

Transformer Loss of Life Mitigation in the Presence of Energy Storage and PV Generation

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Abstract—Energy storage (ES) is becoming used more and more in power distribution system due to the decrease in the cost. ES can be stationary inside buildings or mobile as a part of plug-in electric vehicles (PEV). The use of ES have merits such as peak shaving, load shifting, and backup power supply in the case of loss of power from the grid. The mobile ES poses challenges to the system since the connection location and time may be random. In this paper, the impacts of the stationary and mobile ES on the distribution transformers loss of life are quantified employing a probabilistic approach. Monte Carlo simulation is utilized to model the stochastic behavior of PEVs. For residential demand, ambient temperature and photovoltaic (PV) generation real data from College Station, Texas is used. Using the historical data of one year in this area, the impacts of different ES penetration level in the presence of PEV and PV are studied. This paper provides a better understanding of the negative effects of PEVs on transformers aging and how ES can be employed to mitigate the loss-of-life risk.

Index Terms—loss of life, energy storage, risk assessment, photovoltaic generation.

NOMENCLATURE

$P_{Ti,j}$	Average power flows through the transformer excluding the effect of battery in the last 10 days before the j^{th} day in the i^{th} hour
P_{avg}	Average power flows through the transformer in the last 10 days excluding the effect of battery
P_{Bi}	Power of the battery, charged (+) and discharged (-)
η	Efficiency of the battery and inverter
E_C	Capacity of the battery in KWh
t_{c_1}, t_{c_2}	Starting and ending time of charging
t_{d_1}, t_{d_2}	Starting and ending time of discharging
SOC_t	Battery state of charge at time t
SOC^{PEV}	PEV battery state of charge
E_D^{PEV}	Electricity consumption in KWh/mile
T_{CH}^{PEV}	Required time to charge PEV

Θ_H	Hottest spot temperature
Θ_a	Ambient temperature
$\Delta\theta_{io}$	Top oil temperature rise over the ambient
$\Delta\theta_h$	Winding hottest spot temperature rise over the top oil
K_u	Ratio of ultimate load to the expected load
R	Ratio between loss at rated load and no load
F_{AA}	Aging acceleration factor
F_{EOA}	Equivalent aging factor
τ_w, τ_{to}	Winding and oil time constant

I. INTRODUCTION

Electric vehicles (EVs) provided a promising solution to reduce fossil fuel consumption and greenhouse gas emission. It is expected that government subsidies may be used to reduce the cost of developing charging stations, so the use of EVs will continue growing. This increasing penetration raises concerns how it will affect different distribution system assets. In this paper, PEVs are considered. These types of EVs can be charged using the corresponding outlets.

Growing presence of PEVs will increase the electricity consumption and this increase can impose several problems such as power quality issues [1], under-voltage condition [2] and extra demand on distribution transformers [3]. Usually distribution transformers do not have on-line monitoring and when they operate in overload condition continuously, they will face accelerated aging and risk of their failure will increase [4]. In addition to an unexpected outage, their failure will cause costs of repair or replacement.

One possible solution to mitigate the impacts of the high penetration of PEVs is employing ES. Recent advances in battery technology have made the deployment of ES at large scale possible for different parts of power system including distribution. ES can be employed for different applications such as energy arbitrage [5], peak shaving [6] and congestion management [7]. One of the benefits of using ES can be in reducing the aging of the transformers.

The impact of integrating PEVs on the transformers have already been studied in [8] - [9]. In [3], it is shown how different level of PEV penetration will adversely affect the transformers

in a residential complex. In [10], a probabilistic approach is proposed to investigate the impact of EV on transformers loss of life when PV is present. Reference [11] presents a case study in Canada about the impact of EV demand on distribution transformer overloading.

None of the abovementioned papers considers stationary battery energy storage except [9]. In [9], the main focus is proposing a smart charging approach in a presence of a predetermined ES size. The contribution of our paper is in studying the impact of the battery capacity and battery energy storage system nominal power on the mitigation of transformer loss of life that has not been studied before. The impact of stationary battery storage on the mitigation of the transformers loss of life due to the high penetration of PEVs and PVs is studied. For this purpose, one year data of PEV demand is created using a probabilistic approach. The load [12], irradiation [13] and temperature [14] data in the city of College Station, TX are utilized to provide a realistic evaluation. It is shown that adding PV generation can help decreasing the loss of life, but it was shown that the highest positive impact is when both battery storage and PV generation are added.

