Transformer Loss of Life Mitigation by Coordinating Energy Storage, EV charging, and PV Generation at Consumer Sites

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***Abstract*— Although the penetration of electric vehicles is relatively low today, it is expected to grow in the future, particularly in urban areas exposed to excessive tail-pipe pollution. In some urban areas, this growth may be faster due to a concentrated EV adoption in affluent neighborhoods; hence, the grid power transformers in such areas may be at risk of accelerated ageing. This impact can be mitigated by using consumer-owned battery energy storage and photovoltaic generation. We propose a coordination approach of utilizing such assets not only to support the distribution grid and maximize consumer profit, but also to mitigate the ageing of the distribution transformers. A case study of electric vehicle high penetration consequences is illustrated using data for an urban area of the city of Bryan/College Station in Texas. EV charging data in a residential area were synthesized using a Monte Carlo simulation. Finally, the economic impact of optimal EV charging is studied.**

***Keywords*— Battery energy storage system, PV generation, electric vehicle, loss of life, transformer.**

I. Introduction

While electric vehicles (EVs) may account for a small percentage of vehicles on the market today, adoption is accelerating and gaining momentum. For several reasons, such as financial, social, cultural, and political, this growth in EV deployment varies in different countries, cities, or even neighborhoods. This may lead to high penetration of EVs in some parts of a given distribution grid, which may cause occasional overload of transformer assets in such areas.

Continuous and frequent overloading puts the transformer under thermal stress, which causes accelerated ageing. At the distribution level, power transformers do not have elaborate monitoring systems and, as a result, their loading is usually not closely monitored. EV charging may be concentrated in a given area, causing transformer overloading over an extended time, which may lead to transformer failure [1], [2]. The loss of life and premature failure in large numbers may impose additional financial constraints on electric utilities. Upgrading the grid with a number of larger capacity transformers may be prohibitively expensive and might not be considered a feasible solution for this situation, at least in the short run.

One possible solution to mitigate this impact and help the distribution system assets reach their normal life expectancy is to rely on the customer installation of photovoltaic (PV) generation to shave the peak demand and battery energy storage system (BESS) to shift the time of demand (Fig. 1). BESS can be deployed for different purposes, such as voltage control, peak shaving, and mitigating frequency events [3]. The impact of EV charging on transformers is studied in [4]–[7]. Reference [8] shows how different penetration levels of EVs would accelerate the ageing of transformers in a residential building. Reference [9] utilizes a probabilistic method to assess the impact of EV charging and PV generation on the ageing of transformers. In [10], the authors propose an in-site fuzzy controller that manages the charging of EVs considering the information of EVs next trips, as well as the EV owner's comfort selections. Reference [11] investigates the impacts of EV fast chargers on transformer aging and the effectiveness of deploying solar shingles and battery energy storage to mitigate the impact. A transformer anti-ageing system that uses battery energy storage to mitigate the impact of high renewable energy penetration on transformer aging is proposed in [12]. The optimization formulations provided in [13] and [14] aim to mitigate the risk for transformers using PV and BESS supports. References [15] and [16] introduce rule-based methods to mitigate the risk for transformers by identifying and shaving peak hours.

The contribution of this study is the development of a coordination and management approach by which the consumer profit from employing BESS and PV systems is optimized while the stress on the utility assets is minimized. Use cases with different scenarios are developed to study the effectiveness of the proposed approach. Some use cases show how the implementation of the approach is profitable.

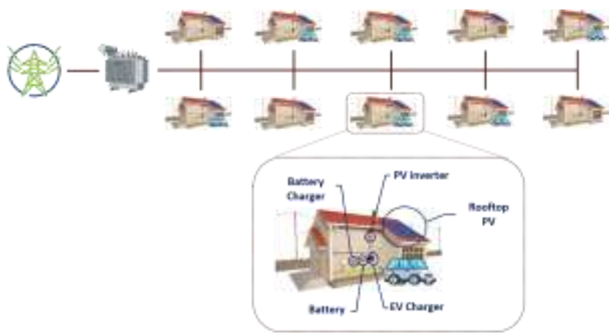

Figure 1. The schematic of the studied system.

