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Novel engineering economic evaluation method for optimal distribution transformer sizing

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ABSTRACT

Selecting the appropriate transformer size is crucial. Therefore, a comprehensive evaluation method is required. This study proposes a novel engineering economic approach to assess transformer performance and suggests the most suitable transformer size for obtaining optimal economic and operational efficiency. The method considers energy losses throughout the transformer's service life, balancing initial investment, energy expenses, and operational performance to ensure reliable operation with low losses. The approach was implemented on 500 kVA, 1,000 kVA, and 1,250 kVA three-phase distribution transformers operating at 50 Hz and voltage levels of 22 kV–400/230 V. The analysis indicates electricity cost, demand charge, initial transformer price, and power losses as the primary factors affecting total and environmental costs. Results indicate that higher interest rates result in a lower present worth factor and a lower cost to own the transformer. Using two 500 kVA units in parallel to supply a 1,000 kVA load obtains a lower cost than using a single 1,000 kVA transformer, whereas the 1,250 kVA transformer provides the lowest overall cost and best economic performance. The proposed method effectively evaluates transformer performance and indicates the optimal transformer size under given operating and economic conditions.

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1. INTRODUCTION

As technology and industry continue to grow rapidly, electrical energy has become an important component in the operation of industrial facilities. For instance, industries such as steel production, petrochemical processing, and food processing require a reliable and effective power supply to enhance continuous operations and to maintain product quality and safety standards. Therefore, efficient electrical energy management is essential for maintaining the stability, reliability, and efficiency of industrial plants. The transformer is regarded as one of the major components in an industrial electrical system. Technically, transformers are not only used for voltage conversion but also play an important role in maintaining the stability and reliability of electrical distribution networks. Since transformers function continuously during their service life, their performance and efficiency have a significant influence on the overall operational reliability, energy consumption, and economic performance of industrial power systems.

High-efficiency transformers with low energy losses normally require advanced manufacturing technologies and materials, which subsequently result in higher initial investment costs. Besides, the related

costs, including operational losses, energy losses, and long-term operating costs, also significantly impact the total investment cost of transformers. In addition, transformer energy losses indirectly contribute to greenhouse gas emissions because electricity generation in many countries still depends greatly on fossil fuel resources. As a result, in addition to the initial investment cost, long-term operational efficiency, economic feasibility, and environmental impact should be considered for transformer selection. Therefore, comprehensive economic evaluation methods are obviously required to obtain a balance between transformer performance, operational efficiency, investment feasibility, and environmental sustainability.

Recently, several works have been conducted to evaluate transformer economics using total ownership cost (TOC) and life-cycle cost (LCC) approaches. Charalambous *et al.* [1] presented a comprehensive method for evaluating the losses and TOC of power transformers. Their proposed method includes both direct operational losses, including the loss of energy, and the long-term costs based on maintenance, capital investment, and replacement. Agha *et al.* [2] suggested a method for evaluating the optimal load of distribution transformers by considering the relationship between the economic value of the transformer and the energy losses that occur when the load changes. Georgilakis and Amoiralis [3] presented a cost evaluation methodology for distribution transformers using the TOC approach, which includes environmental costs in the total assessment. Similarly, Amoiralis *et al.* [4] also utilized the TOC technique to perform an economic evaluation of transformer selection in electrical power systems. Their analysis pointed out that in a competitive market, investing in low-cost transformers with lower efficiency potentially results in increased long-term energy costs. In addition, Zhao *et al.* [5] presented an LCC estimation and analysis of transformers based on failure rates. Their cost evaluation included external maintenance costs, labor, and operational expenses as part of the cost calculation. Evidently, the studies provided useful approaches for the evaluation of investment cost and the performance of transformers. However, most existing works mainly focused on economic assessments using TOC or LCC methods without considering engineering-related operational factors and experimentally measured transformer losses under actual operating conditions [6]-[8]. In addition, many previous studies investigated only a single transformer size, limiting the evaluation of transformer suitability under varying load conditions. From a technical point of view, [9], [10] direct energy loss testing conducted by a manufacturer can provide a more realistic and accurate assessment of transformer performance. Nevertheless, this approach was not sufficiently presented in prior studies. Thus, further investigation combining experimental transformer loss analysis, engineering-economic assessment, and environmental impact evaluation is still required.

