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ORIGINAL RESEARCH

Mitigation of limitation imposed on hosting capacity in low voltage networks by their distribution transformer loading and degradation considerations

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Abstract

A distribution transformer's thermal operating conditions can impose a limitation on the Hosting Capacity (HC) of an electrical distribution feeder for PV interconnections in the feeder's low-voltage network. This is undesirable as it curtails PV interconnection of both residential and commercial customers in the secondary networks at a time when there are record numbers of interconnection requests by utilities' customers. The authors analyse the limitations on HC due to transformer loading and degradation considerations. Then, the paper proposes a battery energy storage system (BESS) dispatch strategy that will mitigate the limitation on distribution feeder HC by distribution transformers. Three scenarios of HC were simulated for a test network—HC evaluation without restrictions by the distribution transformer (scenario 1), HC evaluation with restrictions by the distribution transformer (scenario 2), and HC evaluation without restriction by the distribution transformer, and with the implementation of the proposed BESS mitigation strategy (scenario 3). Simulation results show that transformer lifetime is depleted to about 6% of expected lifetime for unrestricted HC in scenario 1. Curtailing the HC by 32% in scenario 2 improves the lifetime to 149% of expected lifetime. Implementing the proposed BESS in scenario 3 improves the transformer lifetime to 127% and increases the HC by 62% above the curtailed value in scenario 2, and by 10% above the original HC in scenario 1. The BESS strategy implementation produced cost savings of 49% and 27% of the transformer cost in scenarios 2 and 3, respectively, due to deferred transformer replacement. Conversely, there is a 1600% replacement cost incurred in scenario 1, which underscores the need for a mitigation strategy. The proposed BESS strategy does not only improve the HC of a distribution feeder but also increases a distribution transformer's lifetime leading to replacement cost savings.

KEYWORDS
distributed power generation, distribution networks, load flow, photovoltaic power systems

1 | INTRODUCTION

Integration of renewable energy resources, especially photovoltaic (PV), is reaching higher and higher penetration levels in residential and commercial settings. Extensive research into its effect on the performance of the distribution network has been and is still a subject of interest. A fundamental topic on the effect of integration of renewable energy resources on the performance of distribution networks is the concept of Hosting Capacity (HC). HC is defined as the maximum allowable renewable energy resources penetration in a network before adverse effects on normal network operations are recorded. This definition is consistent across researchers, with minor variations in how narrow or broad each user defines the interconnected renewable energy resource. While the authors in Ref. [1, 2] narrowed the renewable energy resource to PV in their definition, the authors in Ref. [3, 4] made it broader by using distributed energy resource (DER), which includes wind turbines, fuel cells, microturbines, reciprocating engines, combustion turbines, cogeneration, and energy storage systems [5]. The key takeaways from these definitions are that the resource to be integrated is a renewable energy resource, the level of integration is at the distribution network, the network infrastructure and control settings remain unchanged, and the system continues to operate as it was before the integration of the renewable energy resource—that is, no violations of operating condition thresholds. HC is calculated using power flow analysis.

The power flow analysis of a distribution feeder establishes its steady state operating conditions. Some power flow operating conditions associated with HC include voltage at buses [2], equipment thermal loading, voltage deviation at buses [3], reverse power flow at the distribution substation [6], voltage unbalance at three phase buses [7], and regulator voltage deviation [8]. Under nominal operating conditions, all operating parameters are within the confines of their operating limits before PV interconnection. Specifically, the voltages at all the buses are within the 0.95 per unit to 1.05 per unit voltage range for normal power system operations given in Range A of ANSI C84.1 [9], voltage unbalance at three phase buses are less than 1% as per recommendations by NEMA [10], transmission lines loading does not exceed their ampacities, and loading on distribution transformers do not exceed their temperature-adjusted nameplate rating as prescribed by IEEE Standards C57 [11]. As PV is interconnected in a distribution feeder, the operating conditions recorded in an initial power flow evaluation of the distribution feeder begins to change. To study this change in operating conditions, PV is interconnected incrementally in the distribution feeder, and for each increment, the power flow of the distribution feeder is evaluated. The maximum amount of PV interconnection for which the first violation of the limits of any operating condition is recorded is the HC of the distribution feeder. To improve this HC threshold, mitigation of the constraining network condition must be implemented where possible.

Different methods have been employed to evaluate and mitigate the adverse effect of PV or other DER interconnection in distribution networks to improve HC among other benefits, such as minimising daily system operational costs and accounting for operational uncertainties [12, 13]. For example, voltage-related violations due to loading or DER interconnection in distribution networks can be alleviated using methods such as demand response for voltage excursion management [14, 15], volt-var control via smart inverters [16, 17], battery storage systems [18], and voltage control devices (on-load tap changers, substation capacitor banks, and line capacitor banks) [19]. Besides voltage issues, one other important effect of PV interconnection in low-voltage networks of distribution feeders of concern is the reverse power flow introduced into the feeder. Whereas power flows towards loads through distribution transformers before PV interconnection in a low-voltage network of a distribution feeder, with high penetration of PV in the low-voltage network, the power flow is reversed through the distribution transformer to the medium voltage network of the distribution feeder whenever PV generation exceeds the sum of load demand and losses in the low-voltage network. Similarly, if the total generation from interconnected PV in the entire distribution feeder exceeds the sum of load demand and losses in the entire feeder, reverse power flow is recorded through the substation transformer to the transmission network. For situations where reverse power flow could be allowed through the distribution transformers to other parts of the distribution feeder, but not through the substation transformer to the transmission grid, the amount of PV penetration in the distribution feeder before recording reverse power flow through the substation transformer becomes the HC of the distribution feeder, that is, assuming no other operating condition limit is violated before the occurrence of the substation reverse power flow. Given the acceptability of reverse power flow through distribution transformers, overloading issues of distribution transformers caused by PV penetration in low-voltage networks must be carefully studied for the implementation of appropriate overload mitigation measures to prevent loading situations that can deplete the transformer's lifetime.

A transformer's lifetime is dependent on the cumulative loading and wear-out of that transformer over time. The loading of a transformer determines the temperatures of the insulating oil and windings insulation. Of particular interest is the winding hottest-spot temperature (WHST), which determines how the transformer ages, and ultimately, its lifetime. PV interconnections in low-voltage networks, such as commercial and residential roof-top installations, could potentially overload distribution transformers when the reverse power, which flows through the distribution transformer to other parts of the network, is greater than the maximum transformer loading rating. However, a nominal transformer overload situation does not necessarily signify a depletion of the expected transformer life, as the ambient temperature at which the overload situation occurs also plays a key role in how much the transformer ages. To avoid detrimental transformer overload situations, PV penetration in low-voltage networks is sometimes curtailed. This curtailment, however, would mean preventing customers from connecting their rooftop PV installations to the grid at a time where there are record numbers of interconnection requests being made by utility customers [20]. Consequently, it is important to develop a strategy that allows PV penetration in low-voltage networks up to, at least, the full extent of the feeder's HC.