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The paper first provides the economic model in Section II, then proposes the BESS coordination strategy in Section III, explains the use cases in Section IV, demonstrates the results in section V, and finally provides conclusions in section VI.

II. The Economic Model

The thermal conditions of transformers are mainly affected by the ambient temperature and transformer loading. Increased copper loss during an overload raises the temperature near the windings and leads to an accelerated transformer loss of life. To quantify the transformer loss of life and aging due to thermal conditions, IEEE Standard C57.91 is used [17]. This approach is thoroughly explained in [18] and [19]. A brief explanation of the loss of life calculation can be found in the appendix.

The equivalent daily cost (EDC) reflects the cost of owning and operating the transformer [20], and it is utilized to assess the economic impact of the transformer loss of life on the economic impact. The *EDC* at time slot *t* can be calculated as shown in (1).

$$EDC_t = \frac{Asset\ Current\ Value \cdot r}{1 - \dfrac{1}{(1+r)^{Remaining\ Life}}} \tag{1}$$

where r is the interest rate. When the transformer is new, the *EDC* is calculated using (2).

$$EDC_0 = \frac{Transformer\ Price \cdot r}{1 - \dfrac{1}{(1+r)^{Expected\ Life}}} \tag{2}$$

This can be employed to calculate the transformer current value (*TCV*) at time slot *t* using (3), which is derived from (1).

$$TCV_t = \frac{EDC_t}{r} \cdot (1 - (1+r)^{-Remaining\ Life}) \tag{3}$$

Two TCV_t values can be calculated for two scenarios: a) when the loss of life is mitigated and b) when the loss of life is not mitigated. The difference between the *TCV*s in these scenarios reflects the financial benefit of mitigating the impact.

As explained in [20], the difference between the present value of all inflows and outflows is the *NPV*. In this study, the inflow is the investment in the transformer, which is the transformer value, and outflow is the transformer loss of life. Using [20], the formula for calculating the *NPV* is shown in (4). T_{PB} is the time required to recover the initial investment, namely, the payback period, which can be calculated using (5).

$$NPV_t = -Inv_0 + \sum_{i=0}^{T} \frac{(Cost(i+t) - Profit(i+t))}{(1+r)^{i+t}} \tag{4}$$

$$if \quad \exists T_{PB} : NPV \geq 0, \forall T > T_{PB} : NPV < 0 \tag{5}$$

The cost, which is caused by the loss of life of a transformer in a day, is the difference between the *EDC* before and after the investment in PV and/or BESS.

$$NPV_t = -Inv_0 + \sum_{i=0}^{T} \left(\begin{array}{l} \dfrac{(Cost(i+t) - Profit(i+t))}{(1+r)^{i+t}} \cdots \\ \cdots + EDC_{t,2} - EDC_{t,1} \end{array} \right) \tag{6}$$

The payback period can be calculated using Equations (5) and (6).

III. The BESS Coordination Strategy

A. System Description

A schematic of the system under study is shown in Fig 1. The main elements of the system are residential buildings, which, as shown in the enlarged part, host a load, stationary BESS, PV, and mobile BESS (EV) connected to the grid through the same transformer. It is assumed that both the mobile and fixed BESSs can operate in charging and discharging modes. The generation of a PV system depends on the weather and the related solar irradiation. Optimization algorithms are required to coordinate the operation of each building. A central controller coordinates the energy exchange between the different parts of the system. Market-based management decisions are made and implemented by sending coordination commands to each element.