Therefore, this study proposes a comprehensive engineering-economic evaluation approach for distribution transformers by considering engineering-related operational expenses, experimentally measured transformer losses, and environmental impact assessment. Three commonly utilized transformer sizes of 500 kVA, 1,000 kVA, and 1,250 kVA (3-phase, 50 Hz, 22 kV–400/230 V) were investigated under comparable operating conditions. The analysis includes transformer loss measurements, electricity cost, demand charge, interest rate, service life, and environmental costs related to greenhouse gas emissions. The proposed approach is used to determine the most suitable transformer size for industrial applications. Simultaneously, it can be utilized to promote operational efficiency, long-term ownership costs, and environmental impact reductions. The findings from this study can be used as important references and guidance for selection and investment decisions of transformers in industrial electrical systems, which can contribute to economic efficiency and sustainable energy management.

2. METHOD

2.1. Research design and framework

This study employed an experimental and engineering-economic evaluation approach to investigate the suitability of distribution transformer sizing under industrial operating conditions. The overall research framework adopted in this study is illustrated in Figure 1. Three oil-immersed three-phase distribution transformers with rated capacities of 500 kVA, 1,000 kVA, and 1,250 kVA (22 kV–400/230 V, 50 Hz) were selected for investigation. The experimental setup consisted of a three-phase power supply, variac, voltmeters, ammeters, and wattmeters for measuring transformer electrical parameters and power losses. Transformer testing was conducted according to IEC 60076 and TIS 384-2543 standards.

Initially, transformer testing was performed to determine the electrical power losses of the investigated transformers. Subsequently, the measured losses were incorporated into the engineering-economic analysis, including present worth (PW) and transformer ownership cost (COT) calculations. Environmental assessment was then conducted based on the greenhouse gas emissions associated with transformer energy losses. Finally, the investigated transformer sizes were evaluated and compared in terms of electrical power loss, transformer ownership cost, environmental cost, and transformer efficiency to determine the most suitable transformer size for industrial applications.

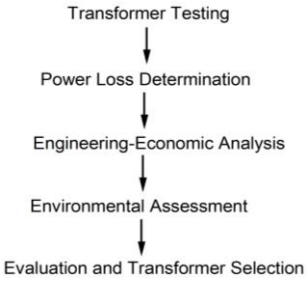

Figure 1. Research framework for transformer evaluation and selection

2.2. Testing electrical power loss in transformers

The electrical power loss in transformers is essential for understanding the performance and cost-effectiveness. The overall power loss (P_T) in a transformer basically consists of two main sections: core losses and copper losses, as mathematically shown in (1) [6]-[8]. Technically, hysteresis and eddy-current effects promote core losses, and the resistance of the transformer during current flow under load causes copper losses.

$$P_T = P_{Core} + P_{CU} \quad (1)$$

Where P_T represents the total power loss of the transformer, P_{Core} denotes the core loss, and P_{CU} denotes the copper loss (W), each expressed in watts.

2.2.1. Core losses

To evaluate the core losses of the transformer. The open-circuit test is conducted, as shown in Figure 2. In this test, voltage is applied to the low-voltage (LV) side. At the same time, the high-voltage (HV) side remains open. The core losses consist of hysteresis losses and eddy-current losses. These losses remain constant under all electrical operating conditions. The relationship can be expressed as (2) [6], [7].

$$P_{Core} = P_H + P_E \quad (2)$$

Where P_{core} is the core loss, P_H is the hysteresis loss, and P_E is the eddy-current loss, respectively, expressed in watts. The hysteresis loss can be obtained using (3) [9].

$$P_H = K_s \cdot B^{1.6} \cdot f \quad (3)$$

Where K_s *is* the material coefficient of the core, B is the maximum magnetic flux density (in teslas, T), and f is the frequency (Hz). The eddy-current loss can be determined using (4) [9].

$$P_E = K_e \cdot f^2 \cdot B^2 \cdot d^2 \cdot 10^2 \quad (4)$$

Where K_e is the eddy-current constant, d is the thickness of the laminated core (mm), B is the maximum magnetic flux density (T), and f is the frequency (Hz).