The remainder of this paper is organized as follows. Section II shows the battery scheduling methodology and the utilized data. In Section III, the employed method for generating PEVs demand is illustrated. Section IV presents the transformer aging model. In Section V, a risk assessment method is proposed. In Section VI, the results are demonstrated and discussed and finally, in Section VII, the main conclusions achieved.

II. BATTERY CHARGING/DISCHARGING OPTIMIZATION

The residential building considered in this paper is shown in Figure 1. The nominal power of the transformer is 63KVA and PV system size is 10KW. The building load is connected to the same bus as PV panel, battery storage, and charging station. It is assumed that PEV can only be charged, i.e. it operates in the grid to vehicle mode. The stationary battery storage operates both in charging and discharging modes. The charging station is located in the parking lots of the residential building.

The load data employed in this paper are obtained from the dataset made available by the National Renewable Energy Laboratory (NREL) on OpenEI [14]. To obtain the PV generation, PVWatts Calculator is utilized [15]. The temperature data is extracted from Iowa Environmental Mesonet [16].

In this paper, the assumed role of the battery is the peak load shaving. It is assumed that the battery is scheduled to be charged or discharged the day before and the state of charge cannot become lower than 20%. Frequent charging/discharging decreases the life of the battery, thus, it is assumed that the battery can be charged and discharged once a day. In order to determine the optimization problem, the following should be defined

$$P_{T_i,j} = \sum_{k=1}^{10} \frac{(P_{Load_{i,j-k}} + P_{PEV_{i,j-k}} - P_{PV_{i,j-k}})}{10} \quad (1)$$

For simplification, index j in further equations is removed. The optimization problem for the current day (j^{th} day) is formulated as follows:

$$\text{Min } C = \sum_{i=1}^{24} |P_{T_i} + P_{B_i} - P_{avg}| \quad (2)$$

The battery should not be charged more than 100% and should not be discharged to less than 20% of state of charge. Therefore, constraints (3) and (4) can be defined as follows:

$$\sum_{i=t_{C1}}^{t_{C2}} P_{B_i} \leq \eta E_C (1 - SOC_{t_{C1}}) \quad (3)$$

$$\sum_{i=t_{D1}}^{t_{D2}} -P_{B_i} \leq \eta E_C (SOC_{t_{C3}} - 0.2) \quad (4)$$

Furthermore, the charging or discharging power should not be more than the nominal power of the battery charger that leads to the constraint (5).

$$|P_{B_i}| \leq P_n \quad (5)$$

The starting time of charging and discharging should be less than the ending time, i.e. it must be a positive number. The problem should obey the following constraints (6) – (8).

$$t_{C1} \leq t_{C2} \quad (6)$$

$$t_{D1} \leq t_{D2} \quad (7)$$

$$t_{C1}, t_{C2}, t_{D1}, t_{D2} \geq 0 \quad (8)$$

Finally, two scenarios can be considered. First, in any given day, charging is scheduled before discharging for which constraint (9) is defined. Second, when discharging is scheduled before charging, the constraint (10) is defined.

$$\text{If } t_{C1} < t_{D1} \Rightarrow SOC_{t_{D1}} = SOC_{t_{C1}} + \frac{\sum_{i=t_{C1}}^{t_{C2}} P_{B_i}}{\eta E_C} \quad (9)$$

$$\text{If } t_{C1} > t_{D1} \Rightarrow SOC_{t_{C1}} = SOC_{t_{D1}} + \frac{\sum_{i=t_{D1}}^{t_{D2}} P_{B_i}}{\eta E_C} \quad (10)$$

Since the planning is day ahead, heuristic optimization methods can be utilized to solve this optimization problem. In this paper, genetic algorithm is employed.

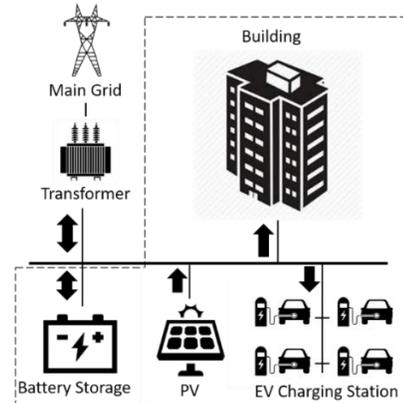


Figure 1. Schematic of the system under study.

