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Amorphous core transformers efficiency analysis in Turkish electrical distribution systems

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Abstract: Transformers are an indispensable element in the transmission and distribution of electricity. While they are highly efficient, the increasing global demand for electrical energy has prompted efforts to improve their performance. No-load power losses constitute the majority of total losses within electrical energy distribution, especially when looking at load ratio. In recent years, some studies have found that no-load power losses of amorphous core transformers are less than those of laminated steel core transformers by as much as 60% to 70%. For this paper, we have manufactured an amorphous distribution transformer prototype rated 33 kV and 1 MVA. By quantifying its design considerations, power losses, and the energy efficiency value, we studied the outcome of replacing laminated steel core transformers with this new type of machine.

Key words: Electrical distribution system, distribution transformer, transformer design, no-load losses, amorphous core, energy efficiency

1. Introduction

The most important characteristic of electrical energy is that it can be transferred long distances from its generation unit. To transfer and distribute electric energy through power lines with high efficiency and minimal energy losses, the voltage of conducted electrical energy must be as high as possible and the current must be as low as possible. Thus, the voltage value of electrical energy must be increased where it is generated and then transformed to a low voltage at the point of supply [1].

The electrical energy generated at stations must be delivered to consumers. Transmission, subtransmission, and distribution voltage levels are factors considered by generating stations and consumers. Cheaper long-distance transmission at both high and low voltage is necessary, so voltage levels from the transmission system to the distribution system continue to decrease. Because of this, there are fewer but more powerful transformers in electrical transmission systems; however, less powerful transformers are required in large numbers in electrical distributing systems [2]. The most efficient distribution transformers, which are in service continuously except for maintenance and failure breaks, record a loss of approximately 2% to 4% of the electricity they conduct. Consequently, electric utilities and industries are searching for methods and technologies to reduce operating costs and energy losses. Electrical energy is produced using scarce resources and is becoming more expensive. New transmission and distribution technologies are being introduced to solve this problem.

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Ever since the invention of the transformer, scientists have labored to find better materials for its core; this would allow the transformer to reach the desired frequencies while maintaining low losses at high flux density. A loss rate of 6 W/kg at 1 T in 1895 dropped to 0.6 W/kg at 1.5 T in the 1990s through improvements made to cold-rolled grain-oriented (CRGO) steel cores [3]. No-load losses in standard grain-oriented Si steel have decreased as a result of treatment improvements like cold-rolling and laser-scribing, but no significant future gains in standard Si steel losses are expected.

Owing to the importance of the no-load losses in total distribution transformer losses, no-load losses in electrical steel has been studied since the invention of the transformer. No-load losses of transformers manufactured from electrical steel cores are very high compared to those recorded in the early days of transformers. However, an amorphous material discovered in the 1950s became usable as a core by the 1990s instead of the classic electrical steel core. Studies have found that no-load loss rates of 60%–70% in classic electrical steel core transformers are achievable only when amorphous laminated strips are used [4–9].

Utilizing ferromagnetic materials in the production of the magnetic circuits of distribution transformers could help reduce the losses caused by Fe cores and diminish operating costs of the service providers. The scale of the gains achieved depends on the loss evaluation. Transformer design is the most important component when it comes to gains, according to optimization calculations.

In this research paper, we start by clarifying transformer losses in the second section, followed by a clear discussion of amorphous transformer design considerations. After that, we present a prototype design that can be used in Turkish electrical distribution systems, and then we provide our test results in Section 4. We then analyze the reduction in the losses that would result if an amorphous core transformer replaced classic electric steel transformers in Turkey in Section 5. Finally, we present the conclusions of our research.

2. Transformer losses

Although zero power loss is expected from an ideal transformer, practically, when energized, a transformer will have some losses that occur in the windings, core, and the surrounding structures. When the transformer is energized, but no load is applied, no-load power loss occurs due to the material that is used in the core. This loss value is constant; it occurs whether or not current flows in the secondary windings. When current flows in the secondary windings, load losses occur due to the flow of the load current through the winding resistance. Thus, total transformer losses can be determined using the following expression.

$$P_t = P_0 + P_k \tag{1}$$

In Eq. (1), the first term P_0 corresponds to the no-load losses and the second term P_k stands for the load losses.