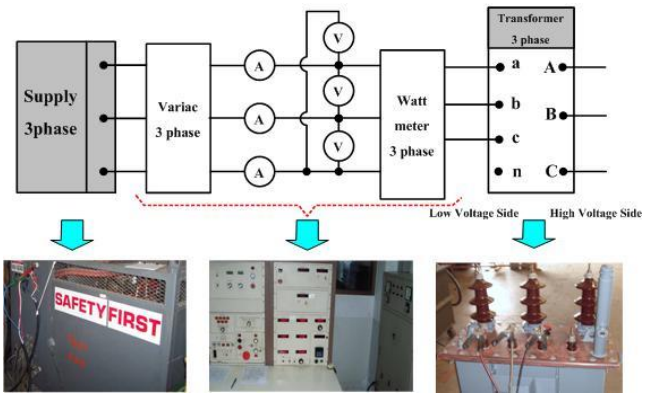

Figure 2. Open-circuit test configuration used for measuring transformer core losses (high-voltage side open-circuited)

2.2.2. Copper losses

The copper losses of the transformer in this test can be measured using the short-circuit test. Figure 3 illustrates the schematic diagram and the experimental setup of the short-circuit test. During the test, the LV side is short-circuited, and voltage is connected to the HV side. The input voltage is slowly raised until the rated current flows on the high-voltage side. This procedure makes it possible to obtain the copper losses that take place due to the electrical resistance of the transformer conductors under load conditions. Copper losses can be estimated using (5) [9], [10].

$$P_{CU} = 3(I_{HV}^2 \cdot R_{HV} + I_{LV}^2 \cdot R_{LV}) \quad (5)$$

Where R_{HV} is the resistance of the high-voltage side, I_{HV} is the current on the high-voltage side, $R_{LV\ is}$ the resistance of the low-voltage side, and I_{LV} is the current on the low-voltage side.

2.3. Engineering-economic analysis

2.3.1. Present worth

Economic analysis plays a crucial role in decision-making in various engineering situations, particularly when evaluating investment choices and project possibilities. Certainly, choosing the appropriate project or equipment is of great importance to make sure that operations are efficient and sustainable. One approach to comparison is to calculate the present value of the investment and expected costs of different projects or machines. This concept is normally known as "present worth (PW)" [11], [12].

Technically, the present worth is a numerical value employed for converting future cash flows, i.e., annual payments or collections, into an equivalent amount at the present time. This conversion considers the interest rate and duration. It is known that the money value changes over time. Hence, the PW technique is useful for assessing project feasibility and potential investments [13]. The present worth can be computed using (6).

$$PW = \frac{(1+i)^n - 1}{i(1+i)^n} \quad (6)$$

Where PW represents the present worth, i is the interest rate, and n is the number of periods (duration).

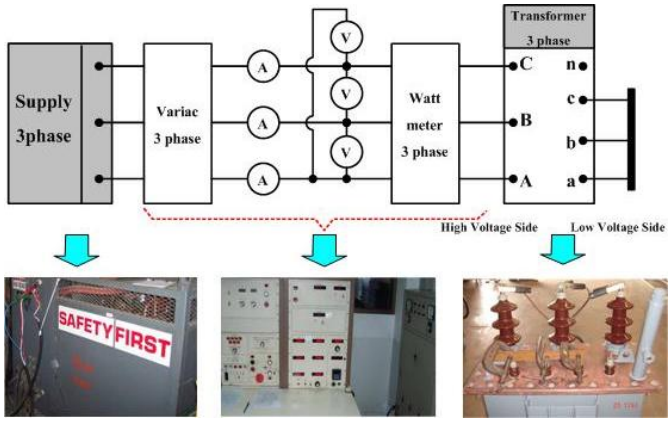

Figure 3. Short-circuit test configuration used for measuring transformer copper losses (low-voltage side short-circuited)

2.3.2. Transformer cost calculation

To assess the expense of a transformer and identify the suitable transformer size for a specific load. The COT is principally considered as a key parameter, which can be obtained by (7) [6], [12]-[14].

$$COT = C + PW\left[C\frac{FC}{100} + K_c L_c + K_w L_w\right] \quad (7)$$

Where C is the initial cost of the transformer [12], and FC is the depreciation cost [13].

