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RESEARCH ARTICLE

Specification Design and Techno-Economic Analysis of Green Distribution Transformers with Amorphous Iron Cores and Natural Ester Oil for Sustainable Power Systems

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Abstract

The initiatives for renewables and energy efficiency necessitates upgrading the design of distribution transformers, which still rely on petroleum-based mineral oil and contribute significantly to network losses. This research focuses on the design, development, and testing of a novel green distribution transformer. Green distribution transformers are defined as transformers that utilize environmentally friendly natural ester insulation oil and high-energyefficiency amorphous iron cores. The design of the transformer is determined based on key characteristics and appropriate technical specifications and construction requirements, including the setting of new, very low no-load loss and load loss limit values. The prototype was developed and rigorously tested to assess its compliance with technical standards and evaluate its performance. The results demonstrate that the green distribution transformer meets the required specifications and exhibits significantly lower losses. A comprehensive economic analysis using total cost of ownership, considering the initial cost and operating costs, reveals that the green distribution transformer offers a lower total cost of ownership over its lifetime compared to conventional transformers. These findings highlight the potential of green distribution transformers to contribute to a more sustainable and efficient power grid.

Keywords: green distribution transformer, natural ester oil, amorphous iron core, energy efficiency, total cost of ownership, transformer design, transformer testing, sustainable energy

1. Introduction

Global climate change has prompted many countries to prioritize achieving net-zero emissions [1]. As part of initiatives to reduce carbon emissions, electrical power utilities are increasingly adopting renewable materials in every possible aspect and implementing strategies to improve power efficiency by minimizing losses in electricity networks [2], [3]. Distribution transformers, a critical component of the electrical grid, still rely on petroleum-based mineral oil and contribute approximately 9–10% of total distribution network losses [4], therefore, requiring significant upgrades.

This research aims to design, develop, and test a novel green distribution transformer. Green distribution transformers are defined as transformers that utilize environmentally friendly natural ester insulation oil and high-energy-efficiency amorphous iron cores. A prototype of this green distribution transformer will be designed, developed, and rigorously tested to verify compliance with technical standards and assess its overall performance. To ensure widespread adoption, a comprehensive economic analysis will be conducted to evaluate the financial feasibility of the green distribution transformer compared to conventional one. The findings of this research are expected to contribute to the development of standardized specifications for green distribution transformers, accelerating the transition towards a more sustainable and resilient power grid.

While numerous studies have investigated the use of natural ester oil and amorphous iron cores in distribution transformers, these studies have typically focused on each technology separately. A study integrating both technologies within a single transformer unit remains limited.

Reference [5] has already explored the combined use of an amorphous core and vegetable insulating oil in distribution transformers, including prototype development, technical and economic feasibility studies, and several performance tests. However, the previous research did not design the distribution transformer based on specific requirements to develop it into a standardized market-ready product. The tests conducted also were limited and did not fully comply with international standard methods.

This research aims to address these gaps by comprehensively designing green distribution transformers with detailed specifications that align with market demands, developing the prototype according to factory standards using commercially available components (including the iron core and insulating oil), conducting complete type tests based on international standards—including the lightning impulse test, direct applied short circuit withstand test, and sound power level measurement test—and performing a more comprehensive economic analysis of the novel green distribution transformer. These enhancements will represent a significant step forward in bridging the gap between existing studies and the practical implementation of green distribution transformers.

This paper is structured into seven sections. Section 1 introduces the research background. Section 2 delves into the key characteristics of green distribution transformers. Section 3 presents the design specifications, while section 4 discusses the development of a prototype. Section 5 outlines the testing procedures and results. Section 6 conducts economic analysis.

Finally, section 7 summarizes the key findings and proposes future research directions.

2. Key characteristics of green distribution transformers

2.1 Natural ester oil

The primary component targeted for substitution in distribution transformers is the insulation oil. Conventional transformers typically rely on petroleum-based mineral oil, which is not environmentally friendly due to its non-biodegradable properties [6] and its waste is classified as hazardous waste.

Transformer insulation oil serves dual purposes: cooling and insulating the transformer. To effectively fulfill these roles, it must possess specific properties, including high dielectric strength, low viscosity, high flash point, extremely low water content or moisture, and high specific resistivity [7].

Natural ester oil, derived from plants like sunflower, soybean, canola, jatropha, and palm plants, offers sustainable and environmentally friendly and possesses all the fundamental properties of transformer oil [7]. Natural ester oil is fully biodegradable, non-toxic nature, and its status as a sustainable, carbon-neutral resource [8]. Natural ester oil also exhibits characteristics suitable for transformer applications [9]. Therefore, natural ester is a superior alternative to conventional mineral oil.

Another advantage of natural ester oil is its significantly higher flash and fire points compared to conventional mineral oil, classifying it as a "K-class" fluid. A drawback of natural ester oil is its higher water saturation limit, allowing it to absorb more water. However, due to its hygroscopic nature, water remains in liquid form and does not migrate into solid insulation, thereby extending the life of the solid insulation. Also, the poor oxidation stability of natural ester oil necessitates special care and sealed tank construction [7].

2.2 Amorphous steel core

To attain the high efficiency of green distribution transformers, amorphous iron cores are necessary. Distribution transformers with amorphous iron cores exhibit energy-efficient characteristics due to the atomic structure and thinness of amorphous iron-based metal. The random molecular structure of amorphous metal results in lower friction when a magnetic field is applied [10] so that no-load losses (i.e. hysteresis and eddy current) in transformers can be reduced. Amorphous iron cores possess excellent magnetic properties: low coercivity, high permeability, and high electrical resistivity, making them highly suitable for use as transformer cores [11].

