ENERGY SAVING IN ELECTRICITY DISTRIBUTION NETWORKS THROUGH THE USE OF AMORPHOUS METAL DISTRIBUTION TRANSFORMERS

A case study of The Kenya Power & Lighting Company Distribution Network

BY

SIMON KIPTUM KIMITEI (F56/63937/2010)

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DECLARATION

I declare that this work has not been previously submitted and approved for the award of a degree by this or any other University. To the best of my knowledge and belief, the project report contains no material previously published or written by another person except where due reference is made in the report itself.

Simon Kiptum Kimitei

APPROVAL

This project report has been submitted with our approval as the university supervisors.

Dr. Cyrus Wekesa

Department of Electrical and Electronics Engineering

Prof. J. A. Nyang'aya

Department of Mechanical and Manufacturing Engineering

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ABSTRACT

Transformer power losses are made up of losses in the windings, referred to as copper loss (or load losses), and those in the magnetic circuit, referred to as iron losses (or no-load losses). Winding resistance dominates load losses, whereas hysteresis and eddy currents losses contribute to over 99% of the no-load loss (iron losses).

The no-load loss constitutes a constant drain on the electrical supply and is a running cost.

Minimising hysteresis loss depends on the use of a material having a minimum area of hysteresis loop, while minimising eddy current loss is achieved by building up the core from a stack of thin laminations and increasing resistivity of the material in order to make it less easy for eddy currents to flow.

The magnetic core of Amorphous Metal Distribution Transformer is made with amorphous metal which is easily magnetized / demagnetized and the thickness is approximately 0.03mm, which is about 1/10 compared with Cold Rolled Grain Oriented (CRGO) Silicon Steel. Typically, core loss can be 70% less than the CRGO Silicon Steel (traditional) counterpart.

The present study was designed to quantify the energy saving in the electricity distribution network of KPLC through the use of amorphous metal distribution transformers.

The increase in efficiency in using amorphous metal distribution transformers in KPLC network would result in energy cost savings of Ksh 621 million per year and reduction in CO_2 emissions of 37,000 tons per year.

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LIST OF ABBREVIATIONS

AMDT	Amorphous Metal Distribution Transformer
CDM	Clean Development Mechanism
CER	Certified Emission Reductions
CO_2	Carbon Dioxide
CRGO	Cold Rolled Grain Oriented
emf	electromotive force
GEF	Grid Emission Factor
IEC	International Electrotechnical Commission
KPLC	Kenya Power & Lighting Company Ltd
Ksh	Kenya Shilling
kV	Kilo Volt
KVA	Kilo Volt Amperes
mmf	magnetomotive force
MWh	Mega Watt Hours
NLL	No Load Losses
NPV	Net Present Value
PB	Pay Back Period
TOC	Total Ownership Cost (also TCO: Total Cost of Ownership)
UNFCCC	United Nations Framework Convention on Climate Change

1. CHAPTER ONE: INTRODUCTION

1.1 BACKGROUND

1.1.1 Existing Distribution Network

The Kenya Power & Lighting Company Ltd (KPLC) undertakes distribution of electricity throughout Kenya. The distribution is through 11kV and 33kV lines, the total lengths being approximately 25,485km and 13,812km respectively [1].

Step-down transformers (distribution transformers) are connected to the 11kV and 33kV lines to feed various loads that include residential (at 240V or 415V), commercial (at 240V or 415V) and industrial (mainly at 415V). A few large power customers (large consumers) are metered at high voltage (11-132kV) through power transformers and metering equipment.

Distribution transformer power ratings in use in KPLC range from 5KVA to 1000KVA on both the 11kV and 33kV systems.

The current system losses in the KPLC network as reported in 2010 stand at 16% [1]. This means that out of the 6,692GWh the company purchased in 2010, some 1,071GWh were lost as system losses.

System losses consist of technical losses and non-technical losses.

Technical losses occur as a result of:

a) The heating of conductors in power lines and transformers as electric current (I) flows through them; this is proportional to the square of the current as expressed in the formula: I^2R, where R is the resistance of the system.

b) Iron losses (no-load losses) in transformers which are independent of power flow.

On the other hand non-technical losses are largely associated with pilferages or commercial leakages from the system and include: metering & billing errors, theft of electricity and corrupt practices [2].

Previous efforts in reducing system losses have focused on re-conductoring, pre-paid metering, and reactive power compensation (power factor correction). However, these initiatives target, mainly, reducing I^2R losses and non-technical losses. There had been no effort addressing iron losses, which occur all the time.

The focus of this project is iron losses in distribution transformers with a view of reducing technical losses in the electricity distribution network.

1.1.2 Transformer Core Materials

In a transformer, the core provides a low-reluctance path for the magnetic flux linking primary and secondary windings. The core experiences iron losses due to hysteresis and eddy currents flowing within it which, in turn, show themselves as heating of the core material. In addition, the alternating fluxes generate noise.

Core losses (iron losses) are present whenever the transformer is energised; they therefore represent a constant and significant energy drain on any electrical system.

Efforts in the reduction of core losses (no-load losses) in transformers have resulted in development of new materials worldwide over the years. These materials include hot rolled steels, cold rolled grain oriented steels, high permeability steels, domain-refined steels, amorphous steels and microcrystalline steels. The amorphous steels generally have the lowest no-load losses.

1.2 PROBLEM STATEMENT

Distribution transformers already installed in the KPLC network and those being procured annually are of the cold rolled grain oriented (CRGO) silicon steel design. None of the transformers are of the low loss design (amorphous steel type). Generally, CRGO distribution transformers have higher no-load losses than the amorphous type.