I is the interest rate (%) [14], N is the service life of the transformer (years) [6], PW is the present worth [12], L_c is the no-load loss (kW) [12], and L_w is the load loss (kW). Additionally, K_c และ K_w are constants that are applied to the transformer cost analysis, as shown in (8) and (9).

$$K_c = C_d + T_c C_e \quad (8)$$

$$K_w = D^2 (C_d + T_w C_e) \quad (9)$$

Where T_c is the number of hours per year that the transformer sends out energy [12], T_w is the number of hours per year the transformer operates under constant load [12], C_e is the electricity cost (THB per unit) [12], C_d is the demand cost for electricity (THB per kW per year) [12], and D is the load factor at rated load [12].

2.4. Environmental cost and efficiency evaluation

2.4.1. Environmental costs

The production of electricity generates a variety of environmental concerns, which are mainly caused by the fuel source. In particular, the use of fossil fuels has a grater negative consequence than renewable energy sources [15], [16]. Therefore, the consumption and loss of electricity also affect environmental conditions. According to the standards set by the Greenhouse Gas Management Organization (Public Organization), the greenhouse gas emission coefficient for electricity consumption (from the electricity distribution system) is 0.4857 kgCO2-e/kWh [17]. Greenhouse gas emission is related to load losses of the transformer and its annual operating duration, normally expressed in hours per year [18], [19]. The value of the greenhouse gas emission coefficient is then used to compute the total greenhouse gas emission, as shown in (10).

$$Greenhouse\ gas\ emission = 0.4857 \times Load\ losses \times Annual\ operating\ duration \quad (10)$$

Where greenhouse gas emissions are measured in kilograms of CO_2 equivalent ($kgCO_2$-e), the number 0.4857 is the greenhouse gas emission coefficient for electricity use, and annual operating duration refers to the total number of hours that the transformer produces the load per year.

2.4.2. The efficiency of a transformer

The efficiency (η) of a transformer is considered as the ratio of output power to input power. The input power is the sum of output and the power losses. Therefore, the efficiency of a transformer can be estimated using (11).

$$\eta\ (\%) = \frac{\text{Output power}}{\text{Output } power + \text{Power losses}} \times 100 \quad (11)$$

2.5. Transformer testing procedures

2.5.1. Open-circuit test for core loss measurement

The open-circuit test, also known as the no-load loss test, is performed according to IEC 60076 or TIS 384-2543 standards. As clearly exhibited in Figure 1, the test circuit is set up so that voltage is applied to the LV winding and the HV winding remains open. Subsequently, the input voltage is set to the rated value of 400 volts, regardless of the current level. The value in the wattmeter indicates the core loss of the transformer, which remains unchanged under all load conditions.

2.5.2. Short-circuit test for copper loss measurement

The load loss test, usually known as the short-circuit test, is conducted as per IEC 60076 or TIS 384-2543 standards. This loss is caused by the current passing through the transformer windings and simultaneously supplying a load, as depicted in Figure 2. The LV winding is short-circuited [20]-[23]. At the same time, voltage is applied to the HV winding. The input voltage is subsequently adjusted until the rated current is obtained. The (12) can be used to calculate the copper loss:

$$I = \frac{S}{\sqrt{3} \times V} \quad (12)$$

Where I is the current flowing through the winding (A), S = is the rated apparent power of the transformer (VA), and V = the voltage of the transformer (V). The current for a 500 kVA transformer is 13.12 A, regardless of the voltage value. For 1,000 kVA and 1,250 kVA transformers, the currents are 26.24 A and 32.80 A, respectively. The wattmeter value obtained under these conditions indicates the copper losses of the transformer.

2.6. Evaluation criteria

The investigated transformer sizes were evaluated and compared based on four major criteria: electrical power loss, COT, environmental cost, and transformer efficiency. The measured core losses and copper losses derived from the open-circuit and short-circuit tests were included in the engineering-

economic, environmental, and efficiency analyses. To maintain consistency in the comparison, all transformer sizes were assessed under comparable operating conditions, including electricity cost, demand charge, service life, interest rate, and load conditions.

The COT was considered as the key criterion for economic evaluation. Simultaneously, electrical power loss and transformer efficiency were employed for technical performance assessment. In addition, environmental cost corresponding to transformer energy losses was used to evaluate environmental impact. The transformer exhibiting the lowest ownership cost and the most effective technical and environmental performance was considered the most appropriate transformer size for the given operating conditions.

