability performance.

In this study, reliability is defined as the ability of the microgrid system to supply the demand when failures of network components occur.

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