2.1. No-load losses

Amorphous core transformers play an important role in reducing no-load losses. These transformers use an amorphous alloy for the Fe core, around which the transformer windings are coiled. Whether or not a load is present, there will still be power loss. This power is necessary to sustain an energized core. The losses that exist if the unit is energized are called no-load losses, or core losses. Voltage and frequency are the base factors of no-load losses, and under operational conditions they change, depending slightly on system variations. The losses stem from the magnetization of the core, dielectric losses in the insulation, and winding losses due to the flow of the exciting current and any circulating currents in parallel conductors. No-load losses are calculated using the following mathematical expression in Eqs. (2) and (3) [10,11].

$$P_0 = P_{hys} + P_{eddy} + P_{ano} \tag{2}$$

$$P_0 = (k_h \times f \times B_m^n) + \left(k_g \times f^2 \times B_m^2\right) + \left(k_a \times f^{1.5} \times B_m^{1.5}\right) \tag{3}$$

In Eq. (2), P_{hys} represents hysteresis losses, P_{eddy} represents eddy-current losses, and P_{ano} represents anomalous losses. In Eq. (3), k_h, k_g, and k_a constants are obtained by the experimental data; f is frequency of primary voltage; B_m is the maximum flux density in the core; and the Steinmetz constant n is 1.6. When the no-load power losses are due to the microstructure of the material, the conductivity is dependent on the cross-sectional area and lamination. Eq. (3) is valid in a certain range of frequencies and flux densities.

Hysteresis losses are defined as the loss equal to the area of the static magnetization loop times the cycle rate. They are the first component of the no-load power losses that are known as "core losses". The area of the hysteresis loop times the frequency at very low frequencies is an accurate estimate of no-load losses. At low frequencies, hysteresis losses are a large part of the no-load power losses, compared to eddy-current losses and anomalous losses [11].

Based on Maxwell's equations, but not including domain wall theory, eddy-current losses are the second component of the no-load power losses and are caused by the change in the density of the flux with respect to time because of magnetic materials. In order to reduce eddy-current losses, high-strength core material and laminating of a thin core are used.

The last component of no-load power losses are anomalous losses: losses that appear on the tests that are not in the class of hysteresis or eddy-current losses. Scientists are still trying to discover what causes these losses.

2.2. Load losses

Load losses, which are known as copper losses, show the flow of the load current the windings cause in the transformer. These losses are the result of the conductor's resistance to the current. Friction and heat are generated by the electron motion causing the conductor molecules to move. These losses are mostly caused by the load on the transformer in the usage of electricity. The energy produced due to this motion can be calculated using the following formula.

$$P_k = I^2 \cdot R \tag{4}$$

In Eq. (4), the first term I is the current that flows in the windings, and R is the resistance of the windings.

3. Amorphous core transformer design considerations

A crucial aspect of transformer design is selecting the ferromagnetic material for the cross-section core and the conductor's cross-section area. Suitable values for the peak flux density, the winding space factor, the stacking factor, and the full-load rms current density in the windings are the main factors in the determination of these areas. Ferromagnetism is the basic mechanism by which certain materials (e.g., Fe) form permanent magnets or are attracted to magnets. The strongest type creates forces strong enough to be felt. The current density depends on the transformer's operation mode, whether in an intermittent or in a continuous form. Today, the thickness of a sheet of grain-oriented silicones has been reduced to 0.18–0.30 mm. Development of classic Fe–Si steel has led to production of a low material loss including:

-normal Si steel (0.35 mm thickness, 0.9 to 1.1 T),

-hot-rolled grain-oriented Si steel (HRGO; 1.2 to 1.4 T),

-cold-rolled grain-oriented Si steel (CRGO; 0.14 to 0.28 mm thickness, 1.4 to 1.7 T).

Transformer cores are built from thin sheets of steel. These sheets are manufactured specifically for use in transformers. Core steel has a low carbon content of 0.1%. Increased carbon content has a detrimental influence on hysteresis losses as well as the aging properties. If it is alloyed with Si, which increases the specific electrical resistance, this reduces eddy-current losses in the core and also makes the core brittle; hence, the Si content should be kept below 3%. Nowadays, grain-oriented steel produced with cold-rolled steel sheets is used. The magnetic domains in the steel sheet will tend to be oriented in the rolling direction. The material obtained has good loss properties in the rolling direction and correspondingly poor properties in the transverse direction. The grain-oriented core steel is available in several grades, depending on raw material composition, the degree of cold rolling, and different finishing treatments.

Amorphous metals have high relative permeability, so they are suitable for magnetization, as illustrated in Figure 1 and summarized by the values given in Table 1 [12].