3. RESULTS AND DISCUSSION

3.1. Experimental results

In this experiment, we tested three transformers rated at 500 kVA, 1,000 kVA, and 1,250 kVA (3-phase, 50 Hz, 22 kV-400/230 V) to evaluate their overall electrical power losses. The entire power loss of a transformer is comprised of copper losses and core losses. Table 1 summarizes the specifications and measured electrical parameters of the investigated transformers. As stated in Table 1, the measured no-load losses were 838 W, 1,251.9 W, and 1,950 W for the 500 kVA, 1,000 kVA, and 1,250 kVA transformers, respectively. The corresponding load losses at rated load were 4,949.5 W, 11,690.4 W, and 12,338 W. The overall losses from the measurements were 5,787.5 W, 12,942.3 W, and 14,288 W for the three transformer sizes. In addition, the measured short-circuit impedance values were 4.00%, 6.00%, and 6.49%, with corresponding voltage regulation values of 1.07%, 1.35%, and 1.19%.

To evaluate the influence of loading conditions on transformer performance, load losses were measured under load conditions ranging from 0% to 120% of the rated load. The measured results are summarized in Table 2. For the 500 kVA transformer, the measured load losses increased from 49.5 W at 10% load to 4,949.5 W at 100% load. Similarly, the measured load losses of the 1,000 kVA transformer increased from 116.9 W to 11,690 W, whereas the corresponding values for the 1,250 kVA transformer increased from 123.4 W to 12,338 W. The measured data presented in Table 2 were then used for the engineering-economic and environmental analyses.

The measured load losses in Table 2 are graphically shown in Figure 3. The graph presents the relationship between load percentage and measured load losses for the investigated transformer sizes. Throughout the investigated working range, the 1,000 kVA and 1,250 kVA transformers exhibited higher load losses compared to 500 kVA transformers. Under rated load conditions, the measured load losses were 4,949.5 W, 11,690 W, and 12,338 W for the 500 kVA, 1,000 kVA, and 1,250 kVA transformers, respectively.

Table 1. Specifications of the 500 kVA, 1,000 kVA, and 1,250 kVA transformers used in the tests

Specifications	500 kVA	1,000 kVA	1,250 kVA
Capacity (kVA)	500	1,000	1,250
High voltage (V)	22,000	22,000	22,000
Low voltage (V)	400/230	400/230	400/230
HV. current (A)	13.12	26.24	32.80
LV. current (A)	721.71	1,443.42	1,804.27
No load losses (W)	838.00	1,251.90	1,950.00
Load losses (W)	4,949.50	11,690.40	12,338.00
Total losses (W)	5,787.50	12,942.30	14,288.00
Short-circuit impedance (%)	4.00	6.00	6.49
Percentage regulation (%)	1.07	1.35	1.19

Table 2. Measured power losses of the 500 kVA, 1,000 kVA, and 1,250 kVA transformers from the tests

Load (%)	500 kVA		1,000 kVA		1,250 kVA	
	HV current (A)	Load losses (W)	HV current (A)	Load losses (W)	HV current (A)	Load losses (W)
0	0.00	0.00	0.00	0.00	0.00	0.00
10	1.31	49.50	2.62	116.90	3.28	123.38
20	2.62	197.98	5.25	467.60	6.56	493.52
30	3.94	445.46	7.87	1,052.10	9.84	1,110.42
40	5.25	791.92	10.50	1,870.40	13.12	1,974.08
50	6.56	1,237.38	13.12	2,922.50	16.40	3,084.50
60	7.87	1,781.82	15.74	4,208.40	19.68	4,441.68
70	9.18	2,425.26	18.37	5,728.10	22.96	6,045.62
80	10.50	3,167.68	20.99	7,481.60	26.24	7,896.32
90	11.81	4,009.10	23.62	9,468.90	29.52	9,993.78
100	13.12	4,949.50	26.24	11,690.00	32.80	12,338.00
110	14.43	5,988.90	28.86	14,144.90	36.08	14,928.98
120	15.74	7,127.28	31.49	16,833.60	39.36	17,766.72

The greenhouse gas emissions related to transformer power losses were calculated using the greenhouse gas emission coefficient of 0.4857 kgCO_2-e/kWh provided by the Thailand Greenhouse Gas Management Organization (Public Organization). Figure 4 shows the calculated greenhouse gas emissions. The estimated emissions increased with increasing load percentage for all investigated transformer sizes. The highest greenhouse gas emissions were observed at the maximum load condition, corresponding to the highest measured transformer power losses.