With very thin amorphous metal laminations of approximately 0.03 mm [11], eddy current losses are significantly reduced. On the other hand, the atomic structure of amorphous metal alloys results in a low magnetic flux density saturation value. Another feature of amorphous material is its single-stage manufacturing process, which significantly reduces production costs [10].

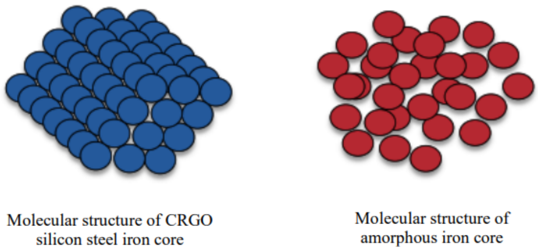

Figure 1. Molecular structure of iron core material

Core losses of amorphous metal-core distribution transformers are approximately 25-30% of conventional transformers with cold-rolled grain-oriented (CRGO) silicon steel cores [10]. Amorphous cores can reduce no-load losses by up to 70% and enable the construction of highly efficient distribution transformers [12].

Amorphous metal cores also require magnetic annealing to achieve the lowest possible losses and excitation level, but this process makes the material brittle [13]. To overcome the brittleness of the material, epoxy coating is then applied to some parts of the core to improve mechanical stiffness. Amorphous metal laminations can be assembled into three-phase transformer cores into either 5-leg or 3-leg core groups (see Figure 2) [10]. Figure 3 shows the appearance of amorphous metal sheets and various types of amorphous core designs.

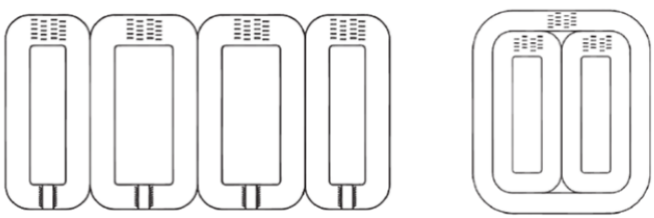

Figure 2. Types of 5-leg and 3-leg core groups [10]

Figure 3. Examples of constructed amorphous cores [14]

2.3 Loss limits of the green distribution transformers

The determination of loss limits is important when it comes to the design of green distribution transformers, which in theory is designed to exhibit very low losses. The losses consist of no-load loss and load loss, which should be minimized while at the same time still being practical to be manufactured.

As a starting point, the main reference standards for transformer specifications currently used worldwide is standard of International Electrotechnical Commission (IEC) 60076-20: 2017 [15] and for Indonesia is Standar Perusahaan Listrik Negara (SPLN) D3.002-1: 2020 [16], were consulted. The loss limit values stated on both standards are shown in Table 1.

Table 1. Transformer loss specifications according to IEC and SPLN standards

No	Transformers capacity [kVA]	IEC 60076-20: 2017 Level 1		IEC 60076-20: 2017 Level 2		PLN Standard SPLN D3.002-1: 2020	
		NLL [W]	LL [W]	NLL [W]	LL [W]	NLL [W]	LL [W]
1	50	90	1100	81	750	90	800
2	100	145	1750	130	1250	145	1420
3	160	210	2350	189	1750	210	2000
4	250	300	3250	270	2350	300	2750

Note:
NLL: no-load loss in watt [W]
LL: load loss in watt [W] at nominal current

The IEC and SPLN standards set loss limits for conventional distribution transformers that are not specifically designed for low losses performance. In IEC 60076-20: 2017, there are two classes of loss limit values, Level 1 and Level 2, with Level 2 having lower limits. In SPLN, the no-load loss limit refers to the same as IEC Level 1, while the load loss sets its own value. For green distribution transformers, much lower loss limits are required.

The following on the Table 2 are references from the global market and scientific articles in related journals on loss limits for three-phase distribution transformers with a rated power of 100 kVA that are designed for low losses characteristic using amorphous iron cores.

Table 2. References for losses of 100 kVA distribution transformers with amorphous iron cores

References	NLL [W]		Remarks
China, GB 20052-2020 [17]	60	1270 (Al)	Energy efficiency Grade 1 (highest)
United Kingdom, EN 50588-1: 2015 [18]	75	1250 (Al)	AAA0Ak (most efficient)
Japan [19]	67	1210 (Al)	EX- α
India, IS 1180 (Part 3): 2021 [20]	NL + LL = 1242		STAR 4
Thailand [21]	75	1250 (Al)	"Super low loss transformers"
Vietnam [22]	75	1258 (Al)	Three phase oil immersed amorphous transformers
Ferranti-Packard Ltee research [23]	50	826 (Cu)	-
Note NLL: no-load loss in watt [W] LL: load loss in watt [W] at nominal current Al: using aluminum windings Cu: using copper windings			

Based on this data, the subsequent section will detail the specific numerical values selected to serve as the reference for designing green distribution transformers.

3. Determining the specification design of green distribution transformers

While the design specifications for green distribution transformers are generally similar worldwide, the specifications presented here are tailored to meet the specific requirements of the Indonesian electrical grid.

3.1 Iron core and insulating oil

3.1.1 Amorphous iron core

The energy-efficient green distribution transformer is designed using an amorphous iron core. The amorphous iron core, characterized by its random molecular structure and extremely thin metal laminations, significantly reduces no-load losses such as hysteresis and eddy current losses. With the ability to reduce losses by up to 70% compared to conventional CRGO silicon steel cores, green distribution transformers with amorphous iron cores can achieve exceptionally low no-load losses [10]. Additionally, amorphous iron cores possess low coercivity, high permeability, and high electrical resistivity [11].

3.1.2 Natural ester insulating oil

As a key feature of the environmentally friendly green distribution transformer, natural ester insulating oil is utilized. For this prototype, commercially available natural ester oil was selected. The chosen oil has been confirmed to be biodegradable and non-toxic. Additionally, the insulating oil used has been tested to have a high flash point and is classified as a K-class fluid. The complete properties of the insulating oil used are as follows in the Table 3.