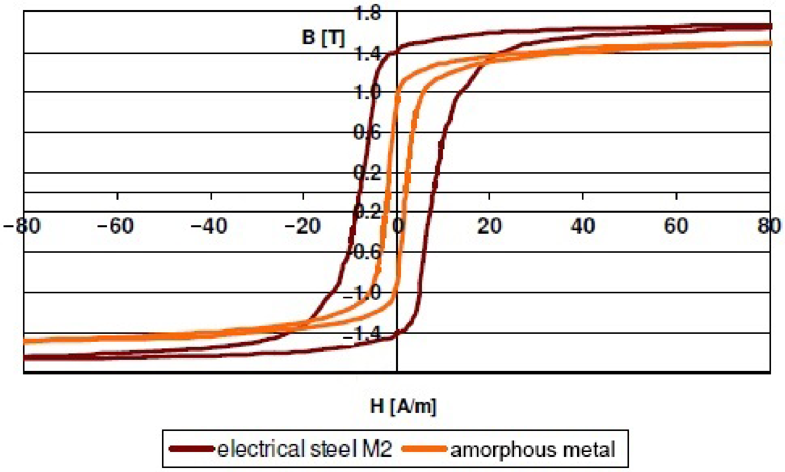

Figure 1. B-H curve for amorphous metal alloy and crystalline M2 grade silicone steel [12].

Table 1. Comparison of magnetic characteristics between amorphous metal and CRGO steel [12].

Characteristics	Amorphous metal	CRGO steel
B saturation [T]	1.56	2.0
B design admisb. [T]	1.35	1.8
Magnetic permeability	3.5e5 for H < 10A/m	6.0e4 for H < 10 A/m

To minimize eddy-current losses, the sheets must be insulated from each other using an inorganic material that is compatible with transformer oil and is corrosion- and temperature-resistant. The coating is very thin (4 μm), which enhances a good core fill factor. The core is built up from many layers of core steel sheets. If the core limb was built from a solid iron bolt, the core would be a short-circuit winding around itself, and the transformer would not work. The common thickness varies from 0.18 to 0.3 mm. This value for the amorphous alloy is 0.025 mm and is 7 to 12 times smaller than typical silicon steels. Sheet thickness and uneven surface leaves the amorphous material with a space-factor of only 80% (86% that we can use, Metglas), compared to 95% found with Si-Fe [3]. The reference core material used is the amorphous alloy (Fe, B, Si) produced by Metglas 2605HB1M in this study.

The other significant difference between amorphous core transformers and classical electrical transformers is the cross-sectional structure of the core. Because of the difficulty of producing amorphous strips, there are limited production sizes available (213 mm, 170 mm, and 140 mm). Although conventional electrical steel transformers can be oval or round in cross-section, amorphous cores may be square or rectangular in shape. This is a huge disadvantage in terms of cost for amorphous core transformer.

Since the amorphous alloys are produced as ribbons, they can be easily applied to transformers with a shell-type core. We used 5-limb core types due to the power rate of the prototype transformer, which is why the outset amorphous alloy is longer than what is currently available. The reduced flux density saturation of Fe-based amorphous alloys is less than 1.3 T (based on our design and 1.4 T for Metglas) versus the 1.7 T (for design value due to saturation) of classical electric steel. Although some disadvantages of the amorphous design include large and expensive transformers, scientists have worked to solve these problems; some can in theory achieve a maximum flux density of 1.90 T [13]. Amorphous material tends to save significant amounts of energy because of the load ratio of the transformers in the electrical distribution systems. As a result, it is becoming more popular in the industry.

4. Prototype design

There is no mandatory European standard on the scope of energy efficiency of distribution transformers. The prevailing document describing losses in transformers is the European Standard EN 50464-1, which has superseded the HD428 protocol for oil-cooled transformers [14]. Different distribution transformer efficiency classes are used in Europe at the 22 kV voltage level, for example C_0C_k in Belgium; A_0A_k, B_0B_k, and B_0C_k in France; A_0C_k, B_0A_k, and C_0C_k in Germany; C_0C_k in the Netherlands; and C_0C_k in Spain. However, in Turkey, oil-cooled distribution transformers are used at the 36 kV voltage level with the C_{036} B_{k36} energy class, according to EN 50464-1 [15].

The distribution level is 11 kV in France, the United States, New Zealand, and Australia; 33 kV in the United Kingdom; and 22 kV in South Africa [16]. Meanwhile, the electric distribution system operates at 33 kV, 15.8 kV, 10.5 kV, and 6.3 kV in Turkey. As to total transformer quantity in Turkey, 86% of transformers' primary voltages are rated as 33 kV. Approximately 99% of 33 kV primary voltage transformers are rated as 33/0.4 kV. It is estimated that 95% of these distribution transformers are rated 1 MVA and below [17]. Prototype amorphous transformer design parameters are given in Table 2.

Table 2. Prototype design parameters.