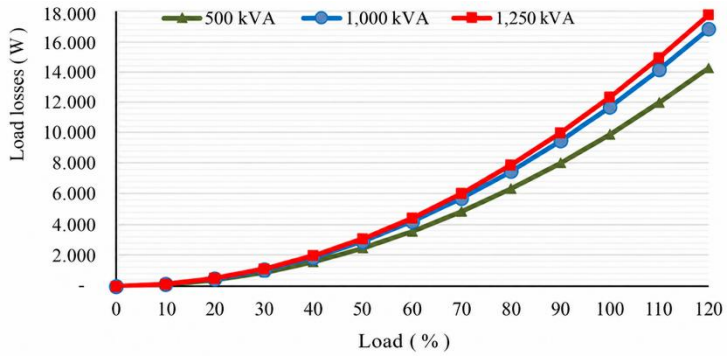

Figure 3. Relationship between load percentage and measured load losses of the investigated distribution transformers

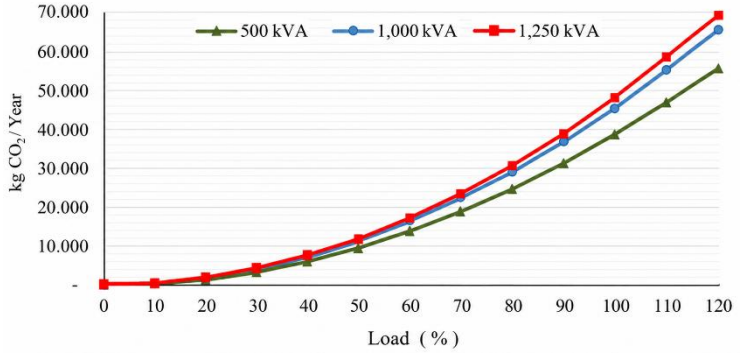

Figure 4. Estimated annual greenhouse gas emissions associated with transformer power losses under different loading conditions

3.2. Engineering-economic analysis and interpretation

In this investigation, three transformers with ratings of 500 kVA, 1,000 kVA, and 1,250 kVA (3-phase, 50 Hz, 22 kV–400/230 V) were analyzed under constant load conditions for their service life of 15 years. The analysis used interest rates of 6% and 8%, corresponding to the average loan interest rates of Thai commercial banks in early 2025 [16]. It was predicted that each transformer would provide electricity for 8,760 hours annually, with a constant load operation of 8,000 hours per year. Based on the rate in 2025, the price of energy was fixed at 4.15 THB/unit, and the demand charge was 2,355.12 THB/kW per year. The transformers were assessed under a constant load of 1,000 kVA for 8,000 operating hours, and the PW was computed using (6). The no-load and load losses were obtained from Table 1, and the resulting parameters for cost evaluation are summarized in Table 3.

Parameters given in Table 3 were then used to calculate the quantities determined by (7)-(9) and (11). The parameters presented in Table 3 were subsequently used to calculate the quantities defined by (7)-(9) and (11). These parameters represent the key economic and operational variables required for the engineering-economic assessment of the investigated transformers. The calculated results are summarized in Table 4 and serve as the basis for evaluating COT and efficiency under the specified operating conditions.

Based on the load supplied by the transformer (the ratio of actual load to rated load) with a capacity of 1,000 kVA, the comparison of the transformer cost and efficiency for the 500 kVA, 1,000 kVA, and 1,250 kVA units can be made, as illustrated in Table 5. The comparison provides a direct assessment of the economic and technical performance of the transformer alternatives under identical operating conditions. These results are useful for identifying the most suitable transformer size from both economic and efficiency

perspectives. The results indicate that transformer sizing significantly affects both technical and economic performance. As shown in Table 4, increasing the interest rate from 6% to 8% lowers the transformer ownership cost for all investigated transformer sizes. This behavior is ascribed to the decrease in the PW factor at higher interest rates, which results in a decrease in the present value of future operating expenses. Nevertheless, the relative ranking of the transformer alternatives remains unchanged under both interest-rate conditions.