Researchers have studied distribution transformer ageing and lifetime vis-à-vis its loading and/or PV interconnection in its low-voltage network. The authors in Refs [21, 22] showed how PV penetration in low-voltage networks improves a distribution transformer lifetime by offsetting load demand in the secondary low-voltage network, but their work did not describe what happens when the PV penetration causes reverse power flow through the transformer. Similarly, the authors in Ref. [23] investigated the effect of supplying a load through a transformer in parallel with PV a system and asserted that such arrangement improves the transformer thermal performance. Again, the effect of reverse power flow through the transformer was not considered. In closely related studies, while the authors in Ref. [24] showed that penetration of EVs in a low-voltage network increases the ageing of the distribution transformer and that PV interconnection in the low-voltage network can improve the transformer lifetime, the authors in Ref. [25] proposed separately powering EVs in the low-voltage network with PV systems, thereby offsetting the otherwise higher loading of the distribution transformer to improve the transformer lifetime. Both the authors in Refs [24, 25] focused on improving the transformer lifetime that was being degraded by a forward direction power flow overload caused by loading in the low-voltage network rather than by reverse direction power flow from distributed generation in the low-voltage network. The authors in Ref. [26] incorporated energy storage and PV in their analysis of the effect of plugin EVs on distribution transformer ageing. The energy storage was used to store PV generation in the day, which is discharged in the evenings when the peak loading of the transformer due to high penetration of the plugin EVs most adversely affects the transformer lifetime. Again, their effort was focused on the transformer loss of life due to forward direction loading rather than the reverse power flow from the PV. Conversely, the authors in Ref. [27] investigated the effect of PV penetration level on transformer loss of life due to reverse direction power flow and found that there is a maximum PV penetration in the low-voltage network after which the transformer loss of life increases. However, they did not provide a means of mitigating the loss of life for PV penetration beyond the found maximum. The cited related literature provides valuable information on the effect of network loading and/or PV interconnection in low-voltage networks on distribution transformers; however, they are either lacking in addressing the adverse effect of PV penetration in low-voltage networks on the thermal properties and lifetime of distribution transformers, or they curtailed PV penetration in the low-voltage network for cases where reverse power flow is recorded rather than device a means of preventing the curtailment. Therefore, in this paper, the adverse effect of reverse power flow on distribution transformer lifetime and thermal properties due to PV penetration in low-voltage networks is analysed, and a battery energy storage system (BESS) mitigation strategy is developed to prevent the curtailment of the feeder HC. The BESS strategy developed in this paper does the following:

- Substantially improves the HC of a distribution feeder where the PV interconnection is in the low-voltage network.
- Extends the distribution transformer life, which consequently leads to cost saving due to deferred transformer replacement.
- Provides the BESS sizing required for the HC improvement and transformer overload mitigation.

2 | METHODOLOGY

In this section, the methods employed to establish the adverse effect of PV penetration in low-voltage networks on distribution transformers, as well as mitigate the restrictions imposed by distribution transformer lifetime and WHST on HC where the PV penetrations are in low-voltage networks are discussed.

The first step in the study is to execute the power flow analysis of a distribution feeder to obtain the operating state of the feeder. Subsequently, centralised HC evaluations are implemented with PV penetration in the low-voltage network. Centralised HC involves identifying a desired bus in the network, incrementally interconnecting PV to the bus, and running the power flow of the feeder while checking for a network operating parameter limit violation after each PV increment and power flow [28]. The PV penetrations for centralised HC in this work analyses up to a maximum of 200 kW PV penetration at increments of 1 kW. The PV is interconnected at the secondary bus of the distribution transformers, which represents the sum of all random PVs interconnected in the low-voltage networks. In addition to checking for a network operating parameter limit violation after each PV increment and power flow, the power flow magnitude and direction through the distribution transformer is recorded. The recorded power flow magnitude through the distribution transformer is then used to evaluate its thermal properties and associated loss of life. The transformer properties evaluated are compared to prescribed standards, and HC is restricted to prevent violation of these standards. However, to prevent restricting the HC without violating the standards, sets of equations are developed to model the sizing and operation of a BESS, which is interconnected at the secondary bus of the distribution transformer. In the following sections, the transformer thermal model used for evaluating the transformer thermal parameters in this study is presented, the set of equations for sizing and operation of the BESS is developed, and the sets of data and test distribution feeder used for the study are presented.

2.1 | Transformer thermal model

A transformer thermal model is required for the analysis of a transformer's useful lifetime based on its loading in a circuit. It is also required for developing the proposed BESS strategy for mitigating the restrictions imposed by a distribution transformers' operating temperatures and lifetime on HC, where the PV penetration is in its low-voltage network. Equations (1–14) is the thermal model of a self-cooled mineral-oil-immersed distribution transformer [11].

$$\%\,Loss\ of\ life = \frac{F_{EQA} \times t \times 100}{Normal\ insulation\ life} \tag{1}$$

$$F_{EQA} = \frac{\sum_{j=1}^{J} F_{AA_j} \Delta t_j}{\sum_{j=1}^{J} \Delta t_j} \tag{2}$$

$$F_{AA_j} = exp^{\left[\frac{15000}{383} - \frac{15000}{\theta_H + 273}\right]} \tag{3}$$

$$\theta_H = \theta_A + \Delta\theta_{TO} + \Delta\theta_H \tag{4}$$

$$\theta_{TO} = \theta_A + \Delta\theta_{TO} \tag{5}$$

$$\Delta\theta_{TO} = \left(\Delta\theta_{TO,U} - \Delta\theta_{TO,i}\right)\left(1 - exp^{-\frac{1}{\tau_{TO}}}\right) + \Delta\theta_{TO,i} \tag{6}$$

$$\Delta\theta_{TO,i} = \Delta\theta_{TO,R}\left[\frac{(K_i^2 R + 1)}{(R+1)}\right]^n \tag{7}$$

$$\Delta\theta_{TO,U} = \Delta\theta_{TO,R}\left[\frac{(K_U^2 R + 1)}{(R+1)}\right]^n \tag{8}$$

$$\tau_{TO} = \tau_{TO,R}\frac{\left(\frac{\Delta\theta_{TO,U}}{\Delta\theta_{TO,R}}\right) - \left(\frac{\Delta\theta_{TO,i}}{\Delta\theta_{TO,R}}\right)}{\left(\frac{\Delta\theta_{TO,U}}{\Delta\theta_{TO,R}}\right)^{\frac{1}{n}} - \left(\frac{\Delta\theta_{TO,i}}{\Delta\theta_{TO,R}}\right)^{\frac{1}{n}}} \tag{9}$$

$$\tau_{TO,R} = \frac{C\,\Delta\,\theta_{TO,R}}{P_{T,R}} \tag{10}$$

$$\Delta\theta_H = \left(\Delta\theta_{H,U} - \Delta\theta_{H,i}\right)\left(1 - exp^{-\frac{t}{\tau_w}}\right) + \Delta\theta_{H,i} \tag{11}$$

$$\Delta\theta_{H,i} = \Delta\theta_{H,R}K_i^{2m} \tag{12}$$

$$\Delta\theta_{H,R} = \Delta\theta_{H/A,R} - \Delta\theta_{TO,R} \tag{13}$$

$$\Delta\theta_{H,U} = \Delta\theta_{H,R}K_u^{2m} \tag{14}$$

Equations (1) and (4) are the key transformer output indices—transformer life and WHST—needed to evaluate the HC of a feeder with PV penetration in the low-voltage network. Normal distribution transformer life is expected if a transformer operates continuously at a WHST of 110°C or its equivalent over a daily transient load cycle (i.e. the WHST may fluctuate above and below 110°C subject to an upper limit of 140°C to avoid gassing in the solid insulation and oil, or a maximum limit of 200°C at the extreme). The parameters of a distribution transformer used in the transformer lifetime analysis in this study are summarised in Table 1.

2.2 | Transformer loading and ambient temperature

The transformer thermal model in Equations (1–14) is based on a 24-h average ambient temperature of 30°C. A transformer using this model will have its nameplate power rated at 30°C. Such a transformer when loaded up to the nameplate power rating will age normally and reach its expected 100% lifetime. The transformer could also be loaded beyond its nameplate rating without adversely affecting its expected lifetime if the ambient temperature around the transformer falls below 30°C. Conversely, when the ambient temperature rises above 30°C, the transformer must be loaded below the nameplate power rating to maintain a lifetime of 100%. Therefore, it is possible to estimate the maximum loading of a transformer for an expected 100% lifetime based on ambient temperature. To approximate the maximum loading of a transformer, [11] prescribes factors by which the power rating of different types of transformers can be decreased or increased based on ambient temperatures between −30°C and 50°C as shown in Table 2.