III. MODELLING PEV CHARGING DEMAND UNCERTAINTIES

To model the uncertainty of the demand imposed by PEVs, the approach introduced in [8], and [9] is employed. The PEV load profile is estimated using several variables such as driving distance, arrival time and PEVs' characteristics. The flowchart of the estimation process is shown in Figure 2.

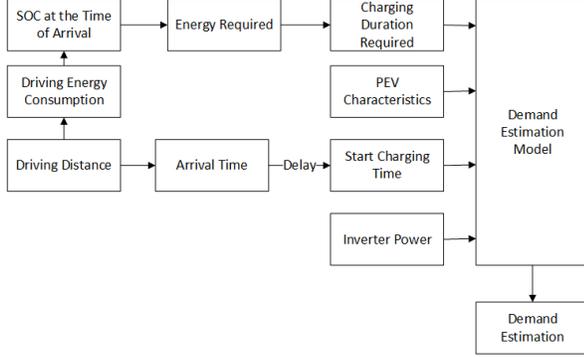


Figure 2. PEV demand estimation flowchart.

One of the important variables in this model is the start time of charging. Since the building considered in this paper is a residential building, it is more probable that PEV owners leave the building in the morning and return in the evening. Thus, the following distribution function is employed. The time of arrival is modeled with a normal distribution with the mean value of $\mu_d = 17:00$ and standard deviation of $\sigma_d = 2.28$. The daily driving distance can be modeled using log-normal distribution with the mean value of $\mu_d = 3.37$ and standard deviation of $\sigma_d = 0.5$.

$$AT = Gauss(\mu_{AT}, \sigma_{AT}^2) \quad (11)$$

$$d = Ln(\mu_d, \sigma_d^2) \quad (12)$$

The SOC when the PEV gets home will be:

$$SOC_{ini}^{PEV} = 1 - \frac{E_D^{PEV} \cdot d}{E_C} \quad (13)$$

It is assumed that the required SOC is 95%. Thus, considering the PEVs are charged with constant power, the required time to charge the vehicle can be calculated as follows:

$$T_{CH}^{PEV} = \frac{(SOC_{req}^{PEV} - SOC_{ini}^{PEV}) \cdot E_C^{PEV}}{\eta^{PEV} \cdot P} \quad (14)$$

The electric vehicle studied in this paper is Nissan Leaf. The battery capacity in this car is 24KWh and it consumes 340Wh/mile. It is assumed the residents own 12 PEVs cars and there are 10 charging slots in the parking.

IV. TRANSFORMER AGEING

Two main factors that affect the thermal condition of the transformer are ambient temperature and loading. When transformers work in an overload, mainly, due to the increased copper loss in the winding of the transformer, the temperature near the windings increases and affects the insulation. The high temperature will cause accelerated aging for the insulation and

makes the transformer vulnerable to different types of faults. Therefore, the life of the transformer will be decreased. To evaluate the transformer aging and loss of life due to increased temperature, IEEE Standard C57.91 is utilized [17].

Firstly, the hottest spot temperature should be calculated:

$$\theta_H = \theta_a + \Delta\theta_{to} + \Delta\theta_h \quad (15)$$

For which the changes in temperature can be calculated as follows:

$$\Delta\theta_h = (\Delta\theta_{h,ult} - \Delta\theta_{h,ini}) \cdot (1 - e^{-\frac{t}{\tau_w}}) + \Delta\theta_{h,ini} \quad (16)$$

$$\Delta\theta_{to} = (\Delta\theta_{to,ult} - \Delta\theta_{to,ini}) \cdot (1 - e^{-\frac{t}{\tau_{to}}}) + \Delta\theta_{to,ini} \quad (17)$$

$$\Delta\theta_{h,u} = \Delta\theta_{h,rated_load} \cdot K_u^{2m} \quad (18)$$

$$\Delta\theta_{to,ult} = \Delta\theta_{to,rated_Load} \cdot \left[\frac{K_u R + 1}{R + 1} \right]^n \quad (19)$$

Where m and n are empirically derived based on transformer type. Furthermore, *ini* and *ultra* refer to initial and ultimate values respectively Using IEEE Standard C57.91, the aging acceleration factor F_{AA} , and the equivalent aging factor F_{EQA} can be calculated and loss of life can be calculated as follows:

$$F_{AA}(t) = e^{\left(\frac{15000}{110+273} - \frac{15000}{\theta_h+273} \right)} \quad (20)$$

$$F_{EQA} = \frac{\sum_{n=1}^N F_{AA,n} \Delta t_n}{\sum_{n=1}^N \Delta t_n} \quad (21)$$

$$Loss\ of\ Life = \frac{F_{EQA} \cdot Analysis\ Time}{Insulation\ Life} \quad (22)$$