Table 3. Properties of insulating oil for prototype [24]

Test Item	Unit	Test Method	Specification	Typical Data
Specific gravity (15 / 4°C)	-	ASTM D 1298	≤0.96	0.9207
Kinematic viscosity (40°C)	mm^2/s	ASTM D 445	≤50.0	34.01
Kinematic viscosity (100°C)	mm^2/s	ASTM D 445	≤15.0	7.801
Flash point	°C	ASTM D 92	≥300	324
Fire point	°C	ASTM D 92	≥320	330
Pour point	°C	ASTM D 97	≤-20.00	-24.0
Total acid value	mg KOH/g	ASTM D 974	≤0.06	0.040
Dielectric strength (2.0mm)	kV	ASTM D 1816	≥40.0	74.2
Water content	mg/kg	ASTM D 1533	≤200	≤40
Fish, acute toxicity test	-	OECD TG 203	No dead Fish	No dead Fish
Biodegradation	%	OECD 301 F	≥70	≥80
Polychlorinated biphenyls (PCBs)	mg/kg	KS C 2375	Not detected	Not detected

3.2 Technical specifications

3.2.1 Rated power, vector group, voltage, and frequency

In Indonesia, newly installed three-phase distribution transformers commonly have ratings of 50 kVA, 100 kVA, 160 kVA, 250 kVA, 400 kVA, and 630 kVA. Among these, 100 kVA transformers are the most common, accounting for approximately 30% of new installations. The 100 kVA distribution transformers are typically produced in two vector groups: Yzn5 and YNyn0. While Yzn5 is the more common, YNyn0 is specifically installed for systems with solidly grounded neutrals. The Yzn5 distribution transformers also present higher production complexity, which provides a more challenging and comprehensive case study for analysis. Therefore, in this research, as the scope, rated power of 100 kVA and Yzn5 was selected for the new developing green distribution transformers specification design.

Referring to the applicable voltage standards in Indonesia, the rated voltage of the green distribution transformer is 20 kV for the primary voltage and 400 V for the secondary voltage. The voltage tap uses a 2.5% tap step with 7 steps, with tap number 3 being the main tap, so the tap range is +2×2.5%, −4×2.5% [16]. The impedance voltage at the main tap is 4%, at a reference of 75°C with a tolerance of ± 10%. The rated frequency is 50 Hz, in accordance with the operating frequency of the Indonesian electrical system.

3.2.2 No-load and load loss limit

This research selects a design for 100 kVA green distribution transformers with a no-load loss (NLL) of 50 W, the lowest value from Table 2. Similarly, the load loss (LL) will be set at 1200 W, the rounded-down value of 1210 W, the lowest achievable loss using aluminumwindings as indicated in Table 2. Using these specified values, Table 4 compares the percentage reduction in losses compared to conventional transformers.

Table 4. Percentage reduction in 100 kVA distribution transformers losses

Green distribution transformers		Reduction compared to IEC 60076-20: 2017 Level 1		Reduction compared to SPLN D3.002-1: 2020	
No-load loss [W]	Load loss [W]	No-load loss	Load loss	No-load loss	Load loss
50	1200	65.5 %	31.4 %	65.5 %	15.5 %

3.2.3 Insulation class and temperature rise

Green distribution transformers, which utilize natural ester oil and rely solely on natural convection cooling for both the fluid and air, are classified as "KNAN" cooling-type that offer higher heat resistance. However, distribution transformers are rarely overloaded, and increasing the insulation class would require the use of thermally upgraded paper (TUP), which would increase production costs. Therefore, the maximum temperature rise limits for these green transformers will have the maximum temperature rise limit refers to the limit values for conventional transformers as stated in SPLN D3.002-1: 2020 [16], which is 50 K for the top oil and 55 K for the average winding.

3.2.4 Noise level

Amorphous core transformers inherently produce higher noise levels compared to CRGO silicon steel core transformers due to their extremely thin laminations, which cause higher vibrations magnitude and subsequently louder noise [25]. However, to maintain customer comfort regarding transformer humming noise, the noise level limit for green distribution transformers is set equal to that of conventional transformers. Referring to SPLN D3.002-1: 2020 [9], the maximum averaged A-weighted sound power level ($\overline{L_{WA}}$) under no-load conditions for a 100 kVA distribution transformer is 51 dB. To enhance quality and mitigate risks associated with the higher noise susceptibility of amorphous cores, noise level testing is conducted under 105% of the rated voltage at no-load conditions.

3.3 Construction requirement

The construction of the 100 kVA Yzn5 green distribution transformer will have the following general construction:

1. The transformer unit is designed for outdoor installation.
2. Weight $\leq$ 1000 kg to allow installation on a single pole substation structure.
3. Length dimension < 1200 mm to allow center installation on a twin pole substation structure.
4. The tank system used is hermetically sealed – fully filled, where the oil fills the entire empty space inside the tank.

The whole construction of the green distribution transformer will be similar to conventional distribution transformers, but the dimensions will be larger due to the lower magnetic saturation of the amorphous steel core compared to silicon steel cores. In addition, to obtain lower winding losses, it will be necessary to use windings with a larger cross-sectional area. Consequently, a larger tank and more insulating oil will be required.

3.4 Components

The green distribution transformer is equipped with the following components: high voltage bushing, low voltage bushing, bushing connector, oil filler pipe, oil level indicator, overpressure protection, tap changer, thermometer pocket, grounding terminal, oil drain, lifting lug, hanger, and surge arrester support

4. Prototyping the green distribution transformers

A green distribution transformer prototype was successfully developed through a research and development collaboration with an Indonesian transformers manufacturer. The transformer specifications fully comply with the designed specification, primarily utilizing natural ester oil and exhibiting very low losses.