B. Coordination Strategy

In this section, the optimization model for the energy-exchange coordination strategy is explained. An optimal planning scheme for the exchange should simultaneously maximize the profit for the customer and utility at the same time. The nature of the relationship between utility and customer and incentives for customers are out of the scope of this paper and will be discussed in a separate publication. As shown in (7), the objective function of the optimization model consists of the cost of power supplied by the grid, the power lost during the energy exchange process, and the economic impact of loss of life mitigation.

$$\overbrace{Min\ C_{total}}^{\text{Totla Cost}} = \sum_t (\overbrace{C_{G,t}}^{\text{Cost of the power supplied by the grid}} + \overbrace{C_{L,t}}^{\text{Cost of the power lost in exchange}}) + \overbrace{C_{LOL,t}}^{\text{Cost of transformer Loss of Life}} \tag{7}$$

The costs shown in (7) can be calculated using (8)-(10).

$$C_{G,t} = \sum_b (\overbrace{E_{b,t}}^{\text{Consumption of Building b at t}} + \overbrace{E_{BESS,t}}^{\text{Battery Energy Exchange at t}}) \times \overbrace{Pr_t}^{\text{Energy Price at t}} \tag{8}$$

$$C_{L,t} = \sum_b (E_{BESS,t} \times (1-\eta)) \times Pr_t \tag{9}$$

$$C_{LOL,t} = TCV_t \tag{10}$$

The constraints are:

$$-P_{BESS}^{Max.D} \leq P_{BESS,t} \leq P_{BESS}^{Max.Ch} \tag{11}$$

$$P_{BESS,t}^{Ch} \leq \eta E_{Ch} (\mathrm{SOC}_{BESS}^{Max} \text{-} \mathrm{SOC}_{BESS,t}) \tag{12}$$

$$P_{BESS,t}^{D} \leq \eta E_{Ch} (\mathrm{SOC}_{BESS,t} \text{-} \mathrm{SOC}_{BESS}^{Min}) \tag{13}$$

$$\sum_i \overbrace{P_{EV,i}}^{\text{EV system Power}} + \overbrace{P_{Load,i}}^{\text{Load Power}} - \overbrace{P_{PV,i}}^{\text{PV Power}} + \overbrace{P_{BESS,i}}^{\text{Battery System Power}} = \overbrace{P_G}^{\text{Power Exchange with the grid}} \tag{14}$$

where P_{BESS}^{D} and P_{BESS}^{Ch} are the powers that can be exchanged through the inverter for battery discharging and charging, respectively. E_{ch} is the energy capacity of the battery. *Max* and

Min refer to the maximum and minimum values, respectively. $P_{BESS,t}$ is the power exchange for the battery at time step t, where a positive value means that the battery is getting charged and a negative value means that the battery is discharged. η is the efficiency of the battery energy storage system. SOC_{BESS} is the state of charge of the battery. $C_{G,t}$ is the cost of power supplied by the grid. $C_{L,t}$ is the cost of power lost in the energy exchange, and $C_{LOL,t}$ is the cost of loss of life. The inequalities shown in (11)–(13) represent the limit of the BESS inverter, and the limits of charging and discharging based on the battery capacity and state of charge. Equation (14) is also used to balance the power.

The optimization problem is constrained nonlinear and solved using an interior point algorithm [21].

IV. Case Study

A case study is developed to test the proposed coordination strategy for use cases covering one year of different scenarios. Some of the required data, such as temperature, are readily available. Some data, such as the EV demand history that is not available, should be synthesized.

The vehicles used in the case study are Nissan Leaf and Chevy Bolt, and their specifications are listed in Table I. In this study, there are 12 EVs owned by residents and 10 charging slots in parking spaces.

TABLE I. Specifications of EVs Used in the Case Study.

	Capacity of EV Battery (kWh)	**Electricity Consumption (kWh/100miles)**
Chevy Volt	16	0.36
Nissan Leaf	24	0.34

The nominal power of the transformer connected to these 10 buildings is 63 kVA and the total PV generation capacity of each building is 10 kW. The sum of the rated power of the BESS inverter is considered to be 5 kW. It is assumed that the EV charger is unidirectional, and the EV can only be charged.