Characteristic		Prototype liquid-filled hermetically amorphous core transformer
Type	Unit	
Rated power	kVA	1000
Primary voltage	kV	33
Secondary voltage at no load	kV	0.4
Frequency	Hz	50
Number of phases		3
Vector group		Dyn-11
Ambient temperature max.	°C	40
Max. average temp. rise (oil/winding)	°C	60/65
Standards		IEC 60076
Impedance at nominal voltage	%	6.0
No-load losses	W	Minimum
Load losses at 75 °C	W	Below standards
Sound power level	dB	Minimum
Cooling		ONAN
Pri./sec. winding conductor material		Cu (Copper)

The Hitachi/Metglas group produces amorphous metals and amorphous distribution transformers and is the biggest supporter of the technology. Metglas's low saturation induction compensates for the lack of a new amorphous material and is an improvement from the previous SA1 material, HB1M. The new material, which is typical of conventional magnetic steel, is close to reaching the saturation induction level. To manufacture an amorphous core prototype transformer prototype, we used Metglas 2605HB1M core alloys [18]. The prototype amorphous transformer electrical design parameters are given in Table 3.

Table 3. Prototype amorphous transformer electrical design parameters.

Electrical design parameters				
1.	Core design			
	Material:		Metglas 2605HB1M	
	Core Type:		E-core 5-limb	
	B	1.3	T	Maximum flux density in the core
	A	5.001	dm^2	Net cross-sectional iron of the core
	k	0.89		Stacking factor
	a × b	213 × 264	mm^2	Amorphous alloy cross-section
	n	5260	Pieces	One limb
2.	High-voltage design			
	Connection	Delta		
	S	1000	kVA	Power
	U	33,000	V	Primary voltage
	W	16	turn	Primary no. of turns
	I	10.1	A	Nominal current
	C	2.45	mm	Cu conductors
	J	2.14	$\mathrm{A/mm}^2$	Current density
	Uw	14.43	V/turn	Voltage per spur
3.	Low-voltage design			
	Connection	Star		
	S	1000	kVA	Power
	U	400	V	Secondary voltage
	W	2494	turn	Turn of the LV
	I	1443.76	A	Nominal current
	C	550 × 1.35	mm	Cu conductors dimensions
	J	1.94	$\mathrm{A/mm}^2$	Current density
	Uw	14.43	V/turn	Voltage per spur

A comparison between the 2 types, which both conforming to EN 50464-1 with energy class A_{036} A_{k36}, is shown in Table 4. It is clear that amorphous metal material is an ecologically advanced material for distribution transformers. It reduces no-load loss to as low as one-third of that in grain-oriented electrical steel.

5. A case study of an electrical distribution system

Generally, core loss with amorphous cores can be 60% to 70% lower than with typical crystalline materials. This leads to saved energy, reduced electricity generation, lowered CO_2 emissions, and a reduced demand for scarce natural resources like fossil fuels. It has been exploited by developing countries like China and India, where energy conservation and CO_2 emission reduction are crucial. These countries can potentially save 25 to 30 TWh electricity annually, eliminate 6 to 8 GW of generation investment, and reduce 20 to 30 million tons of CO_2 emissions by using this technology [19,20]. Due to the geographical structure, population, industrialization, etc. of the electrical distribution system of Turkey, the country was divided into 21 regions for power delivery. Private sector companies provide electricity to consumers in a cost-effective and environmentally friendly way. Başkent EDAŞ is one of the private companies used. It represents 10.1% of subscribers to the distribution system, 8.3% of total consumption, and 3.08% of internal loss/theft ratio [21].

Table 4. Comparison of transformer test results.

Characteristic		Liquid-filled hermetic transformer with amorphous core	Liquid-filled hermetic transformer with CRGO steel core
Type	Unit		
Rated power	kVA	1000	
Primary voltage	kV	33	
Primary tappings (off load)		6 pos + 2–3 1500 V	
Secondary voltage at no load	kV	0.4	
Primary insulation level	kV	LI 170 / AC 70 / Um 36	
Secondary insulation level	kV	LI - / AC 3 / Um 1.1	
Frequency	Hz	50	
Number of phases		3	
Vector group		Dyn-11	
Ambient temperature max.	°C	40	
Max. average temperature rise (oil/winding)	°C	60/65	
Altitude (a.s.l.)	m	< 1000	
Location		Indoor/outdoor	
Performance values			
Standards		IEC 60076	
Impedance at nominal voltage	%	6.0	
No-load losses	W	470	1100
Load losses at 75 °C	W	8700	8900
Sound power level	dB	70	73
Preliminary dimensions and weight		Tolerance in weight & dimensions ±10%	
Length	mm	2000	1700
Width	mm	1230	1050
Height	mm	1870	1710
Roller distance (c/c)	mm	820	
Oil weight	kg	850	550
Total weight	kg	4160	3250
Type of design			
Tank construction		Corrugated wall, hermetically sealed	
Cooling		ONAN	
Primary/secondary winding conductor		Cu (Copper)	

Figure 2 shows a 33/0.4 kV 1 MVA transformer single-line diagram from the Tunç 1 district in Başkent EDAŞ; Figure 3 illustrates the real-time load curve over 2 days using this transformer. Figure 4 illustrates the real-time loss-load curve over 2 days of a transformer conforming to EN 50464-1 with energy class C_{036} B_{k36} and that of its substitution, a prototype amorphous core transformer. Figure 5 also illustrates the CO_2 emission value of the 2 types of transformers. The analyzed transformer is in an urban area with high energy demands.