Figure 4 and Figure 5 show the appearance of the completed green distribution transformer prototype and its nameplate

Figure 4. Green distribution transformer prototype

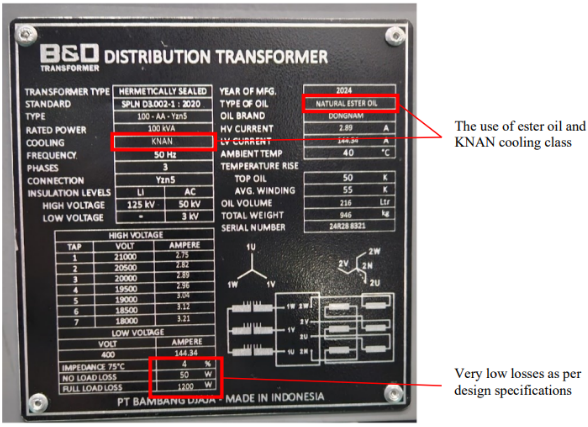

Figure 5. Nameplate of the green distribution transformer prototype

The technical data of the developed green distribution transformer prototype is presented in Table 5.

Table 5. Technical data of the developed green distribution transformer prototype

No.	Descriptions	Specifications
1	Rated power	100 kVA
2	Rated frequency	50 Hz
3	Vector group	3 (three)
4	Rated voltage	Yzn5
5	Rated current	Primary: 20 kV (+2x2.5%; -4x2.5%) Secondary: 400 V
6	Rated current	Primary: 2.89 A Secondary: 144.34 A
7	Impedance	4%
8	Winding conductor material	Primary: Aluminum Secondary: Aluminum
9	Cooling method	KNAN
10	Type of oil	Natural ester
11	Oil volume	216 liters
12	Total weight	946 kg
13	No-load loss	50 W
14	Load loss	1200 W
15	Insulation levels	50 (3) / 125 kV
16	Temperature rise	Top oil: 50 K Average winding: 55 K
17	Year of manufacture	2024

To achieve a no-load loss of 50 W, the green distribution transformer was designed with several strategic and technical optimizations. This design incorporates an amorphous iron core with a lamination thickness of approximately 0.03 mm. The magnetic flux density was set at approximately 1.0 T to ensure efficient operation without reaching magnetic saturation, which also contributes to improved noise control. Additionally, the use of a 3-limb core type structure provides a shorter magnetic path and enhanced magnetic flux distribution, significantly reducing no-load losses. Its symmetric design minimizes vibration and mechanical stress, resulting in quieter and more reliable operation.

To achieve a load loss of 1200 W, the green distribution transformer utilizes aluminum windings with a larger cross-sectional area, increasing the total winding weight to 140% compared to conventional transformers with a load loss of 1420 W.

The dimensional data of the green distribution transformer prototype is shown in Table 6.

Table 6. Dimensional data of the green distribution transformer prototype

No.	Description	Specifications
1	Total height	1420 mm
2	Tank height	945 mm
3	Total width	810 mm
4	Total length	1085 mm

In addition to technical specifications, it is important to assess the manufacturing cost of the prototype. Determining the manufacturing cost of a green distribution transformer based on a single prototype is challenging due to the variability in material and process costs. Since the prototype was not produced on a mass production line, an estimated cost was calculated based on the increased material costs compared to conventional transformers.

Table 7 presents the data used to calculate the cost increase of the green transformer compared to a conventional transformer.

Table 7. Data inputs for cost calculation of the green distribution transformer prototype

Components	Conventional transformer		Cost increase in green transformers
	Percentage of cost composition	Base cost	
Iron core	40%	100%	65 %
Winding conductor	30%	100%	40 %
Oil	10%	100%	220 %
Tank and others	20%	100%	55 %

Based on this data, the manufacturing cost of the green distribution transformer prototype is estimated to be 171% higher than that of a conventional transformer. Using Indonesian market price for a 100 kVA Yzn5 conventional distribution transformer (comply to SPLN D3.002-1: 2020) as a reference at Rp44,500,000, the estimated cost of the green transformer is Rp76,095,000. This number will be used for calculating the cost capitalization.

It's important to note that this estimated cost for the prototype does not account for potential efficiencies in material pricing, production processes, design optimization, or competitive bidding.

5. Testing the green distribution transformer prototype

The 100 kVA–Yzn5 green distribution transformer prototype was subjected to a comprehensive type test to assess its technical compliance. The test was conducted in an accredited short-circuit laboratory owned by PLN Indonesia. The test results are summarized in Table 8.

Table 8. Test results of the green distribution transformer prototype

No	Test item	Methods/Procedures	Results
1	Measurement of voltage ratio and check of phase displacement	IEC 60076-1: 2011 subclause 11.3 [26]	Passed, Yzn5
2	Measurement of winding resistance	IEC 60076-1: 2011 subclause 11.2	Passed
3	Measurement of no-load loss and current	IEC 60076-1: 2011 subclause 11.5	No-load loss: 51 W No-load current: 0.550 A
4	Measurement of short-circuit impedance and load loss	IEC 60076-1: 2011 subclause 11.4	Impedance: 4.00 % Load loss: 1057 W
5	Dielectric test - Inductanced voltage test - Applied voltage test - Insulation resistance test	IEC 60076-3: 2018 [27].	Passed Passed >4 GΩ
6	Sound power level measurement	IEC 60076-10: 2016 [28].	$\overline{L_{WA}}$ at 105 % nominal voltage: 50.1 dB
7	Short circuit withstand test	IEC 60076-5: 2006 subclause 4.1 dan 4.2 [29]	Passed
8	Lightning impulse test	IEC 60076-3: 2018	Passed
9	Temperature rise test	IEC 60076-2: 2011 [30]	Top oil: 28.5 K HV windings: 32.9 K LV windings: 36.2 K
10	No-load energize test	105% rated voltage at no load, 2 hours	Passed

5.1 Measurement of voltage ratio and check of phase displacement

The voltage ratio measurement and vector group verification were conducted according to IEC 60076-1:2011 subclause 11.3 [26], with an allowable deviation at the nominal tap of the lesser value between 10% of the impedance or 0.5%. The results in Table 7 confirm that the green distribution transformer prototype meets the standard requirements for voltage ratio deviation and correctly adopts the Yzn5 vector group.