The load data are from the National Renewable Energy Laboratory's (NREL's) OpenEI dataset [22]. The amount of PV system generation is calculated using PVWatts [23]. The temperature data with a resolution of one hour is extracted from the Iowa Environmental Mesonet [24]. Electricity price data is obtained from the ERCOT data repository [25]. The deployed tools and data are presented in Fig. 2.

Figure 2. Utilized tools for case study.

The proposed coordination strategy is implemented for the following use case scenarios:

a) w/o PV, w/o EV, and w/o BESS.
b) w/o PV, w/ EVs, and w/o BESS.
c) w/ PV, w/ EVs, and w/o BESS.
d) w/o PV, w/ EVs, and w/ BESS, whose charging schedule is optimized using (8), which means that only the real-time price of electricity is considered.
e) w/o PV, w/ EVs, and w/ BESS, whose charging schedule is optimized using (16), which means both the real-time price of electricity and the cost of transformer loss of life are considered.
f) w/ PV, w/ EVs, and w/ BESS, whose charging schedule is optimized using (8), which means only price is considered.
g) w/ PV, w/ EVs, and w/ BESS, whose charging schedule is optimized using (16), which means that both the real-time price of electricity and the cost of transformer loss of life are considered.

The implemented scenarios with different capacities of battery are as follows:

I) BESS capacity is 10 kWh.
II) BESS capacity is 20 kWh.
III) BESS capacity is 40 kWh.

Two main approaches for scheduling optimization are taken: a) coordination strategy and its cost function shown in (8), where the loss of life of the distribution transformer is considered in the calculations, and b) the loss of life is not considered, as shown in (15). The results for these two approaches will be compared to illustrate how employing each approach will impact the risk of the loss of life and payback period for BESS and PV.

$$Min\ C_{total} = \sum_{t} C_{G,t} + C_{L,t} \tag{15}$$

As can be seen in (16), it is assumed that it is possible to forecast the load and PV with a normal distribution error. The accuracy of the predictions decreases when they are made further in the future. Hence, the standard deviation of the error depends on the time at which the prediction is for. The entire programming framework to provide this forecast can be seen in (16)–(19). For the normal distribution, the mean value is considered to be 0. The standard deviation is given by (17).

$$FC\_dist = Gauss(\mu_{FC}, \sigma_{FC}^2) \tag{16}$$

$$\sigma_{FC} = (T_{FC} - T_{Current}) \cdot er \tag{17}$$

$$FC\_random = random\ number\ in\ FC\_dist \tag{18}$$

$$FC = (Load\ or\ PV\ generation\ data)... \\ ...\times(1 + FC\_random) \tag{19}$$

where FC is the abbreviation for forecasting. *FC_dist* represents the distribution of forecasts. T_{FC} is the time of the forecast, and $T_{Current}$ is the moment when the analysis is taking place.

The load forecast and data, PV generation and data, and BESS coordination when considering loss of life and when not considering it for February 9, 2018, at 12 A.M. are shown in Fig. 3, 4, and 5, respectively. The forecast results were generated using probabilistic methods to illustrate that. to illustrate that even if the forecast is inaccurate, the results of the proposed management tool are still acceptable. A more detailed forecast method is beyond the scope of this study.

V. Results

The results of implementing the optimization approach for different scenarios are presented in this section. To evaluate each scenario, a one-year study is conducted using the data available for 2018 in Bryan/College Station, Texas. The synthesized EV data are added to the load curve, and the

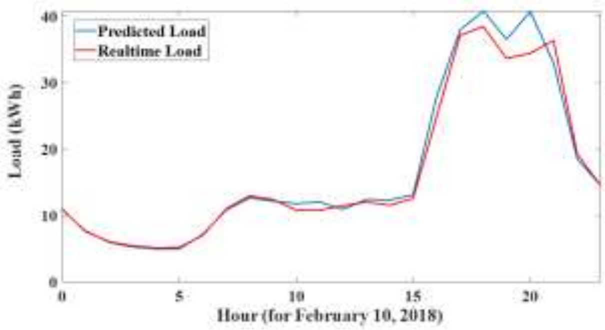

Figure 3. Predicted and real-time load.