V. RISK ASSESSMENT

Risk matrix is a useful method for qualitative risk analysis when probability or severity cannot be estimated precisely. In this paper, this method is employed to assess the risk of transformer loss of life. Risk matrix is formed by considering the category of probability or likelihood against the category of consequence severity. In this method, risk level is defined using terms such as “low” and “high”. This method is based on two main characteristics of the event which are probability and severity. Probability is the likelihood of the event occurrence and severity is the amount of harm that the event may cause. Therefore, F_{EQA} can be utilized as the measure to quantify severity.

As suggested in [8], the qualitative definition of probability and severity is illustrated in Table I. The values of F_{EQA} are calculated daily based and the ranges are determined using the temperature rise of the transformer. To perform these calculations, equation (20) is used to calculate the associated F_{AA} to each temperature rise, and equation (21) is utilized to obtain daily F_{EQA} . The probability also is classified in 5 different classes. The risk matrix of the transformer loss-of-life is also shown in Table II. The probability of the event is denoted by $P(e)$.

TABLE I. PROBABILITY AND SEVERITY DEFINITIONS

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

TABLE II. RISK MATRIX FOR TRANSFORMER LOSS OF LIFE

Severity	Probability				
	Rare	Occasional	Probable	Frequent	Likely
Insignificant	Low	Low	Low	Low	Low
Normal	Low	Low	Low	Medium	Medium
Critical	Medium	Medium	Medium	High	High
Severe	High	High	High	Extreme	Extreme
Catastrophic	Extreme	Extreme	Extreme	Extreme	Extreme

VI. SIMULATION RESULTS

The method was implemented in MATLAB and the transformer loss-of-life was studied for the following scenarios.

- a) No PV, no PEV, and no storage.
- b) No PV, high penetration of PEVs and no storage.
- c) PV generation, high penetration of PEVs and no storage.
- d) No PV generation, high penetration of PEVs and several levels storage.
- e) PV generation, high penetration of PEVs and several levels storage.

The results of seven cases are shown in Table III. In this table, it can be clearly seen how high penetration of PEVs can negatively impact the life of the transformer. If PEVs are added to the grid and its effect are not compensated (scenario b), the transformer life will drop dramatically and it will fail much earlier than it supposed to. Adding PV (scenario c) mitigated the impact, but still, the loss of life of the transformer is too high. It also can be concluded from this table that addition of a suitable capacity of battery energy storage is more effective than PV and the reason is that for a residential building, PEVs are mainly plugged in to get charged in the evening when PV generation is not significant.

TABLE III. TRANSFORMER LOSS OF LIFE FOR DIFFERENT SCENARIOS

Scenario	Transformer Loss of Life (%)
a	0.0124
b	33.45
c	12.23
d.a- d and the capacity of the battery is 20KWh.	6.86
d.b- d and the capacity of the battery is 40KWh.	1.6
e.a- e and the capacity of the battery is 20KWh.	2.3125
e.b- e and the capacity of the battery is 40KWh.	0.45

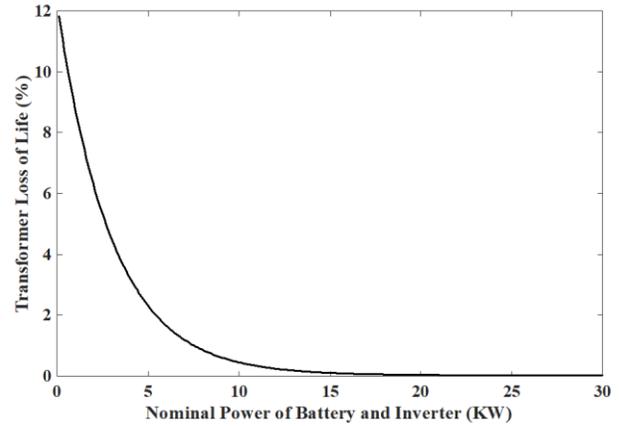


Figure 3. The impact of battery power and size on transformer loss of life

To study the impact of the size of battery which is placed in the building, 300 batteries with different values are used in the simulation and the result is shown in Figure 3. The nominal power of battery and inverter is a quarter of the maximum capacity of battery. Using Figure 3, it can be observed that the size of the battery can have a considerable impact until the knee point. Further, the results do not have a conspicuous improvement.