Table 9. Voltage ratio deviation and vector group

Tap number	Deviation [%]			Requirement
	1U - 1V 2n - 2u	1V - 1W 2n - 2v	1W - 1U 2n - 2w	
1	0.03	0.05	0.06	-
2	0.00	0.02	0.00	-
3	0.00	0.00	-0.01	± 0.4
4	-0.03	-0.03	-0.03	-
5	0.01	0.02	0.02	-
6	0.05	0.06	0.06	-
7	0.06	0.07	0.07	-
Polarity/voltage vector				Yzn5

5.2 Measurement of winding resistance

The winding resistance measurement was conducted to verify the high-voltage winding resistance at all taps and the low-voltage winding resistance at all terminals, following IEC 60076-1:2011 subclause 11.2 [29]. The results, corrected to 75°C, are presented in Table 10, showing that the green distribution transformer prototype has normal winding resistance.

Table 10. Winding resistance

High voltage winding resistance (at 75°C)							
Terminals	Results [ohm] at each tap						
	1	2	3	4	5	6	7
1U - 1V	43.451	42.272	41.116	39.959	38.803	37.685	36.504
1V - 1W	43.685	42.499	41.337	40.177	39.014	37.889	36.708
1W - 1U	43.552	42.370	41.215	40.052	38.895	37.774	36.598
Low voltage winding resistance (at 75°C)							
Terminals	Results [m.ohm]			Terminal	Results [m.ohm]		
2u - 2v	15.8578			2u - 2n	8.0813		
2v - 2w	15.9445			2v - 2n	8.0965		
2w - 2u	15.9293			2w - 2n	8.1217		

5.3 Measurement of no-load loss and current

The no-load loss and current measurements of the distribution transformer were conducted following IEC 60076-1:2011 subclause 11.5. The high-voltage side was left open while the lowvoltage side was energized to its nominal voltage, and the current and power were recorded. This test also determined the transformer's no-load current. The measurement results for the green distribution transformer are presented in Table 11.

The test results show that the green distribution transformer prototype produced a no-load loss of 51 W, slightly above the target of 50 W but still within the ±15% tolerance limit set by IEC 60076-1:2011 [26]. Therefore, the no-load loss measurement meets the standard requirements. This result is satisfactory as it closely approaches the lowest reference value reported by Ferranti-Packard Ltee [23]. It also indicates that the specified design limits are optimal, presenting manufacturing challenges that remain achievable.

Table 11. No-load loss and current

Testing voltage (phase - neutral) mean	rms	Measured power	Correction	No-load loss		No-load current	
V	V	W	-	W	%	A	%
231.0	231.2	50.6	0.9987	51	0.05	0.550	0.38
Requirement, maximum (±15% tolerance)				50	0.05		

A 1 W deviation is acceptable at this development stage due to production limitations typical in prototypes compared to mass-produced conventional units. Challenges include limited technical experience with amorphous iron core materials and the need for further production process optimization. Continuous improvements are expected to achieve more precise no-load loss values in future production stages.

5.4 Measurement of short-circuit impedance and load loss

The impedance and load loss measurements of the distribution transformer were conducted following IEC 60076-1:2011 subclause 11.4. The low-voltage side was short-circuited, and the high-voltage side was supplied with nominal current. Voltage and power were recorded under these conditions, allowing the impedance to be determined. The load loss measurement results for the green distribution transformer are presented in Table 12.

Table 12. Load loss and impedance

	I^2R loss at 75°C		Stray losses at 75°C	Load losses at 75°C		Impedance at 75°C	
	Primary	Secondary					
Tap number	W	W	W	W	%	V	%
1	493.8	497.2	44.9	1036	1.04	854.9	4.07
3	515.4	497.2	44.7	1057	1.06	799.9	4.00
7	565.0	497.2	43.8	1106	1.11	697.0	3.87
Requirements, maximum (Tap 3)				1200	1.2	-	4.0

The test results show that the green distribution transformer prototype achieved an excellent load loss of 1057 W, well below the target of 1200 W. Additionally, the impedance voltage at 75°C met the specification at 4.0%. These results confirm that the prototype meets the required standards for load loss and impedance voltage.

5.5 Dielectric test

The distribution transformer underwent dielectric testing for resistance to induced overvoltage, power frequency overvoltage, and insulation resistance using direct current (DC), following IEC 60076-3:2018 [27]. The test results, presented in Table 13, Table 14 and Table 15, confirm that the green distribution transformer prototype successfully withstood induced and power frequency overvoltages and demonstrated good insulation resistance. Therefore, the prototype meets the required dielectric testing standards.