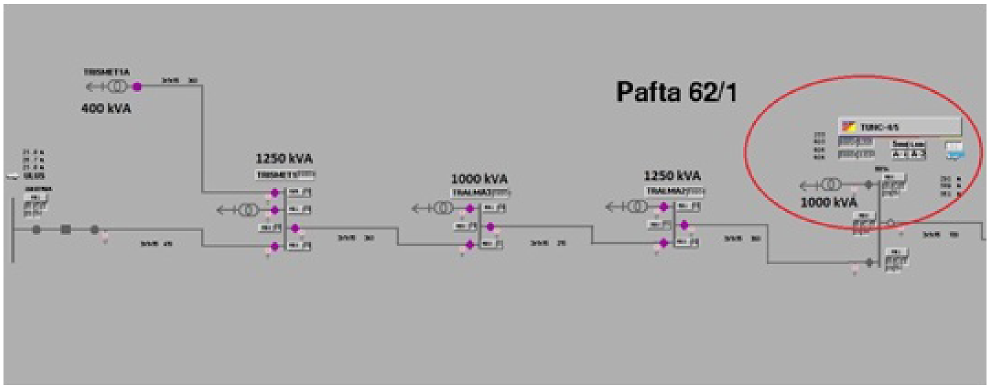

Figure 2. Diagram of the urban area electrical distribution system.

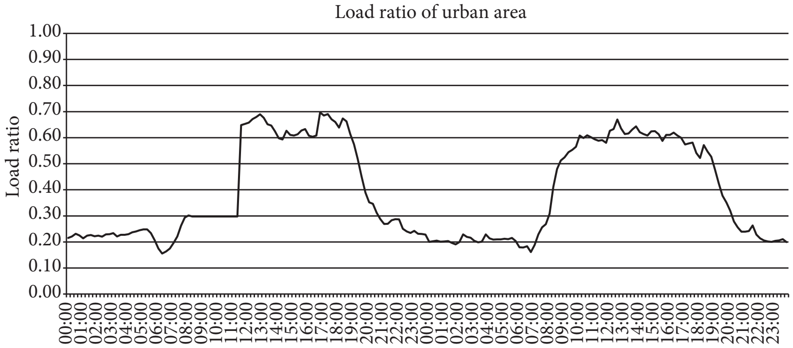

Figure 3. The load ratio of the real transformer.

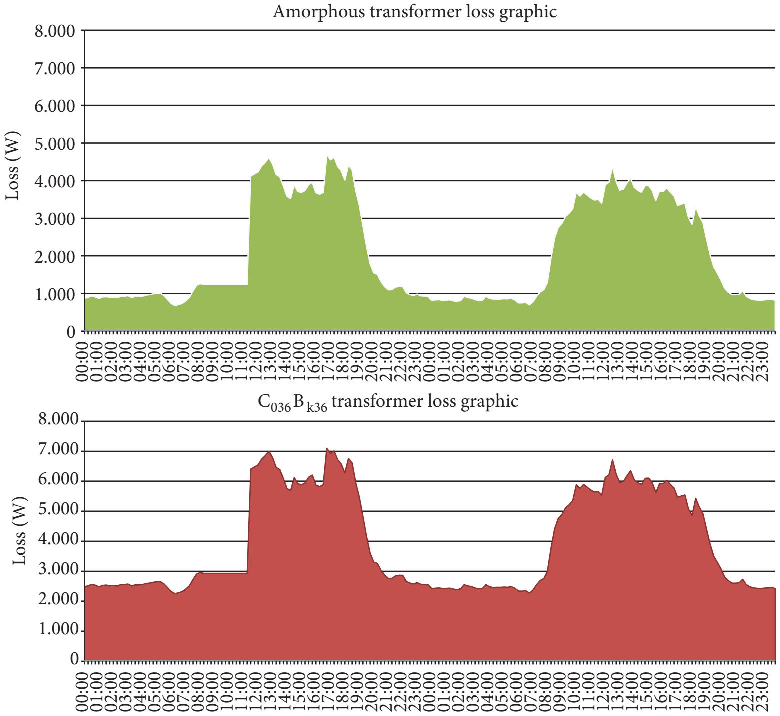

Figure 4. The total losses of the 2 kinds of transformers due to load ratio.