Therefore, for a self-cooled distribution transformer, the time series approximate maximum loading based on ambient temperature is given by Equation (15).

$$Xfmr_{Max,j} = \begin{cases} S_{rated} + \left[\left(\frac{(30-\theta_{A,j})}{100}\right) \times S_{rated}\right], & \theta_{A,j} < 30\ ^{\circ}\mathrm{C} \\ S_{rated}, & \theta_{A,j} = 30\ ^{\circ}\mathrm{C} \\ S_{rated} - \left[\left(\frac{((\theta_{A,i} - 30)/1.5)}{100}\right) \times S_{rated}\right], & \theta_{A,j} > 30\ ^{\circ}\mathrm{C} \end{cases} \tag{15}$$

TABLE 1 Typical distribution transformer thermal parameters [11, 29].

Parameter	Value
M	0.8
N	0.8
$\Delta\theta_{TO,R}$	55°C
$\Delta\theta_{H/A,R}$	80°C
$\tau_{TO,R}$	3 h
τ_w	4 min

TABLE 2 Transformer loading based on ambient temperature [11].

	% of KVA rating	
Type of cooling	Decrease load for each °C higher temperature	Increase load for each °C lower temperature
Self-cooled	1.5	1.0
Water-cooled	1.5	1.0
Forced-air-cooled	1.0	0.75
Forced-oil, -air, -water-cooled	1.0	0.75

2.3 | Proposed BESS strategy

A BESS interconnection at the secondary bus of a distribution transformer is proposed in this paper to mitigate the anticipated curtailment of the HC of the distribution feeder where the PV penetration is in the low-voltage network of the distribution transformer. The BESS dispatch is controlled by defining curves that charge and discharge the BESS when a charge or discharge condition is satisfied. The proposed BESS strategy comprises the following parameters: charging curve, discharging curve, BESS capacity, and BESS inverter kW rating. These parameters are designed using the time series approximate maximum transformer loading based on ambient temperature in Equation (15), and the hourly time series transformer loading, $Xfmr_{Loading,j}$, for each successive PV penetration in the low-voltage network. For each step of PV penetration, three transformer loading conditions are possible for each time interval as given in Equations (16a–16c).

$$Xfmr_{Loading,j} > Xfmr_{Max,j} \ (charge\ cycle) \tag{16a}$$

$$Xfmr_{Loading,j} = Xfmr_{Max,j} \ (idle) \tag{16b}$$

$$Xfmr_{Loading,j} < Xfmr_{Max,j} \ (discharge\ cycle) \tag{16c}$$

The charging curve for each interval is defined as the difference between the approximate maximum transformer loading and the transformer loading when the former is less than the later, or defined as zero when the former is either greater than or equal to the later in an interval as given by Equation (17).

$$BS_{charge,j} = \begin{cases} Xfmr_{Max,j} - Xfmr_{Loading,j}, & Xfmr_{Loading,j} > Xfmr_{Max,j} \\ 0, & Xfmr_{Loading,j} = Xfmr_{Max,j} \\ 0, & Xfmr_{Loading,j} < Xfmr_{Max,j} \end{cases} \tag{17}$$

The total BESS charge during the charge cycle is given by Equation (18). This total charge is discharged during the discharge cycle to maintain the BESS charge–discharge balance.

$$BS_{charge,T} = \sum \left(Xfmr_{Loading,j} - Xfmr_{Max,j}\right), \quad Xfmr_{Loading,j} > Xfmr_{Max,j} \tag{18}$$

Figure 1 shows a typical transformer loading for two different loading conditions on a sunny day, and this is used here for illustration purposes. The discharge cycle of the proposed BESS is divided into two periods as shown in Figure 1. The first period, which is the priority discharge period, is the period when the transformer is loaded by the power flowing from the primary network into the secondary network. The loading in this period is referred to as the base loading, $Xfmr_{base,j}$, that is, loading of the transformer with zero PV penetration in the low-voltage network. The total BESS charge from Equation (18) will be discharged first in this period, and then, any remaining charge will be discharged in the second period. The second discharge period is the period where the transformer loading is less than the approximate maximum loading but not equal to the base loading, that is, the loading on the transformer is either reverse power flow that is less than the approximate maximum loading, or reduced power flow from the primary to the secondary network because of some amount of PV penetration in the secondary network. The discharge curve for each period is evaluated thus

1. The total transformer loading of each discharge period is evaluated by Equations (19) and (20).
2. The maximum BESS discharge in the first period is evaluated by adding the sum of the instantaneous approximate maximum loading and the transformer loading for each interval within the first period as given by Equation (21). If the total BESS charge in the charge cycle is greater than this

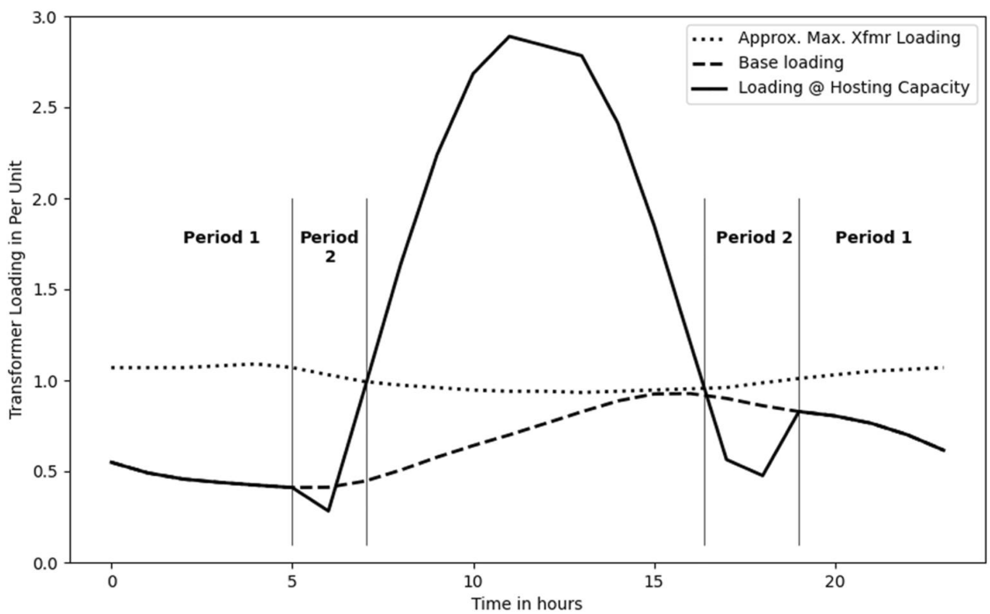

FIGURE 1 Transformer loading scenarios and BESS discharge periods.

evaluated maximum BESS discharge in the first discharge period, the maximum BESS discharge is used to evaluate the BESS discharge curve for the first period as given by Equation (22). Subsequently, the difference between the total BESS charge and the maximum BESS discharge in the first period is used to evaluate the BESS discharge curve of the second discharge period as given by Equation (23). On the contrary, if the total BESS charge is less than the maximum BESS discharge in the first period, the total BESS charge will be used to evaluate the BESS discharge curve in the first period, and the BESS discharge curve in the second period is zero.