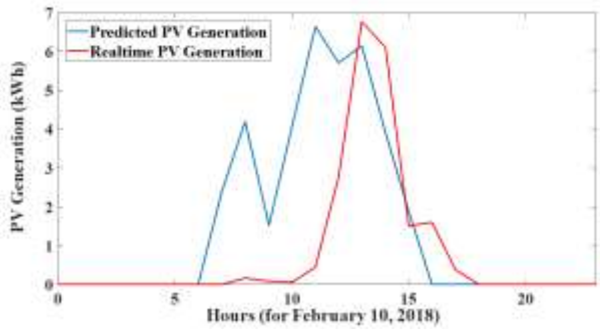

Figure 4. Predicted and real-time PV generation.

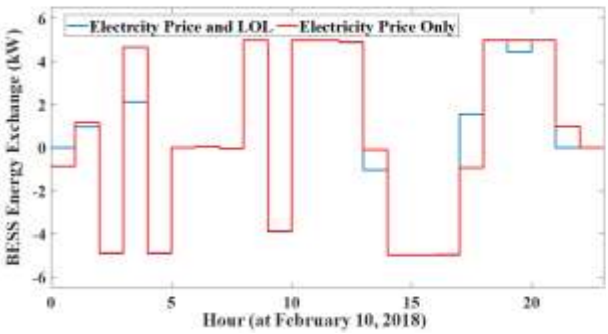

Figure 5. BESS energy exchange with/without considering

optimization problem is used to illustrate the coordination strategy. The optimization is solved using an interior point algorithm to manage the BESS charging/discharging schedule. The economic and risk mitigation impacts of this approach are illustrated in the remainder of this section.

A. Economic Impact

BESS and PV are expensive equipment to purchase, and before the investment decision, the viability of deploying them should be studied. Because the efficiency of the BESS is not ideal, some energy will be lost during the charging/discharging procedure, and hence deploying BESS will increase the total energy consumption. Therefore, it is necessary to study whether deployment scheduling justifies the investment.

There are several retail frameworks in the electricity market, and they vary based on countries, states, and even cities. In College Station, studied in this paper as the use case, the utility has to purchase electricity in the electricity wholesale market based on the prices determined by the Electric Reliability Council of Texas (ERCOT) every 5 minutes. In the current market framework, the utility is the main beneficiary of minimizing the cost of power supplied by the grid.

Utilities as the owners of distribution transformers benefit from the transformer loss-of-life mitigation strategy. In the long term, the lowering expenses for the utility will lead to avoiding an increase in the cost of electricity delivered to the end consumer. Thus, both utility and consumers benefit. There should be additional incentives passed from utilities to consumers to make the investment viable. The distribution of profit as well as the relationship between utility and consumers (or utilities, aggregators, and consumers in a more complex energy exchange system) are beyond the scope of this paper and may be discussed in future studies.

A summary of the parameters utilized in this study is presented in Table II. The transformer's remaining life is 112000 hours out of the initial 180000 hours life expectancy. The costs and rates shown in Table II are obtained from [26]–[31]. The average rate of electricity price increase in the USA in the last 20 years is considered the future electricity price. The interest rate is obtained from the U.S. Federal Reserve Board of Governors announcement in December 2018 [32].

TABLE II. COSTS AND FINANCIAL PARAMETERS

Equipment Costs		**Financial Parameters**	
PV System	$2200/kW	Energy price increase rate	2.6% /year
BESS	$800/kWh	Discount Rate	2.5% /year
Transformer NPV	$5000		
Operating and maintenance Costs			
PV system	$30/kW/year	BESS	$7/kWh/year

Using the introduced model, the payback period and annual profit for different scenarios are calculated and are shown in Fig. 6 and Fig. 7, respectively. In Fig. 7, only the results from scenarios f and g are included because the payback periods for scenarios d and e are much longer than the age of the assets. This shows that in this situation, managing the battery charging/discharging based only on the electricity price will make the project infeasible. The other interpretation of Fig. 7 is that, at least with current prices and costs, employing PV without subsidies is not economic. It can be seen that increasing the battery capacity prolongs the payback period even to the point that it is longer than the asset life, which means an infeasible investment.