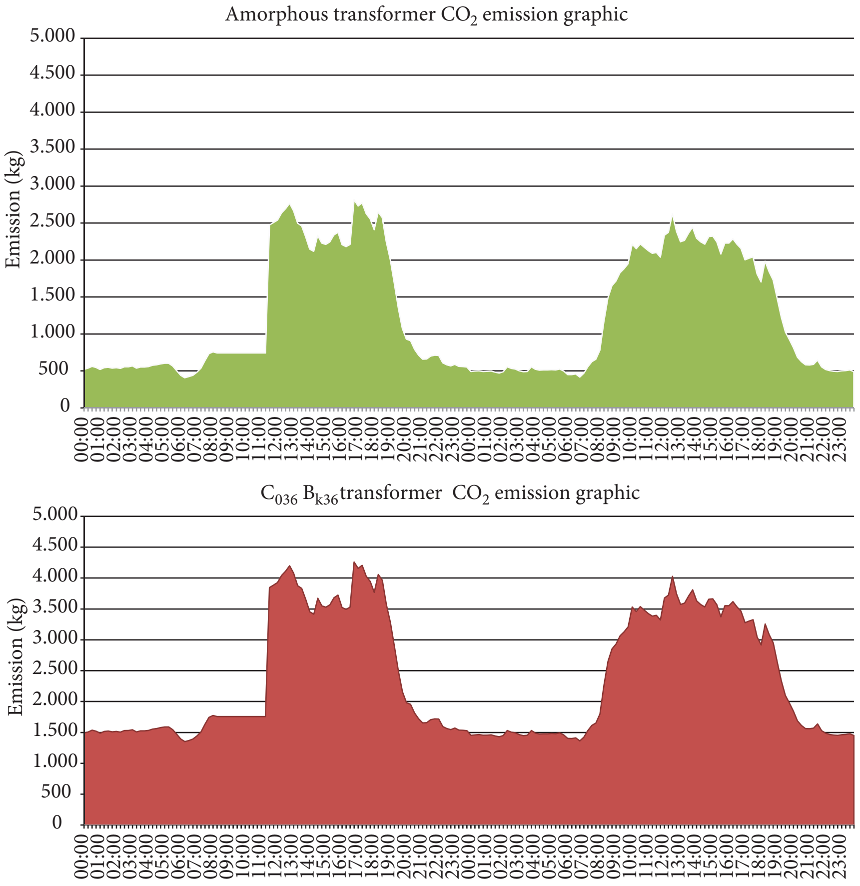

Figure 5. The total CO_2 emissions of the 2 kinds of transformers due to load ratio.

Examining real-time data taken from the transformer rated 1 MVA in the distribution region and located in an urban area, the maximum peak load rate of the transformer is 70%, and the average load rate is 39%. The total annual loss of the transformer under examination, which conformed to EN 50464-1 with energy class C_{036} B_{k36}, is 34.477 kWh per year. In the case of the prototype amorphous core transformer used under the same conditions, total annual loss will be 18.167 kWh per year, a loss reduction of 47%. This means potential energy savings of about 16.310 kWh and reduction of CO_2 emissions of about 9786 tons annually.

Figure 6 shows a 33/0.4 kV 1 MVA transformer diagram in the Kastamonu district of Başkent EDAŞ, and Figure 7 illustrates the real-time load curve over 2 days using this transformer. Figure 8 illustrates the real-time loss-load curve over 2 days using a traditional transformer, conforming to EN 50464-1 standards with energy class $C_{036} B_{k36}$, and its substitution, the prototype amorphous core transformer. Figure 8 also illustrates the CO_2 emissions values of the 2 types of transformers. The analyzed transformer is in a rural area with low energy demands.

Examining real-time data taken from the transformer rated 1 MVA in the distribution region located in a rural area, the maximum peak load rate of the traditional transformer is 40%, and the average load rate is 22%. The total annual loss of the transformer under examination, which conformed to EN 50464-1 standards with energy class C_{036} B_{k36}, is 22.872 kWh per year. In the case where the prototype amorphous core transformer is used under the same conditions, total annual loss will be 8.552 kWh per year, a reduction of 62%. This means potential energy savings of about 14.320 kWh and reduction of CO_2 emissions of about 8.592 tons annually.