3. For both discharge periods in the discharge cycle, the BESS discharge value of an interval of the discharge curve is the product of the allotted total charge of the period and the ratio of the interval loading to the total loading of the period as seen in Equations (22) and (23).

$$Xfmr_{Loading,T1} = \sum Xfmr_{Loading,j},\quad Xfmr_{Loading,j} = Xfmr_{base,j} \tag{19}$$

$$Xfmr_{Loading,T2} = \sum Xfmr_{Loading,j},\quad Xfmr_{Loading,j} \neq Xfmr_{base,j};\ Xfmr_{Loading,j} < Xfmr_{Max,j} \tag{20}$$

$$BS_{discharge1,Max} = \sum \left(Xfmr_{Loading,j} + Xfmr_{Max,j}\right),\quad Xfmr_{Loading,j} = Xfmr_{base,j} \tag{21}$$

The BESS capacity and inverter kW rating are given by Equations (24) and (25), respectively. The BESS is sized to store 125% of the sum of the hourly reverse power flow above the approximate maximum transformer loading (total energy) in a 24-h load cycle. This ensures the BESS maintains a maximum depth of discharge of 80% in a load cycle. Similarly, the inverter kW output is sized to convert the maximum PV production.

$$BS_{kWh} = 1.25 \times \sum \left[Xfmr_{Loading,j} \times pf \times S_{rated}\right]_{(1\ x\ j)},\quad Xfmr_{Loading,j} > Xfmr_{Max,j} \tag{24}$$

$$BS_{kW} = Max\left[\left(BS_{charge,j}\right)_{(J\ x\ 1)}, \left(BS_{discharge1,j} + BS_{discharge2,j}\right)_{(J\ x\ 1)}\right] \times S_{rated} \times pf \tag{25}$$

It is assumed that historic transformer loading data of the feeder is available and used to configure the BESS controller to dispatch as designed in Equations (16–23).

2.4 | Test distribution feeder and HC evaluation

An 88-bus IEEE distribution feeder, *SecondaryTestCircuit_modified*, which accompanies an OpenDSS installation [30] was used to analyse the proposed HC curtailment mitigation strategy for PV penetration in low-voltage networks. Since the analyses in this research require the ambient temperature and solar irradiation that coincides with the daily load profiles of a location, eight daily hourly load

$$BS_{discharge1,j} = \begin{cases} \dfrac{Xfmr_{Loading,j}}{Xfmr_{Loading,T1}} \times BS_{discharge1,Max}, & BS_{discharge1,Max} < BS_{charge,T};\ Xfmr_{Loading,j} = Xfmr_{base,j} \\ \dfrac{Xfmr_{Loading,j}}{Xfmr_{Loading,T1}} \times BS_{charge,T}, & BS_{discharge1,Max} > BS_{charge,T};\ Xfmr_{Loading,j} = Xfmr_{base,j} \\ 0, & Xfmr_{Loading,j} \neq Xfmr_{base,j} \end{cases} \tag{22}$$

$$BS_{discharge2,j} = \begin{cases} \dfrac{Xfmr_{Loading,j}}{Xfmr_{Loading,T2}} \times \left(BS_{charge,T} - BS_{discharge1,Max}\right), & Conditions\{23a\} \\ 0, & Xfmr_{Loading,j} \neq Xfmr_{base,j};\ BS_{discharge1,Max} > BS_{charge,T} \end{cases} \tag{23}$$

$$\text{Conditions}\{23a\}: \quad \begin{array}{c} Xfmr_{Loading,j} \neq Xfmr_{base,j} \\ Xfmr_{Loading,j} < Xfmr_{Max,j} \\ BS_{discharge1,Max} < BS_{charge,T} \end{array}$$

profiles for Tucson, Arizona in the United States were generated from the Electric Power Research Institute (EPRI) Load Shape library [31] and used for each load in *SecondaryTestCircuit_modified* in place of the original annual load profiles of the feeder. Four of the generated load profiles are residential load profiles, defined by EPRI as *Multiple Family Mixed Cooling*, *Single Family Central AC Heat Pump*, *Single Family Central AC electric*, and *Manufactured Home Mixed AC electric*. The remaining four profiles are commercial load profiles, defined as *Education K-12 electric*, *Hotel electric*, *Office/Bank electric*, and *Church electric*. Consequently, a Typical Meteorological Year solar irradiation and temperature data for the city of Tucson were obtained from the National Renewable Energy Laboratory repository [32]. PV penetrations for centralised HC analyses, at an incremental step of 1 kW and up to a maximum of 200 kW, are interconnected at the secondary bus of the distribution transformers, as a representation of the sum of all random PVs interconnected in the low-voltage network of the transformers. *SecondaryTestCircuit_modified* has 12 distribution transformers. Hence, 12 separate centralised HCs are evaluated for the feeder.

3 | SIMULATION, RESULTS AND DISCUSSIONS

The proposed BESS strategy for the mitigation of restrictions imposed on HC by distribution transformers' lifetime and thermal parameters for PV penetration in low-voltage networks was implemented in the OpenDSS software [30] using *SecondaryTestCircuit_modified* as the test network. Three scenarios were considered for evaluating the HC of the feeder: HC evaluation without restrictions by the distribution transformer (scenario 1), HC evaluation with restrictions by the distribution transformer (scenario 2), and HC evaluation without restriction by the distribution transformer, and with implementation of the proposed BESS mitigation strategy (scenario 3). The flowchart in Figure 2 shows the algorithm for the implementation of the simulation in OpenDSS.

3.1 | Feeder HC and effect on distribution transformers

There are 12 distribution transformers in the test feeder, hence, there are 12 low-voltage networks. The daily time series centralised HC of the feeder for the three scenarios was evaluated for one transformer load cycle (24 h), for each low-voltage network on a sunny Summer day, July 1st. The results of the first scenario are presented in Table 3.

The results in Table 3 show the HC of the test feeder for independent PV penetration in the low-voltage networks of the 12 distribution transformers without any restrictions imposed on the HC evaluation by the transformers' thermal parameters and the effect of such amount of PV penetration on the

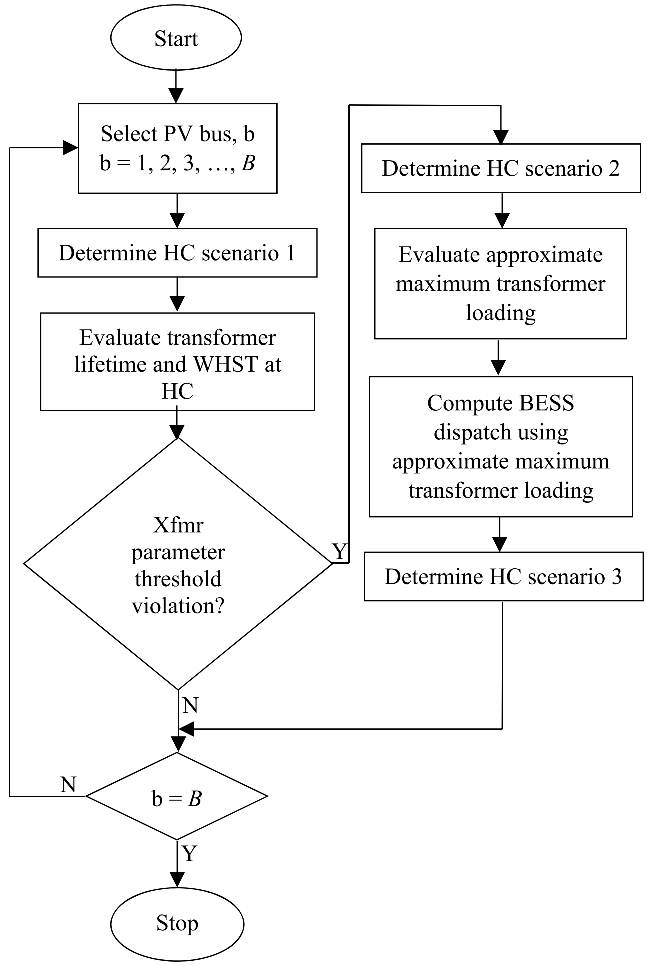

FIGURE 2 Simulation implementation flowchart.

TABLE 3 Scenario 1—HC evaluation result without transformer restrictions for July 1st.

Transformer	HC (kW)	Max WHS (°C)	Ageing factor	Loss of life (%)
Trafo1	163	150.98	31.4	0.42
Trafo2	160	141.29	15.4	0.21
Trafo3	158	146.48	21.6	0.29
Trafo4	160	149.07	26.5	0.35
Trafo5	169	152.0	35.8	0.48
Trafo6	163	147.71	23.9	0.32
Trafo7	175	159.47	64.7	0.86
Trafo8	179	164.6	95	1.27
Trafo9	162	144.45	19.3	0.26
Trafo10	164	147.86	23.97	0.32
Trafo11	151	146.31	21.3	0.28
Trafo12	177	166.90	115.9	1.55

distribution transformers. The results are similar for all 12 transformers, so the analysis of one of the transformers' results would be sufficient for the purpose of this study. A detailed result for Trafo7, one of the 12 distribution transformers, is presented in Table 4 and Figure 3 for a 24-h load cycle.