Clearly, the results show that transformer sizing plays a significant role in both technical and economic performance. The 1,250 kVA transformer has the highest rated capacity and initial investment cost. However, it has the highest efficiency (99.22%) and the lowest COT under the tested operating conditions. This finding suggests that improvements in transformer efficiency can counterbalance higher capital expenditure by lowering energy losses and lifecycle operating costs. In contrast, the 1,000 kVA transformer has the lowest efficiency, resulting in higher energy losses and a larger ownership cost. The results also indicate that the economic advantage of the 1,250 kVA transformer becomes more obvious when long-term operating costs and environmental impacts are considered.

Furthermore, the greenhouse gas emissions as well as transformer losses increase with increasing power losses, as illustrated in Figure 4. Therefore, transformers with higher efficiency not only provide economic benefits but also promote the reduction of the environmental impacts throughout their service life. These findings clearly point out that transformer selection should not be based solely on the initial purchase cost. Instead, transformer efficiency, energy losses, ownership costs, and environmental impacts should be considered simultaneously to achieve the most suitable balance between technical performance, economic feasibility, and environmental sustainability.

Table 3. Important parameters utilized in the analysis of 500 kVA, 1,000 kVA, and 1,250 kVA D transformers

Parameter	500 kVA	1,000 kVA	1250 kVA
C (THB)	310,000.00	421,800.00	520,950.00
FC (%)	5.00	5.00	5.00
I (%)	6, 8	6, 8	6, 8
Service life of a transformer (year)	15.00	15.00	15.00
PW (6%)	9.712	9.712	9.712
PW (8%)	8.559	8.559	8.559
Lc (kW)	0.838	1.252	1.950
Lw (kW)	4.949	11.690	12.338
Tc (H)	8,760.00	8,760.00	8,760.00
Tw (H)	8,000.00	8,000.00	8,000.00
Ce (THB)	4.15	4.15	4.15
Cd (THB/Year)	2,355.12	2,355.12	2,355.12
D (kVA)	500×2 (1.00)	1,000 (1.00)	1,250 (0.80)

Table 4. Calculated parameters used in the analysis of the 500 kVA, 1,000 kVA, and 1,250 kVA transformers

Parameter	500 kVA	1,000 kVA	1250 kVA
K_c	38,709.12	38,709.12	38,709.12
K_w	35,555.12	35,555.12	22,755.28
COT (THB) 6%	2,484,521.96	5,133,996.08	4,233,700.84
COT (THB) 8%	2,226,364.65	4,574,568.35	3,792,926.37
Efficiency (η) (%)	98.86	98.72	99.22

Table 5. Comparison of COT and efficiency for the 500 kVA, 1,000 kVA, and 1,250 kVA transformers at interest rates of 6% and 8%

kVA	COT at 6% interest rate (THB)	COT at 8% interest rate (THB)	Transformer efficiency (%)
500	4,969,043.92	4,452,729.30	98.86
1,000	5,133,996.08	4,574,568.35	98.72
1,250	4,233,700.84	3,792,926.37	99.22

3.3. Practical implications, limitations, and future work

The findings of this study are generally in good agreement with previous investigations employing TOC and LCC approaches for transformer evaluation [1]-[5]. Previous studies have shown that transformer efficiency and energy losses strongly influence long-term ownership costs and investment decisions. The present study confirms these observations using experimentally measured transformer losses obtained from standard open-circuit and short-circuit tests. Unlike conventional TOC and LCC approaches, which mainly focused on economic evaluation, the proposed approach includes experimentally observed transformer losses, engineering-economic analysis, and environmental cost assessment. Consequently, a more comprehensive evaluation framework is provided for transformer selection under practical operating conditions.

From a practical perspective, the proposed methodology can assist engineers, industrial facilities, and project developers in selecting transformer sizes based on technical, economic, and environmental considerations. The integration of experimentally measured transformer losses with ownership cost and environmental assessments allows for a more accurate evaluation of transformer performance over its service life [24], [25]. As a result, the proposed approach can support more informed investment decisions and contribute to improved energy efficiency and sustainable energy management. In addition to economic benefits, the reduction of transformer losses contributes directly to lower greenhouse gas emissions associated with electricity generation. Consequently, the proposed methodology may support industrial energy-efficiency initiatives and broader sustainability objectives through the selection of transformer sizes that minimize energy consumption, lifecycle costs, and environmental impacts.