Also, how the loss of life changes in different seasons of the year should be studied. The results are shown in Table IV. When there is no PV, PEV, and battery, transformer ages during winter and summer more than other seasons. In summer, the gain is due to a high ambient temperature in addition to the high demand for cooling. In winter, in spite of lower temperature, the demand is very high and accelerates transformer aging. Scenario b) illustrates that when there is high penetration of PEV and no PV, transformer considerably ages in summer and this much loss of life in this short period, increases the probability of failure. Considering scenarios d) and e) it can be concluded that the presence of battery storage with an appropriately selected capacity, mitigates the impact of high penetration of PEV.

TABLE IV. SEASON IMPACT ON LOSS OF LIFE AND AGING FACTOR

	Scenario	Winter	Spring	Summer	Fall
Probability of $F_{EQA} > 1$ (%)	a	0	0	0	0
	b	8.99	27.96	50.54	13.13
	c	12.22	13.98	21.51	7.87
	d.a	4.49	7.53	33.33	6.67
	d.b	1.12	2.15	19.35	3.33
	e.a	4.49	3.23	10.75	5.56
Season Portion in Loss of Life (%)	e.b	1.12	0	5.38	2.22
	a	49.85	6.12	40.42	3.62
	b	4.66	6.73	80.42	8.19
	c	11.12	7.44	61.95	19.49
	d.a	4.12	6.89	81.53	7.46
	d.b	3.91	8.54	80.78	6.77
	e.a	10.39	7.04	63.95	18.63
e.b	10.96	6.7	64.5	17.84	

The ES is usually employed for applications such as energy arbitrage, frequency and voltage support, peak shaving and congestion management. In this paper, we illustrate a side advantage of reducing the overload imposed on transformers when PEVs are added to the system. High penetration of PEVs will cause accelerate ageing for transformers and they may fail earlier than expected. Therefore, they should be replaced either when PEVs appear in the grid or later after they fail. In both cases, the price of a new transformer with higher power rating must be paid. We have shown that battery storage can mitigate the impact and help the transformer operate during its normal life. The money supposed to be spent on the transformer replacement will be saved and may cover a considerable portion of the battery placement cost. This positive impact of battery storage should be considered in the economic evaluation. Its impact on payback calculation is yet to be studied considering other benefit of battery storage, which is the peak shaving in this paper.

Finally, in Figure 4, the risk of loss of life for different scenarios is illustrated in a stacked bar chart. The positive effect of PV and battery energy storage in risk reduction is clear in this figure. Not compensated PEVs increase the risk conspicuously. Although PV mitigates the negative impact of PEV, the probability of an extreme event is still too high. Employing battery energy storage, with or without PV, totally removes extreme and high risk conditions and significantly decreases the medium risk conditions.

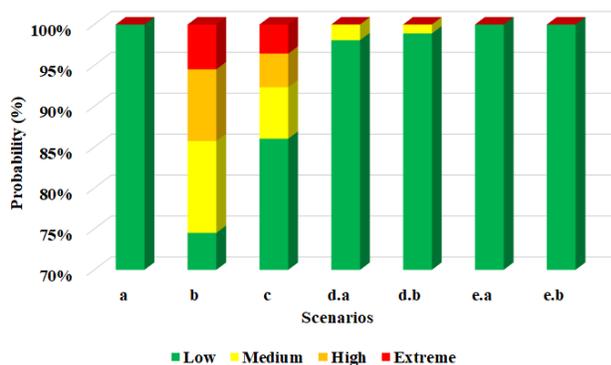


Figure 4. Risk of loss of life for different scenarios.

VII. CONCLUSION

A residential building electricity consumption is simulated for different scenarios of PV and PEV penetration, and how the stationary battery storage with different capacity can mitigate the impact of PEVs on transformer aging is studied. The demand of PEVs is generated using a probabilistic method and the available data for the city of College Station, TX, are employed. The results show that:

- The inclusion of 12 PEVs with 10 charging stations will conspicuously accelerate the aging of the transformer and reduces its life.
- With the high penetration of PEVs, and no support from PV and battery, the transformer will dramatically age.
- PV helps to mitigate the impact of PEV penetration, but due to limited area on the roof and the price of PV panels, PV generation can be limited.