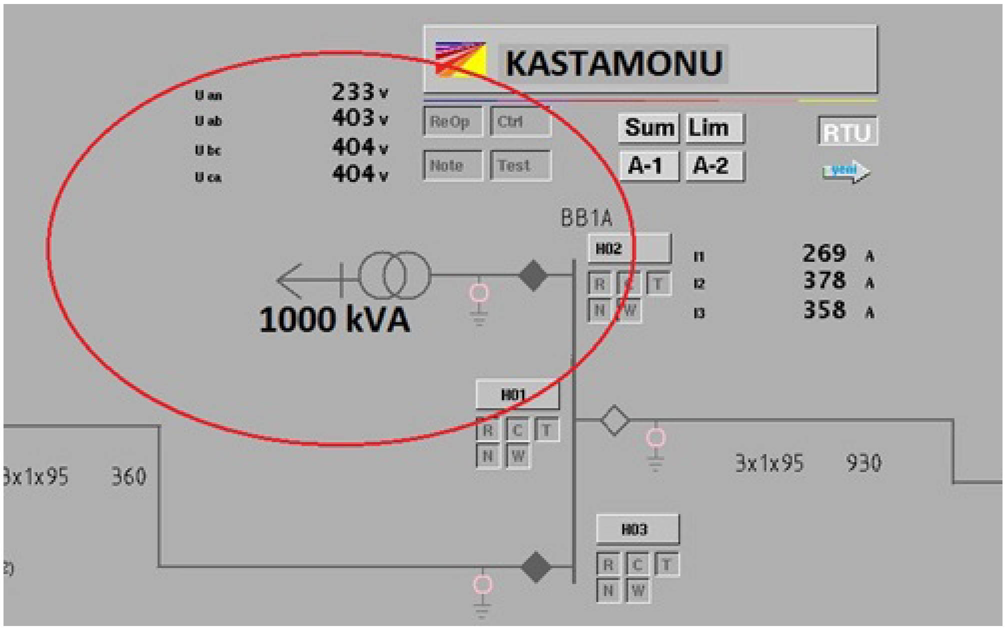

Figure 6. Diagram of the rural area electrical distribution system.

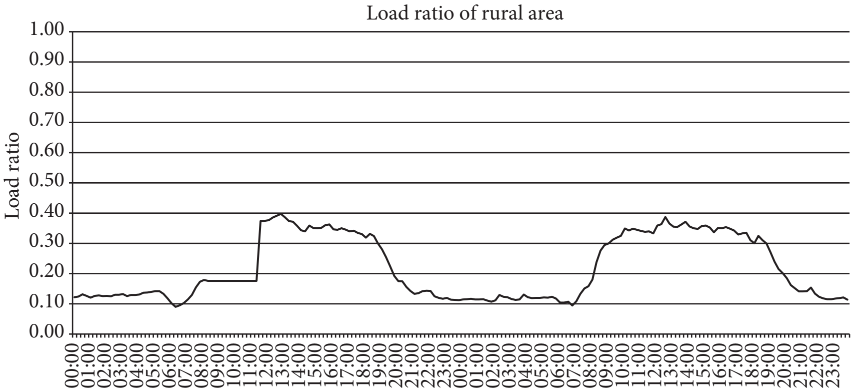

Figure 7. The load ratio of the real transformer.

6. Conclusions

In this study, an amorphous core distribution transformer was designed, manufactured, and tested. The results were compared with classical steel core transformers that are used in existing electrical distribution systems. Turkey is not yet using an amorphous transformer. Although there has been a lot of research on the amorphous core transformers, the distribution voltage level in Turkey's electrical grid is different than that of much of the rest of the world. In this study, we have proven that amorphous no-load power can be less than 76.5% of cold-rolled grain-oriented transformers with the C_{036} B_{k36} efficiency standards that are used generally in Turkey.

The significance of the amorphous core transformer gets more important when the focus is on a real electrical distribution system. Due to the load of the transformer in the real system, the total loss of the transformer decreased by 47% in an urban area and 62% in rural areas disregarding harmonic effects on the losses.