B. Impact on Loss of Life Risk

Risk matrix is a common method used for qualitative risk analysis [18]. Risk matrix is used in this study to visualize the risk of the loss of life of the transformer. The category of

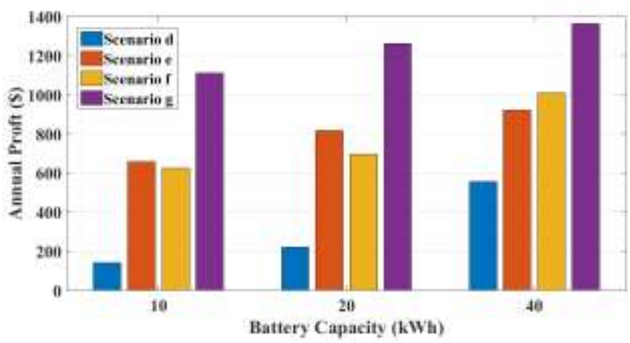

Figure 6. Annual profit for different scenarios.

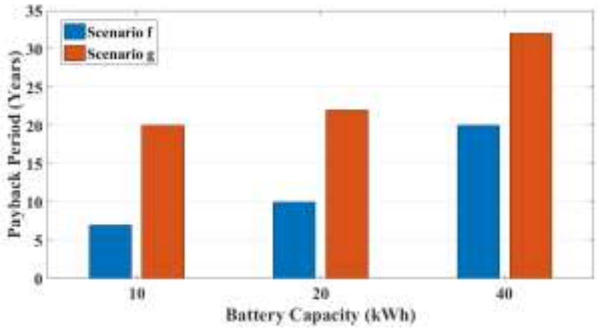

Figure 7. Payback period for different scenarios.

probability of occurrence of a loading level against the category of severity of loss of life are the two main factors that form the risk matrix. Risk levels are defined as "Low" (L), "Medium" (M), "High" (H), and "Extreme" (EX). F_{EQA}, explained in the Appendix, is employed as the measure to quantify the severity of the event.

As discussed in [19], the qualitative definitions of probability and severity are listed in Table III. In this table, *P(e)* is the probability of an event. The F_{EQA} values are calculated hourly. The temperature rise of the transformer is the basis for calculating the ranges shown in this table. To perform these calculations, the associated F_{AA} for each temperature rise is calculated using (30), and F_{EQA} is obtained by employing (31). Probability is also categorized into five different categories. Table IV illustrates the risk matrix of transformer loss of life.

TABLE III. PROBABILITY AND SEVERITY DEFINITIONS

Probability		Severity	
Condition	Range	Condition	Range
Rare	$p(e) < 10\%$	Insignificant	$F_{EQA} < 0.6$
Occasional	$10\% \le p(e) < 40\%$	Normal	$0.6 \le F_{EQA} < 1$
Probable	$40\% \le p(e) < 60\%$	Stress	$1 \le F_{EQA} < 4$
Frequent	$60\% \le p(e) < 90\%$	Critical	$4 \le F_{EQA} < 15$
Likely	$90\% \le p(e)$	Catastrophic	$15 \le F_{EQA}$

TABLE IV. RISK MATRIX FOR TRANSFORMER LOSS OF LIFE

Probability	Severity				
	Insignificant	Normal	Critical	Severe	Catastrophic
Rare	L	L	L	L	L
Occasional	L	L	L	M	M
Probable	M	M	M	H	H
Frequent	H	H	H	EX	EX
Likely	EX	EX	EX	EX	EX