- In comparison with the nominal power of transformer and PV, relatively low capacity battery storage can have a considerable impact in reducing the transformer loss of life.
- The fact that the loss of life in the presence of battery is mainly during summer shows that the storage could mitigate the problem of extra demand, and ambient temperature is playing more important role.
- The performed risk analysis illustrates that battery energy storage utilization significantly decreases transformer operation risk.

REFERENCES

- [1] M. K. Gray and W. G. Morsi, "Power Quality Assessment in Distribution Systems Embedded With Plug-In Hybrid and Battery Electric Vehicles," in *IEEE Transactions on Power Systems*, vol. 30, no. 2, pp. 663-671, March 2015.
- [2] A. Dubey, and S. Santoso, "Electric Vehicle Charging on Residential Distribution Systems: Impacts and Mitigations", *IEEE Access*, vol. 3, pp. 1871 - 1893, Sept. 2015.
- [3] C. M. Affonso, M. Kezunovic, "Probabilistic Assessment of Electric Vehicle Charging Demand Impact on Residential Distribution Transformer Aging", at *International Conference on Probabilistic Methods Applied to Power Systems - PMAPS*, Boise, Idaho, USA, June 24-28, 2018.
- [4] Godina, Radu, et al. "Effect of loads and other key factors on oil-transformer ageing: Sustainability benefits and challenges." *Energies*, vol. 8, no .10, pp. 12147-12186, 2015.
- [5] D. Krishnamurthy, C. Uckun, Z. Zhou, P. R. Thimmapuram and A. Botterud, "Energy Storage Arbitrage Under Day-Ahead and Real Price Uncertainty," in *IEEE Transactions on Power Systems*, vol. 33, no. 1, pp. 84-93, Jan. 2018.
- [6] D. Gayme and U. Topcu, "Optimal power flow with large-scale storage integration," in *IEEE Transactions on Power Systems*, vol. 28, no. 2, pp. 709-717, May 2013.
- [7] H. Pandžić, Y. Wang, T. Qiu, Y. Dvorkin and D. S. Kirschen, "Near-Optimal Method for Siting and Sizing of Distributed Storage in a Transmission Network," in *IEEE Transactions on Power Systems*, vol. 30, no. 5, pp. 2288-2300, Sept. 2015.
- [8] C. M. Affonso, Q. Yan, M. Kezunovic, "Risk Assessment of Transformer Loss-of-Life due to PEV Charging in a Parking Garage with PV Generation," at *IEEE PES General Meeting*, Portland, Aug. 4-10, 2018.
- [9] C. M. Affonso and M. Kezunovic, "Technical and Economic Impact of PV-BESS Charging Station on Transformer Life: A Case Study," in *IEEE Transactions on Smart Grid*. A. D. Hilshey, P. D. H. Hines, P. Rezaei and J. R. Dowds, "Estimating the Impact of Electric Vehicle Smart Charging on Distribution Transformer Aging," in *IEEE Transactions on Smart Grid*, vol. 4, no. 2, pp. 905-913, June 2013.
- [10] S. F. Abdelsamad, W. G. Morsi, and T. S. Sidhu, "Probabilistic Impact of Transportation Electrification on the Loss-of-Life of Distribution Transformers in the Presence of Rooftop Solar Photovoltaic", *IEEE Transactions on Sustainable Energy*, Vol. 6, no. 4, 1565-1573, 2015.
- [11] M. A. Awadallah, B. N. Singh, and B. Venkatesh, "Impact of EV Charger Load on Distribution Network Capacity: A Case Study in Toronto", *Canadian Journal of Computer Engineering*, Vol. 39, 2016.
- [12] OpenEI, "Commercial and Residential Hourly Load Data," [Online]. Available: <https://www.openei.org>
- [13] NREL, "National Solar Radiation Data Base," Available: <https://www.nrel.gov>.
- [14] WeatherUnderground, "Historical weather," Available: <https://www.wunderground.com>.
- [15] NREL, "PVWatts Calculator", Available: <https://pvwatts.nrel.gov/index.php>
- [16] Iowa State University, "Iowa Environmental Mesonet", Available: https://mesonet.agron.iastate.edu/request/download.phtml?network=TX_ASOS
- [17] *IEEE Guide for Loading Mineral-Oil-Immersed Transformers*, IEEE Std. C57.91-1995), March 1995.