Nevertheless, several limitations must be considered. The current analysis was conducted under constant load conditions and considered only three conventional transformer sizes commonly utilized in industrial electrical systems. In addition, the analysis was based on fixed electricity tariffs, interest rates, and service life assumptions. Furthermore, the proposed methodology was applied to the selection of individual transformers and did not consider feeder-level or substation-level optimization involving multiple transformers operating simultaneously within electrical distribution networks. Therefore, the obtained results may differ depending on the operating environments, electricity pricing structures, loading conditions, and load configurations.

Future studies should investigate the influence of variable load profiles, renewable energy integration, distributed generation, EV charging infrastructure, and dynamic electricity pricing on transformer ownership costs and performance. In addition, the proposed methodology may be extended to support transformer sizing and selection in smart grid applications, where transformer loading conditions are influenced by bidirectional power flow, demand response strategies, and load balancing requirements. Future investigations may also expand the analysis to feeder-level and substation-level optimization involving multiple transformers operating within electrical distribution systems. Such studies may provide additional insights into transformer coordination, load allocation, operational efficiency, and lifecycle cost optimization at the system level. Furthermore, the proposed methodology may be expanded to include high-efficiency transformer technologies, thermal behavior, insulation aging, and reliability-related factors for a more comprehensive assessment of transformer selection and long-term operational performance.

4. CONCLUSION

This study introduced a novel comprehensive engineering-economic evaluation approach for distribution transformers by considering engineering-related operational expenses, experimentally measured transformer losses, and environmental impact assessment. Three commonly utilized transformer sizes of 500 kVA, 1,000 kVA, and 1,250 kVA (3-phase, 50 Hz, 22 kV–400/230 V) were investigated under comparable operating conditions to determine the most suitable transformer size for industrial applications.

The analysis clearly indicates that the major variables affecting the total cost include electricity cost, demand charge, initial transformer price, and power losses. These variables simultaneously contribute to environmental costs. In addition, reducing transformer losses contributes directly to lower greenhouse gas emissions associated with electricity generation. Therefore, the proposed methodology may support industrial energy-efficiency initiatives and broader sustainability objectives through the selection of transformer sizes that minimize energy consumption, lifecycle costs, and environmental impacts. The study shows that higher interest rates contribute to reduced PW factors for a transformer load capacity of 1,000 kVA, which subsequently reduces the cost of transformer ownership. In addition, using two 500 kVA transformers in parallel to supply a 1,000 kVA load results in a lower overall cost as compared to operating a single 1,000 kVA transformer. The 1,250 kVA transformer had the best economic performance for the given operating parameters and the lowest total cost among the three transformer sizes studied. The proposed approach is effective in the evaluation of the transformer performance and offers useful information for the selection of the proper transformer size according to specific operational and economic requirements. Nevertheless, this investigation was conducted under certain operating assumptions, including a fixed cost of power, constant load conditions, and a limited number of transformer sizes. Thus, the obtained findings may vary according to operational environments and electricity pricing systems. To further enhance the economic evaluation methodologies and transformer selection for industrial power systems, future studies should focus on other transformer capacities, load profiles, renewable energy integration, distributed generation, electric vehicle (EV) charging infrastructure, and dynamic electricity pricing conditions. Furthermore, the proposed methodology may be extended to support transformer sizing and selection in smart grid applications, where transformer loading conditions are influenced by bidirectional power flow, demand response strategies, and load-balancing requirements. Future investigations may also expand the analysis to feeder-level and substation-level optimization involving multiple transformers operating simultaneously within electrical

distribution networks. Such studies may provide additional insights into transformer coordination, load allocation, operational efficiency, lifecycle cost optimization, and sustainable power system planning under real-world operating conditions.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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C : **C**onceptualization
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R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

This research presents no conflicts of interest whatsoever.

DATA AVAILABILITY

This research can be applied to accurately and quickly evaluate the cost of distribution transformers of various sizes.

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