The risk of loss of life is shown in Fig. 8. As can be seen from this figure, a high penetration of EVs (scenario b) will increase the loss of life for a transformer, which was not a risk until the presence of EVs. In addition, the impact of PV in mitigating this risk is negligible (scenario c). The results for scenarios d and f illustrate that by management based on price only, for some cases, not only isn't the loss of life mitigated, but it also has a negative impact and increases the risk. The results for scenarios e and g can be used to shed light on the fact that the risk for the transformer can be significantly

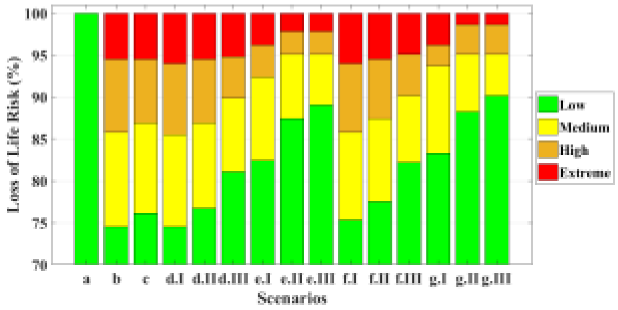

Figure 8. BESS energy exchange with/without considering transformer loss of life mitigation.

reduced by using BESS with the proposed charging/discharging management approach. A comparison of scenarios e and g shows that PV generation in coordination with BESS is also effective for risk mitigation. However, according to Fig. 8, owing to the PV system's price, its economic impact is not enough to make it more profitable. For the scenarios where the investment produces a good return, the utility company benefits. Hence, utility companies should be investors, and this can be done by developing and providing rebates and other incentive programs to motivate consumers to deploy these resources.

VI. CONCLUSION

A coordination strategy to optimally schedule the charging/discharging of the stationary battery energy storage is proposed. Use cases for different scenarios are studied, and economic and risk assessments are performed to evaluate the feasibility and effectiveness of the proposed approach. The key findings of this study are as follows.

- The proposed optimization approach for managing BESS charging/discharging is essential for making the investment in BESS profitable.
- The benefit of including transformer loss of life in BESS charging/discharging management justifies making BESS a viable investment.
- Proper sizing of the BESS is essential to making the system more profitable.
- Impact of PV generation without the support of BESS is relatively low.

APPENDIX

The hottest spot temperature (HST) is the main factor affecting the insulation life. The HST is obtained using (20).

$$\theta_{HST} = \theta_a + \Delta\theta_{TO} + \Delta\theta_H \tag{20}$$

The variables in (20) can be calculated using (21)-(24).

$$\Delta\theta_H = (\Delta\theta_{H,ult} - \Delta\theta_{H,ini}) \cdot (1 - e^{-\frac{t}{\tau_w}}) + \Delta\theta_{H,ini} \tag{21}$$

$$\Delta\theta_{TO} = (\Delta\theta_{TO,ult} - \Delta\theta_{TO,ini}) \cdot (1 - e^{-\frac{t}{\tau_{TO}}}) + \Delta\theta_{TO,ini} \tag{22}$$

$$\Delta\theta_{H,ult} = \Delta\theta_{H,rated\_load} \cdot K_u^{2m} \tag{23}$$

$$\Delta\theta_{TO,ult} = \Delta\theta_{TO,rated\_Load} \cdot \left[\frac{K_u R + 1}{R + 1}\right]^n \tag{24}$$

In (23) and (24), n and m are determined by the transformer structure and type, and are derived empirically. F_{AA} is the aging acceleration factor, and F_{EQA} is the equivalent aging factor, which are shown in (25) and (26) [17].

$$F_{AA}(t) = e^{(\frac{15000}{110+273} - \frac{15000}{\theta_H + 273})} \quad (25)$$

$$F_{EQA} = \frac{\sum_{n=1}^{N} F_{AA,n} \Delta t_n}{\sum_{n=1}^{N} \Delta t_n} \quad (26)$$

Finally, using (30) and (31), the loss of life is quantified as shown in (32):

$$Loss\ of\ \ Life = \frac{F_{EQA} \cdot Analysis\ Time}{Insulation\ Life} \quad (27)$$

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