Table 13. Induced overvoltage test

Supply side	Test parameters	Results
Low voltage terminals	voltage: 800 V frequency: 200 Hz duration: 30 s	Good

Table 14. Power frequency overvoltage test

Tested side	Test parameters	Results
HV side - (LV side + earth)	voltage: 50 kV duration: 60 s	Withstood
LV side - (HV side + earth)	voltage: 3 kV duration: 60 s	Withstood

Table 15. Insulation resistance test

Tested side	Test parameters	Results [G.ohm]
HV side - LV side	DC voltage: 1000 V Ambient temp: 31°C	8.27
HV side - earth		4.85
LV side - earth		4.88

5.6 Sound power level measurement

Noise level testing was conducted to ensure the distribution transformer operates within acceptable noise limits, following IEC 60076-10:2016 [28]. The test involved applying excitation voltage to the transformer and measuring the sound pressure level using a sound level meter around the transformer body.

The results were processed according to standard formulas to obtain the average sound power level ($\overline{L_{WA}}$). The green distribution transformer prototype recorded an average background noise of 33.1 dB and a sound pressure level of 42.0 dB, with a corrected noise level of 41.3dB.

The average sound pressure level obtained was calculated into the sound power level as follows:

Average sound pressure level (L_{pAi})	41.3	dB
Measurement distance (S_0)	0.64	m
Tank height (h)	1.115	m
Measurement perimeter (l_m)	6.39	m
Measurement distance (S)		
$S=1.25.h.l_{m})	8.906	m^2
Sound absorption area (A)		
$A = \alpha.S_v = 0.25.900$	225	m^2
Test room quality factor (A/S)	25.26	
Environmental correction (K)		
$K = 10log(1 + \frac{4}{A/S})$	0.64	dB
Corrected average sound pressure level		
$\overline{L_{pA}} = 10log\left(\frac{1}{2}\sum_{i=1}^{N} 10^{0.1xL_{pAi}}\right) - K$	40.6	dB
Sound power level		
$\overline{L_{WA}} = \overline{L_{pA}} + 10log\left(\frac{S}{S_0}\right)$	50.1	dB
Requirement	$\leq$ 51 dB	

The results indicate that the measured sound power level of 50.1dB meets the standard requirement of $\leq$ 51dB.

5.7 Short circuit withstand test

The short-circuit withstand test was conducted to ensure the distribution transformer's structure is strong enough to withstand thermal and mechanical stresses caused by short-circuit currents. The test followed IEC 60076-5:2006, subclauses 4.1 and 4.2 [29]. With the testing circuit as shown in the Figure 6.

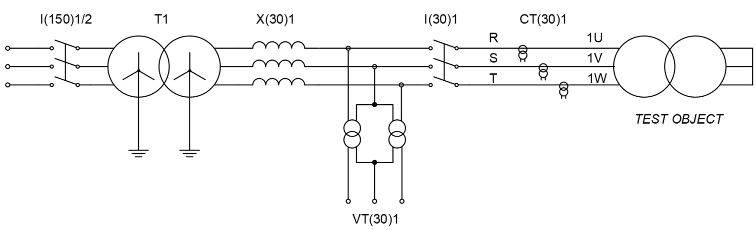

Figure 6. Short-circuit testing circuit diagram

The test was conducted by applying the transformer's nominal current at the nominal voltage with the requirement of peak current. The test was performed 9 times on three taps of each phase.

The test results are presented in Table 16. Based on the test results, it can be concluded that the green distribution transformer prototype is capable of withstanding short-circuit currents, both in terms of thermal and dynamic strength.

Table 16. Short-circuit withstand test results

No.	Test/Inspection	Results
1	Thermal capability	Good
2	Dynamic capability	
2.1	Short-circuit test	
	1) Tap 1 VLN= 12.1 kV, IRpeak=140A±5%, IR=68A±10%, 500ms	Good
	2) Tap 1 VLN= 12.1 kV, ISpeak=140A±5%, IS=68A±10%, 500ms	Good
	3) Tap 1 VLN= 12.1 kV, ITpeak=140A±5%, IT=68A±10%, 500ms	Good
	4) Tap 3 VLN= 11.5 kV, IRpeak=147A±5%, IR=72A±10%, 500ms	Good
	5) Tap 3 VLN= 11.5 kV, ISpeak=147A±5%, IS=72A±10%, 500ms	Good
	6) Tap 3 VLN= 11.5 kV, ITpeak=147A±5%, IT=72A±10%, 500ms	Good
	7) Tap 7 VLN= 10.4 kV, IRpeak=166A±5%, IR=83A±10%, 500ms	Good
	8) Tap 7 VLN= 10.4 kV, ISpeak=166A±5%, IS=83A±10%, 500ms	Good
	9) Tap 7 VLN= 10.4 kV, ITpeak=166A±5%, IT=83A±10%, 500ms	Good
2.2	Dielectric test after short-circuit test	Good
2.3	Short-circuit reactance change	Good, 0.28% – 0.67%
2.4	Condition inspection	Good
2.5	Internal discharge marks	None

5.8 Lightning impulse test

The distribution transformer underwent a standard lightning impulse withstand test in accordance with IEC 60076-3:2013 [27]. The test was conducted using a negative polarity impulse with a front time of 1.30 μs (within the criterion of 1.2 ± 30% μs) and a tail time of 46.80 μs (within the criterion of 40 ± 20% μs) at an impulse voltage of 125 kV.

The test results for the green distribution transformer prototype are presented in Table 17. Based on the test results, it can be concluded that the green distribution transformer prototype can withstand all applications of the standard 125 kV lightning impulse voltage.