Figure 3a shows the per unit loading of Trafo7 at zero PV penetration (base loading), at HC PV penetration and the reference approximate maximum loading for a 24-h load cycle. The approximate maximum loading is not 1.0 per unit because of the effect of ambient temperature on transformer loading as given by Equation (15). When ambient temperature goes below 1 per unit as seen in Figure 3a, approximate maximum loading goes above 1 per unit rated loading and vice versa. According to Ref. [11], loading the transformer at this approximate maximum results in a WHST of 110°C, which is the reference WHST as shown in Figure 3b. Therefore, for loading below the approximate maximum loading, exemplified by the base loading curve in Figure 3a, the WHST remains below the reference temperature as shown in Figure 3b. Furthermore,

TABLE 4 Trafo7 transformer parameters based on the HC.

	HC (kW)	Max WHST (°C)	Ageing factor	Loss of life (%)
Base loading		81.89	0.04	0.0
HC loading	175	159.47	64.7	0.86

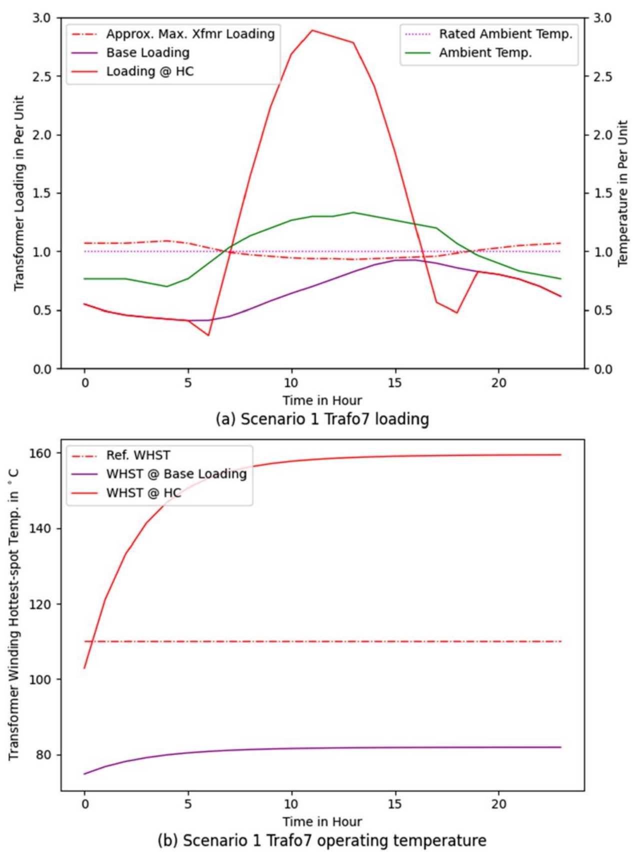

FIGURE 3 Scenario 1–Trafo7 loading and operating temperatures.

reference ([11], p. 10) prescribes that for a 24-h load cycle, the equivalent transformer ageing factor due to loading of a transformer at the reference WHST of 110°C is 1.0, which represents a 0.0133% loss of life of the transformer. A transformer losing 0.0133% of its life per day would remain operational for 100% of its expected lifetime. Since the base loading is substantially less than the approximate maximum loading, resulting in WHST being less than the reference WHST, the evaluated transformer equivalent ageing factor is less than 1.0 and the loss of life for this load cycle is 0% as shown in Table 4. Conversely, the loading on Trafo7 at HC is greater than the approximate maximum loading between the hours of about 8 AM and 4 PM of the load cycle as shown in Figure 3a. Consequently, the WHST is greater than the reference temperature of 110°C for most part of the load cycle as shown in Figure 3b. This results in an equivalent ageing factor of 64.7 leading to a loss of life of 0.86% as shown in Table 4. This result is for one load cycle of July 1st. If this reflects the daily loss of life for the whole 365 days in a year, Trafo7 will only have a lifetime of 1.55% of its expected 100% lifetime. This is inconceivable and rather hypothetical, as the loss of life is expected to vary widely over the course of a year as is analysed in a subsequent section of this paper. One way of preventing the daily loss of life from exceeding 0.0133% is the implementation of scenario 2, which is to curtail the HC of the feeder based on the transformer parameters. To implement the curtailment, the WHST and transformer loss of life were calculated for each step of HC evaluation. The curtailed HC is the value of HC obtained for a maximum loss of life of 0.1133% or WHST of 140°C, whichever came first. The results of the second scenario are presented in Table 5, while Figure 4 shows the detailed results for Trafo7 over a 24-h load cycle.

Table 5 shows that 29.71% of the HC recorded in scenario 1 must be curtailed to keep the transformer ageing factor at 1.0 or less resulting in a loss of life of 0.0133% or less. Figure 4a compares the curtailed loading profile over the load cycle with the loading profile in scenario 1, while Figure 4b shows the effect of curtailing the HC on the WHST as compared to that in scenario 1. Averaged over the load cycle, the WHST of Trafo7 for the constrained Trafo7 loading is at par with the reference WHST. The cost of securing a 100% lifetime for Trafo7 is a curtailment of 29.71% of the HC the feeder would ordinarily accommodate. The implementation of the BESS strategy in scenario 3 does not only eliminate the need for this curtailment but also improves the HC, and yet keeps the conditions necessary for trafo7 to reach its expected 100% lifetime as shown in the results of Table 6. Additionally, Figure 5 shows the loading and WHST profile for the scenario over the 24-h load cycle.

Table 6 shows an improvement in the HC for all 12 distribution networks with the implementation of the BESS strategy. The loading profile of Trafo7 over the 24-h load cycle in Figure 5a shows that with the implementation of the BESS strategy, the transformer loading over the load cycle is largely less than the approximate maximum loading. Correspondingly, Figure 5b shows that the WHST is predominantly less than the reference temperature of 110°C.

TABLE 5 Scenario 2—Low-voltage network PV penetration HC evaluation result with transformer restrictions.

Transformer	HC (kW)	Max WHS (°C)	Ageing factor	Loss of life (%)	HC curtailment (%)
Trafo1	125	112.44	0.95	0.01	23.31
Trafo2	122	111.57	0.98	0.01	23.75
Trafo3	124	112.80	0.98	0.01	21.52
Trafo4	124	112.10	0.91	0.01	22.50
Trafo5	126	112.42	1.0	0.01	25.44
Trafo6	127	112.53	0.95	0.01	22.09
Trafo7	123	111.90	0.92	0.01	29.71
Trafo8	126	111.78	0.91	0.01	29.61
Trafo9	124	111.97	0.96	0.01	23.46
Trafo10	129	112.13	0.91	0.01	21.34
Trafo11	118	112.66	0.98	0.01	21.85
Trafo12	119	111.65	0.91	0.01	32.77

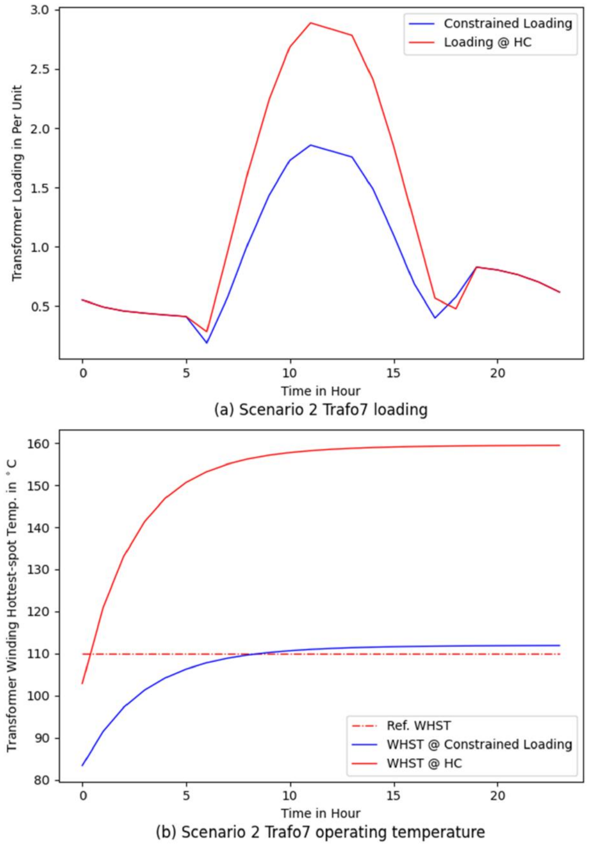

FIGURE 4 Scenario 2–Trafo7 loading and operating temperatures.