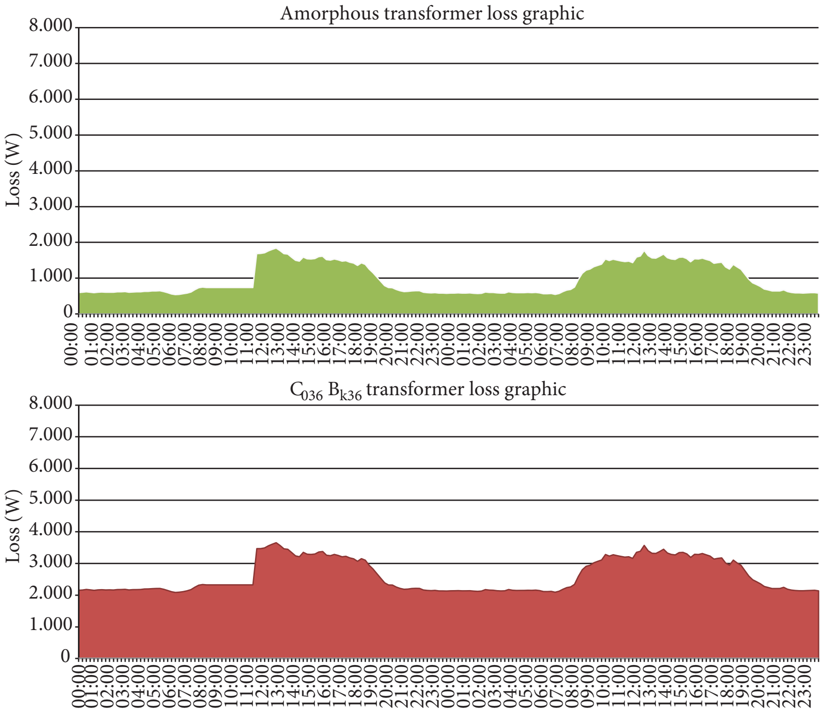

Figure 8. The total losses of the 2 kinds of transformers due to load ratio.

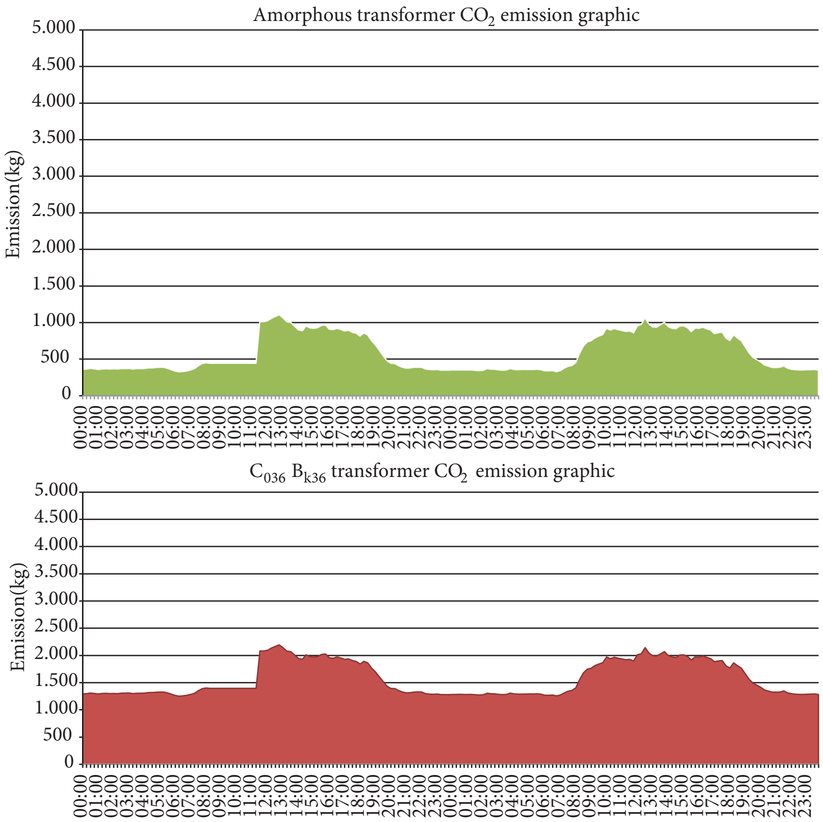

Figure 9. The total CO_2 emissions of the 2 kinds of transformers due to load ratio.

Significant results from this study include:

-A prototype amorphous core transformer rated 36 kV, 1 MVA reduced no-load losses by 67%, compared to classical electrical steel core transformers conforming to EN 50464-1 standards with energy class A_{036} A_{k36}.

-A prototype amorphous core transformer rated 36 kV, 1 MVA reduced losses by 47% in urban areas and 62% in rural areas, excepting harmonic effects, compared to classical electrical steel core transformers conforming to EN 50464-1 standards with energy class C_{036} B_{k36}.

-We demonstrated that using amorphous core transformers in rural areas, where load ratios are less, resulted in more significant energy savings. The prototype amorphous core transformer includes approximately 95% of the most preferred rated power in using Turkish electrical distribution system.

-According to the primary voltage level of 33 kV, the size of the amorphous transformer was bigger than the 11 kV and 22 kV primary voltage levels.

-The amorphous transformers are environmentally friendly high-technology materials that have the potential to reduce CO_2 emissions.

-Although amorphous core transformers in distribution systems provided significant energy savings, design limitations meant they were larger than classic core transformers. This size may be reduced in the future, allowing for its widespread use. As a result of the thin and fragile nature of amorphous strips, the manufacture of amorphous core transformers is difficult and requires a high level of workmanship.

Acknowledgments

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