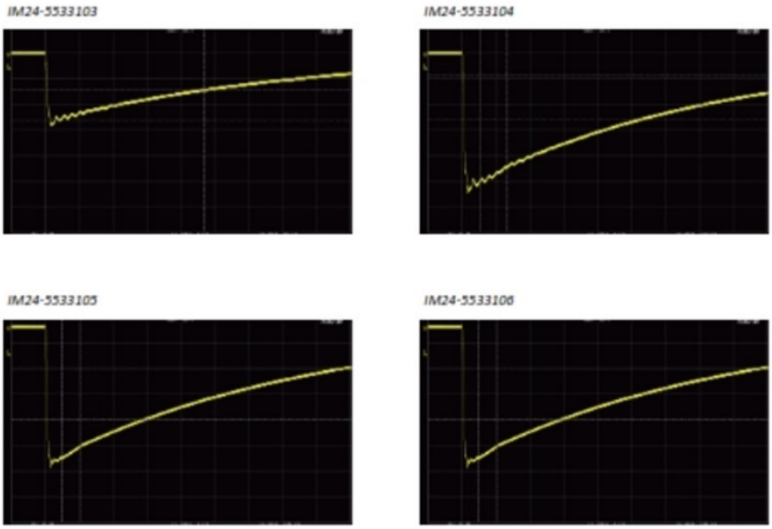

Figure 7. Impulse test voltage

Table 17. Lightning impulse withstand test

Tested winding	Number of applications	Test result
1U	1 × reduced test voltage 3 × full test voltage	Withstood
1V	1 × reduced test voltage 3 × full test voltage	Withstood
1W	1 × reduced test voltage 3 × full test voltage	Withstood

5.9 Temperature rise test

The temperature rise test was conducted to assess the heating characteristics of the distribution transformer under operational load, following IEC 60076-2:2011 [30]. The test involved injecting current and voltage until the measured power equaled the total losses, maintaining this condition for 3 × 1 hour until thermal saturation was reached. During this phase, the transformer's temperature and tank pressure were recorded.

Once thermal saturation was achieved, the load was reduced to match the nominal current at tap 7, causing the winding temperature and resistance to drop. By measuring the winding resistance at specific intervals, a resistance drop curve was obtained and extrapolated to accurately calculate the winding temperature at thermal saturation.

The test results of oil temperature rise and tank pressure for the green distribution transformer prototype can be seen in Table 18 and the average winding temperature rise test results for the green distribution transformer prototype can be seen in Table

19.

Table 18. Oil temperature rise at thermal saturation condition

No.	Descriptions	Result	Requirement
1	Top oil temperature rise [K]	28.5	$\leq$50
2	Oil average temperature rise [K]	22.8	-
3	Tank pressure [kPA]	23.43	<50

Table 19. Winding average temperature rise

No.	Descriptions	Result	Requirement
1	HV winding temperature rise [K]	32.9	$\leq$55
2	LV winding temperature rise [K]	36.2	$\leq$55

The test results showed that the top oil temperature rise reached 28.5 K, well below the maximum limit of 50 K. The average winding temperature rise was 32.9 K for the high-voltage winding and 36.2 K for the low-voltage winding, both below the maximum limit of 55 K. Additionally, the tank pressure during the test was recorded at 23.43 kPa, significantly lower than the standard limit of 50 kPa. After the temperature rise test, the transformer also withstood a no-load energization test for 2 hours at 105% of the rated voltage. Therefore, the green distribution transformer meets the standard requirements for the temperature rise test.

5.10 Testing conclusion

The green distribution transformer prototype can be considered to meet technical aspects as it has met all the requirements in the complete test items. In regards to the resulting losses after the test, the green distribution prototype exhibited a no-load loss slightly deviating from the target of 50 W, with a measured value of 51 W. For a prototype, this result is quite satisfactory as it nearly matches the value from the research of Ferranti-Packard Ltee [23]. However, this indicates that the design specifications were quite challenging to meet and suggests the need for improvements in the manufacturing process by the manufacturer so that the design target and final product have no errors. Meanwhile, the full-load loss obtained was very good at 1057 W, significantly below the target of 1200 W. This proves that it is technically feasible to have a green distribution transformer with very low losses.

6. Total cost of ownership calculation for distribution transformers

Green distribution transformers utilizing amorphous iron cores and natural ester insulating oil employ more expensive raw materials, resulting in a higher initial cost compared to conventional distribution transformers. Conversely, these transformers exhibit lower losses, leading to potential savings in operational costs. Therefore, a capital cost comparison between green and conventional distribution transformers is conducted using the total cost of ownership (TCO) method, which incorporates both the initial investment cost and the loss capitalization cost that calculates operating costs due to losses during the equipment's operation, calculated using the net present worth principle [15].

This loss capitalization method is considered the best method to optimize the economic efficiency of transformers. TCO provides better measures for comparing equipment with higher initial costs but higher efficiency resulting in lower operating costs [31]. By obtaining a comparison of these capitalized costs, the financial feasibility of purchasing a green distribution transformer compared to other conventional options can then be determined, facilitating ease of justification in the procurement process.

To be fully relevant, capitalization should be based on the estimated cost of energy for each year of the transformer's lifetime, and on the actual losses during this period, linking these future cash flows to the current value of money using an appropriate discount rate. The losses used for capitalization evaluation should include no-load losses, which are constantly active, and load losses, which vary due to the load [15].

Referring to IEC TS 60076-20: 2017 Annex A [15], the formulation of the TCO is defined as follows:

$$TCO = IC + [A \times (P_0 + P_{c0})] + [B \times (P_k + P_{cs} - P_{c0})] \tag{1}$$

Where:

IC : initial cost of the transformers

P_0 : no-load loss (kW), measured at the rated voltage and rated frequency, on the rated tap

P_{c0} : cooling power (kW) for no-load operation

P_k : load loss (kW) due to the load, measured at the rated current and rated frequency on the rated tap at a reference temperature

P_{cs} : cooling power (kW) for operation at the rated power

A: factor representing the cost capitalization of no-load losses (cost per kW)

B : factor representing the cost capitalization of the losses due to load (cost per kW)

No-load losses occur as soon as the transformer is energized. Therefore, the capitalization cost is the value of the losses power multiplied by the operating time throughout the entire service life of the transformer.