TABLE 6 Scenario 3—Low-voltage network PV penetration HC evaluation result with BESS.

Transformer	HC (kW)	Max WHS (°C)	Ageing factor	Loss of life (%)	HC improvement (%)
Trafo1	191	111.34	0.94	0.01	17.18
Trafo2	186	81.32	0.72	0.01	16.25
Trafo3	187	104.36	0.91	0.01	18.35
Trafo4	188	107.96	0.95	0.01	17.50
Trafo5	194	100.61	0.85	0.01	14.79
Trafo6	194	106.82	0.96	0.01	19.02
Trafo7	199	113.92	0.98	0.01	13.71
Trafo8	200	126.66	1.02	0.01	11.73
Trafo9	193	90.56	0.81	0.01	19.14
Trafo10	192	106.58	0.94	0.01	17.07
Trafo11	170	91.29	0.81	0.01	12.58
Trafo12	200	97.71	0.87	0.01	12.99

3.2 | Annual analysis

In the foregoing sections, an implementation of the BESS strategy to mitigate the limitations imposed by a distribution transformer's thermal parameters on a feeder's HC where the PV penetration is in the low-voltage network was established for one 24-h load cycle, July 1st. However, the input variables in this study—load profile of the feeder, ambient temperature at the location, and solar irradiation at the location—vary widely over the course of a year. Assuming this variation over the course of a year is similar every year, an annual analysis of the loss of life of a transformer for a year can be a good approximation for evaluating the total lifetime of such a transformer. On this basis, the hourly loading on Trafo7 for each day in a year was evaluated. Similarly, the hourly ambient temperature and solar irradiation data for Tucson Arizona were collected. The time series HC evaluation of the test feeder for the 365 24-h load cycles for the three scenarios were implemented. The simulation results are presented in Figure 6. The sets of curves in Figure 6 show the results for all three scenarios superimposed on each other for easy comparison. As expected, the sets of curves show a wide variation in the evaluated HC, WHST, ageing factor, and loss of life, over the

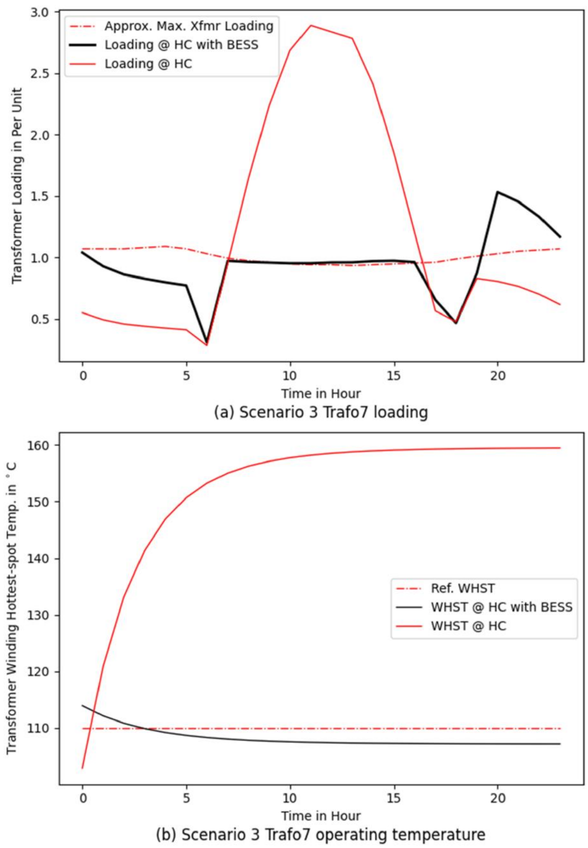

FIGURE 5 Scenario 3–Trafo7 loading and operating temperatures.

course of a year for all three scenarios. Figure 6a shows how the HC of the three scenarios compares. For most part of the year, the HC of the feeder had to be curtailed without the BESS strategy implementation. Conversely, the implementation of the BESS strategy improved the HC substantially over the course of the year with over 75% of the year showing the maximum PV penetration of 200 kW set for the study. Furthermore, except for days where the unrestricted HC was 200 kW, there was improvement in the HC with the BESS implementation over the unrestricted HC. Similarly, in the WHST, ageing factor, and loss of life plots shown in Figures 6b–d, respectively, the resultant effect of the BESS implementation is evident when the three scenarios in all three plots are compared with the reference curves in the plots. Expectedly, in all three plots, the curves for the first scenario (unrestricted HC) exceed the reference curve, while the curves for the second scenario show the constraints that were implemented to curtail the HC in Figure 6a. The curves in the third scenario show that even with the improvement in HC, the three parameters—WHST, ageing factor, and loss of life—do not exceed their reference curves throughout the year, validating the efficacy of the proposed BESS strategy under diverse loading, ambient temperature, and solar irradiation conditions.

Over the course of the year, the sum of the hourly reverse power flow above the approximate maximum transformer loading is found per 24-h load cycle. This is the total energy to be stored by the BESS per day, and it is used to size BESS.

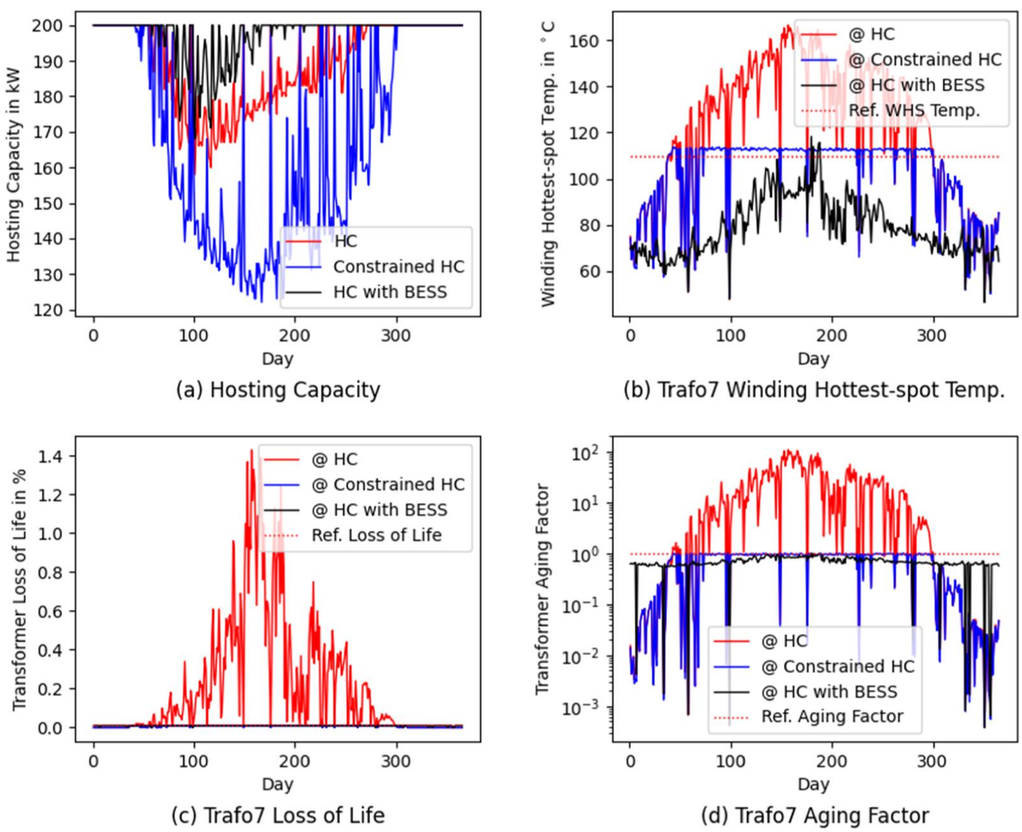

FIGURE 6 Scenario 1–Annual low-voltage network PV penetration HC and Trafo7 thermal parameters.

However, an 80% depth-of-discharge of the BESS is desirable, hence, the BESS is oversized to accommodate this depth-of-discharge as given by Equation (24). Figure 7 shows the BESS sizing required for the implementation of the BESS strategy for Trafo 7. It has been compressed into a monthly box and whisker plot for easy visualisation. For each month, the plot shows that the BESS size needed per day varies. This variation is dependent on the total reverse power flow, which in turn depends on the difference between PV production and the low voltage load for the day. The lower outliers and zero BESS size represent very cloudy days and/or heavy loading which meant there was either very low or no reverse power flow recorded. Conversely, higher outliers, which are present only in the month of April, represent higher reverse power flow relative to other days in the month because of a very sunny day and/or light loading. The metric of concern here is the maximum BESS size, which is approximately 1600 kWh, evaluated for the month of June.

4 | SIGNIFICANCE OF THE BESS IMPLEMENTATION

In this section, the lifetime of Trafo7 for the three scenarios is compared, and an estimate of any savings or otherwise occasioned by a deferred or earlier than expected transformer replacement is evaluated. As discussed earlier, for a transformer to reach its expected 100% lifetime or more, the daily loss of life must be at most 0.0133%. This puts the expected annual loss of life at 4.85%. Additionally, a typical distribution transformer has an expected lifetime of 180,000 h or 7500 days ([11], p. 10), while the web price for a 50 kVA 600 V/120 V/240 V distribution transformer, which is similar to the ratings of Trafo7, is $8388.59 [33]. These figures are used in this section's analysis.

The cumulative loss of life for the three scenarios in Figure 6c is calculated to be 77.29%, 2.45%, and 3.54% for unrestricted HC, constrained HC, and HC with BESS, respectively. For the unrestricted HC scenario, Trafo7 would have lost 139,122 h of the expected 180,000 h of its life by the end of the first year of operation and would need to be replaced 83 days into the next year. This implies that for scenario 1, Trafo7 will need to be replaced every 448 days as opposed to 7500 days, resulting in a lifetime of 5.97% of its original expected lifetime. With unrestricted PV penetration in the low-voltage network of Trafo7, if Trafo7 is operated at HC, it will have to be replaced about 16 times within the period of its expected lifetime under normal conditions. This would be at a cost of about $134,000 as against $8388.59 without PV penetration or constrained PV penetration. This represents 1600% of the originally expected transformer cost.

Constraining the PV penetration using the thermal parameters of the transformer ensures the transformer stays in operation for the expected 100% of its lifetime as shown in the HC analysis of scenario 2, thereby eliminating the need for frequent transformer replacement seen in the cost analysis of scenario 1. For scenario 2, the annual Trafo7 loss of life of 2.45% is less than the expected 4.85% loss of life by 2.4%. This implies that Trafo7 will have its life extended by about 4328 h in one year and by a total of about 88,942 h by the end of its expected lifetime. This implies that Trafo7 lifetime is extended by 49.42%. This translates to a saving of about $4145 or 49.42% of the original

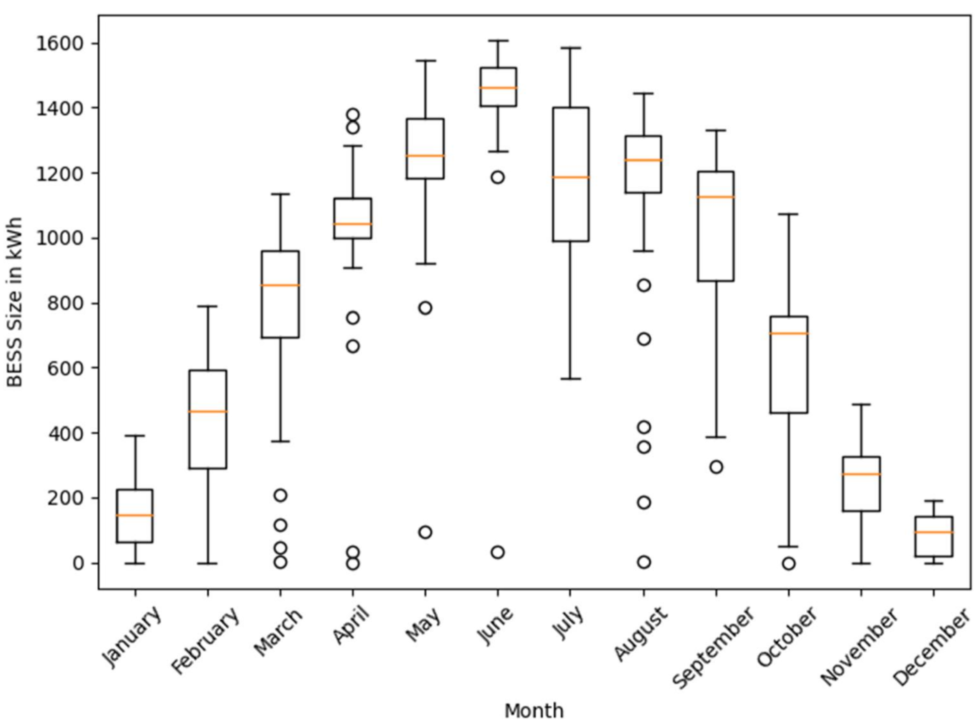

FIGURE 7 BESS sizing scenario 3 implementation for Trafo7.

transformer cost. However, implementing this scenario will lead to losing the benefit of a higher HC provided in scenario 3. In scenario 3, the loss of life per year is less than the expected annual loss of life by 1.31% which translates to an extended transformer lifetime of about 48,623 h (27% lifetime extension) and a saving of about $2266 (27% of original transformer cost). While curtailing the HC produces a transformer cost saving of about $1879 better than the cost saving when the BESS strategy is implemented, Tables 4–6 show that about 61.8% of the constrained HC would be forfeited. Figure 8 is a summary chart of the significance of the BESS strategy implementation on Trafo7. Figure 8a shows the HC for the three scenarios on July 7th. This day had the highest HC curtailment of 58 kW. The maximum PV penetration was set at 200 kW for the purpose of this study. With the BESS implementation, the HC for the day was at the maximum of 200 kW. This suggests that if the upper limits of PV penetration were removed, the BESS implementation benefit would have exceeded what is now reported here.

4.1 | Assumptions and limitations of the study

The data collected for this study is hourly data, hence the time step of the simulations in this study is 1 hour. A smaller time step of about 15 min would have provided tighter results and reduced the error margin.

It was assumed that the load profile of the feeder, ambient temperature at the location, and solar irradiation at the location collected for 1 year remains the same every year throughout the lifetime of the transformer. Furthermore, it was assumed that the transformer ages uniformly throughout its lifetime. In practice, it is expected that the transformer would age slower in the first few years of its life and age faster towards the end of its lifetime. Therefore, the results of this study are an approximation.