$$A = \Sigma_{j=1}^{n} O_{0j} \times C_j \times NPV_j \tag{2}$$

Where:

O_{0j} : operating time of the transformer at year j in h

C_j : valorization of the energy at year j in cost per Wh

NPV_j: net present value constant at year j

n : life expectancy of the transformer in years

The capitalization cost of load losses is obtained by summing up the load factor multiplied by the energy cost, and then adjusting for load growth and an increase in the number of transformers installed. In the following equation, losses are divided into two parts, with each part weighed based on its usage time.

$$B = \Sigma_{j=1}^{n} \mu \times C_j \times \left(O_{aj} \times T_{aj} + O_{fj}\right) \times \left(\frac{1 + C_{\mu j}}{1 + C_{aj}}\right)^{2j} \times NPV_j \tag{3}$$

Where:

μ : average load loss factor

C_j : total cost of the energy at year j in cost per Wh

O_{aj} : operating time of the transformer at variable load during year j in h

O_{fj} : operating time of the transformer at fixed load during year ke-j

T_{aj} : share of variable load in the total load loss factor at year j

T_{fj} : share of fixed load in the total load loss factor at year j

$T_{aj} + T_{fj} = 1$

n : life expectancy of the transformer in years

$C_{\mu j}$: rate of load loss factor increase at year j

C_{aj} : rate of installed power increase at year j

NPV_j: net present value constant at year j

The formula for calculating the net present value (NPV) in year j is given by:

$$NPV_j = \frac{1}{(1 + i_j)^j} \tag{4}$$

Where i_j is the discount rate at year j in per unit.

The TCO calculation can be simplified by making common assumptions such as a constant discount rate, a constant rate of energy cost increase, load is assumed to be fixed throughout the year, fixed load loss factor, fixed installed power, and a fixed load factor. The data used for the calculation in this research are assumed based on the manufacturer location of the transformer (i.e. Indonesia), as shown in Table 20.

Table 20. Data inputs for TCO calculation

No.	Descriptions	Units	Values
1	Electricity energy cost (as per current year), C_0	Rp/kWh	1,599 [4]
2	Inflation rate	-	3%
3	Operating time during year j, O_{0j}	h	8760
4	Discount rate at year j, i_j	-	6%
5	Life expectancy of the transformers, n	year	20
6	Average load loss factor, μ	-	0.5
7	Operating time at fixed load during year j, O_{fj}	h	8760
8	Operating time at variable load during year j, O_{aj}	h	0
9	Share of fixed load at year j, T_{fj}	-	1
10	Share of variable load at year j, T_{aj}	-	0
11	Rate of load loss factor increase at year j, $C_{\mu j}$	-	0
12	rate of installed power increase at year j, C_{aj}	-	0

Data for the green distribution transformer is based on a developed prototype, while data for the conventional transformer is sourced from the latest Indonesian transformer specifications standards, outlined in the SPLN D3.002-1: 2020 [16], as shown in Table 21.

Table 21. Data of the transformers

No	Descriptions	Units	Values	
			Conventional	Green
1	Initial cost, *IC*	Rp	44,500,000	76,095,000
2	No-load loss, P_0	W	145	51
3	Cooling power for no-load operation, P_{c0}	W	0	0
4	Load loss due to the load, P_k	W	1420	1057
5	Cooling power for operation at the rated power, P_{cs}	W	0	0

Using the data and equations (1), (2), (3), and (4), the following results were obtained:

TCO of the conventional distribution transformer: Rp224,123,566

TCO of the green distribution transformer: Rp197,839,819

The trend in the capitalization costs of both transformer types over the years is illustrated in Figure 8.

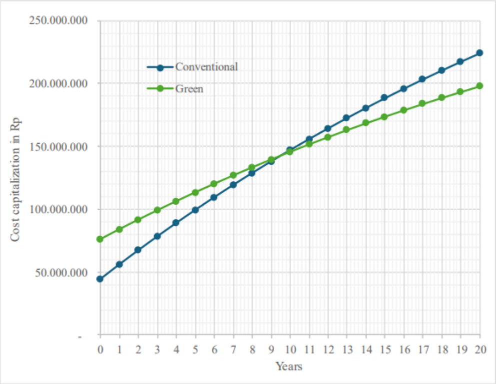

Figure 8. Comparison of the capitalized cost trends for green and conventional transformers

The results show that although the initial cost of the green distribution transformer is higher than that of the conventional one, the TCO of the green transformer is lower at Rp197,839,819 compared to Rp224,123,566 for the conventional transformer. The higher initial capitalized cost of the green transformer, due to its higher purchase price, will intersect with the capitalized cost of the conventional transformer between the 9th and 10th year. With a 20-year life expectancy, this makes the green transformer economically viable.

7. Conclusion

The research successfully developed a green distribution transformer using amorphous iron core and natural ester oil. The prototype, designed with a 100 kVA rating, met all the specified technical requirements as confirmed by comprehensive testing at an accredited laboratory. The transformer exhibited superior performance in terms of lower losses compared to conventional transformers. Moreover, despite a higher initial cost, the long-term economic analysis indicated that the total cost of ownership of the green transformer would be lower than its conventional counterpart, making it a financially viable option in the long operation.

While the prototype proved the technical and economic viability of green transformers, there is still room for improvement. The design specifications can be further optimized to reduce manufacturing costs and enhance overall performance. Additionally, collaboration with a wider range of manufacturers is essential to accelerate the development and adoption of green transformers. By addressing these areas, the future of energy-efficient and environmentally friendly power distribution systems can be significantly advanced

In conclusion, this research has proven that green distribution transformers offer a promising alternative to conventional transformers, providing both environmental and economic benefits. With continued development and industry support, green transformers can play a significant role in achieving a more sustainable and efficient power grid.

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