5 | CONCLUSION

In this paper, a BESS strategy was developed to mitigate the limitations imposed on HC by distribution transformer lifetime and degradation considerations. Distribution transformer thermal parameters restrict the amount of PV that can be interconnected in their low-voltage networks, as overloads caused by reverse power flow from PV interconnections can deplete the transformer lifetime. We suggest an approach that preserves the transformer lifetime, while allowing PV penetration in the low-voltage network up to the maximum amount the entire feeder can allow at that location. In our proposal, sets of equations were used to model the interconnection of a BESS at the secondary of the distribution transformer, which stores energy whenever the power flow through the transformer is greater than the temperature-adjusted approximate maximum transformer loading and discharges the stored energy using a two-tier priority discharge whenever the power flow through the transformer is less than the temperature-adjusted approximate maximum transformer loading. Three scenarios were simulated using a test network —HC evaluation for PV penetration in the low-voltage network without restrictions by the distribution transformer (scenario 1), HC evaluation for PV penetration in the low-voltage network with restrictions by the distribution transformer (scenario 2), and HC evaluation for PV penetration in the low-voltage network without restriction by the distribution transformer and with the implementation of the proposed BESS mitigation strategy (scenario 3). The following results were obtained:

- The day with the maximum HC curtailment had a HC of 181 kW for scenario 1, and this was curtailed to 123 kW by the thermal parameters of the distribution transformer in scenario 2. Implementation of the BESS strategy in scenario 3 saw an increased HC to the maximum PV penetration set

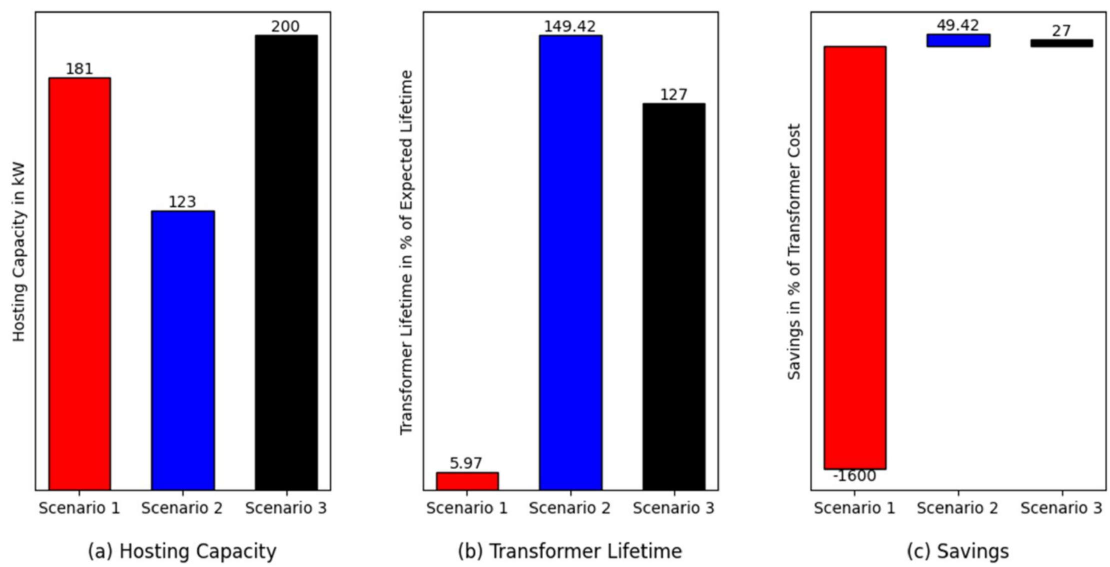

FIGURE 8 Summary of significance of the BESS strategy implementation on Trafo7.

for this study—200 kW. The BESS strategy improved the HC by 77 kW beyond the curtailed HC.

- The transformer lifetime evaluated for scenario 1 was found to be 5.97% of its expected lifetime, which underscores the need for HC mitigation. The nominal cost for this depleted lifetime was found to be 1600% of the expected cost of the transformer with a 100% lifetime. Scenarios 2 and 3 on the other hand see improved transformer lifetime of 149.4% and 127% of the expected lifetime, respectively. The corresponding savings for scenarios 2 and 3 are 49.4% and 27% of the cost of the transformer with 100% lifetime.
- The maximum BESS sizing requirement for the low-voltage network studied is 1600 kWh.

The result of the implementation of the BESS strategy on a test network shows that the BESS strategy does not only improve the HC of a distribution feeder where the PV interconnection is in the low-voltage network, and the distribution transformer is imposing limitations on the HC, but also increases the distribution transformer lifetime. The BESS strategy developed in this paper has, therefore, eliminated the need to curtail the PV penetration in low-voltage networks, as it guarantees a transformer lifetime greater than 100% of its expected lifetime and PV penetration up to the maximum amount allowable for that location by the entire feeder.

NOMENCLATURE

Δt_j	Time interval (hour)
$\Delta\theta_H$	Winding hottest-spot rise over top-oil temperature (°C)
$\Delta\theta_{H,i}$	Initial winding hottest-spot rise over top-oil temperature for $t = 0$ (°C)
$\Delta\theta_{H,R}$	Winding hottest-spot rise over top-oil temperature at rated load on the tap position to be studied (°C)
$\Delta\theta_{H,U}$	Ultimate winding hottest-spot rise over top-oil temperature for load L (°C)
$\Delta\theta_{H/A,R}$	Winding hot spot rise over ambient at rated load on the tap position to be studied (°C)
$\Delta\theta_{TO}$	Top-oil rise over ambient temperature (°C)
$\Delta\theta_{TO,i}$	Initial top-oil rise over ambient temperature for $t = 0$ (°C)
$\Delta\theta_{TO,R}$	Top-oil rise over ambient temperature at rated load on the tap position to be studied (°C)
$\Delta\theta_{TO,U}$	Ultimate top-oil rise over ambient temperature for load L (°C)
θ_A	Average ambient temperature during a load cycle (°C)
$\theta_{A,j}$	Ambient temperature in an interval (°C)
θ_H	Winding hottest-spot temperature (°C)
θ_{TO}	Top-oil temperature (°C)
τ_{TO}	Thermal time constant for transformer oil for load L and for specific temperature differential between the ultimate top-oil rise and the initial top-oil rise (hour)
$\tau_{TO,R}$	Thermal time constant for the transformer rated load beginning with initial top-oil temperature rise of 0°C (hour)
τ_w	Thermal time constant for transformer winding at a hot spot location (minute)
$BS_{charge,j}$	Value of the BESS charging curve in an interval
$BS_{charge,T}$	Total battery charge in J intervals
$BS_{discharge,j}$	Value of the BESS discharging curve in an interval
BS_{kW}	Rating of inverter active power output (kW)
BS_{kWh}	BESS capacity (kWh) at HC
F_{AA_j}	Ageing acceleration factor for the temperature which exists during the time interval Δt_j.
F_{EQA}	Equivalent ageing factor for the total period, t.
i	Initial index
j	Index of a time interval
J	Number of time intervals
K	Ratio of load L to rated load, per unit
m	Empirically derived exponent used to calculate the variation of $\Delta\theta_H$ with changes in load.
n	Empirically derived exponent used to calculate the variation of $\Delta\theta_{TO}$ with changes in load.
R	Ratio of load loss at rated load to no-load loss on the tap position to be studied
S_{rated}	Nameplate power rating of a transformer (kVA)
t	Duration of load cycle (hour)
$Xfmr_{Loading,j}$	Per unit transformer loading in an interval
$Xfmr_{Loading,T}$	Per unit total loading below maximum loading in J intervals
$Xfmr_{Max,j}$	Per unit approximate maximum transformer loading in an interval
$Xfmr_{Max,j}$	Per unit maximum transformer loading in an interval

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CONFLICT OF INTEREST STATEMENT

The authors have no conflicts of interest to declare that are relevant to the content of this article.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available within the article and at reference numbers [30–32].

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