No energy audit has been done to establish the total core losses in the existing KPLC distribution transformers. Further, no study has been undertaken to establish the energy savings and the reductions in carbon emissions that could result with implementation of amorphous metal distribution transformers in place of CRGO distribution transformers.

1.3 JUSTIFICATION

The demand for electricity in Kenya is growing at an average of 8% per annum with peak demand currently at 1,107MW. The effective generation capacity is 1,416MW comprising hydro, thermal, geothermal and wind. However, this capacity is seriously constrained during periods of poor hydrology (drought). It is therefore imperative that in addition to the measures by the Government and the stakeholders in developing additional generation capacity, energy conservation measures through use of energy efficient equipment and practices be adopted.

As stated in 1.1.1 above the total system losses in the KPLC network stand at 16% translating to total system losses of 1,071GWh in the year 2010 alone.

Thirdly, reduction in energy consumption translates directly to reduction in carbon emissions (reduced fossil fuel use) and will earn the company carbon credits under the Clean Development Mechanism (CDM) of the Kyoto Protocol to UNFCC.

1.4 OBJECTIVES

1.4.1 The main objective of the research was to establish the scope for energy saving in electricity distribution networks through the use of Amorphous Metal Distribution Transformers. A case study was carried out on the Kenya Power & Lighting Company (KPLC) distribution network.

1.4.2 The specific objectives of the research were:

a) Determining total annual no-load energy losses of the existing CRGO distribution transformers in KPLC network.

b) Determining corresponding savings in annual no-load energy losses if existing CRGO distribution transformers were replaced by amorphous metal distribution transformers.

c) Establishing the reduction in CO_2 emissions resulting from the energy savings.

d) Cost-Benefit analysis of replacing existing CRGO distribution transformers with the amorphous metal distribution transformers using net present value, pay-back period techniques and total ownership cost analysis.

1.5 SCOPE

The research covered existing CRGO distribution transformers in all the six regions of the KPLC distribution network.

1.6 HYPOTHESIS

Use of amorphous metal distribution transformers will reduce the technical losses in electricity distribution networks and result in cost savings and reduction in CO_2 emissions.

2. CHAPTER TWO: LITERATURE REVIEW

2.1 BASIC TRANSFORMER THEORY

A power transformer normally consists of a pair of windings, primary and secondary, linked by a magnetic circuit (core). When an alternating voltage is applied to one of these windings, generally by definition the primary, a current will flow which sets up an alternating m.m.f. and hence an alternating flux, ϕ, in the core which induces an e.m.f. in each of the windings [3].

This is illustrated in Fig 2.1.

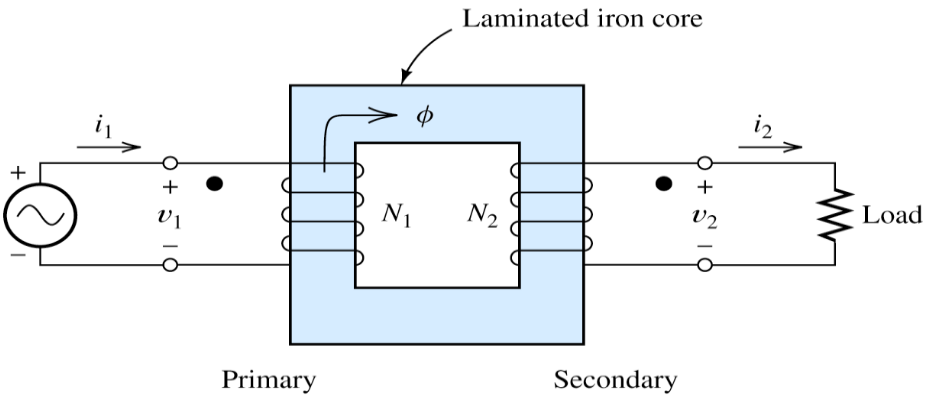

Figure 2.1: Ideal Transformer

The relationship between the induced voltages (v), the currents (i) and number of turns (N) is given by:

$$v_2(t) = (N_2/N_1)\, v_1(t) \qquad (2.1)$$

and

$$i_2 = (N_1/N_2)\, i_1 \qquad (2.2)$$

The voltage is transformed in proportion to the number of turns in the respective windings and the currents are in inverse proportion (and the relationship holds true for both instantaneous and r.m.s. quantities).

For ideal transformer, power in the primary, $p_1(t)$, equals power in the secondary windings, $p_2(t)$. However in practice the transformation between primary and secondary is not perfect. Not all of the flux produced by the primary winding links the secondary so the transformer can be said to possess leakage reactance [3].

The leakage reactance or, in practical terms, impedance, since transformer windings also have resistance is expressed as:

$$V_Z = \%Z = [(I_{FL}Z)/E]*100 \qquad (2.3)$$

Where $Z = \sqrt{(R^2 + X^2)}$, R and X being the transformer resistance and leakage reactance respectively and I_{FL} and E are the full-load current and open-circuit voltage of either primary or secondary windings [3].

Magnetising current is required to take the core through the alternating cycles of flux at a rate determined by system frequency. In doing so energy is dissipated. This is known variously as the core loss, no-load loss or iron loss.

The flow of a current in any electrical system, however, also generates loss dependent upon the magnitude of that current and the resistance of the system. Resistance of transformer windings give rise to the load loss or copper loss of the transformer.

Load loss is present only when the transformer is loaded, since the magnitude of the no-load current is so small as to produce negligible resistive loss in the windings. Load loss is proportional to the square of the load current [3].

The equivalent circuit of practical transformer in Figure 2.2 shows the components that give rise to the losses described in the preceding paragraphs.

2.2 TRANSFORMER LOSSES

Transformer losses are divided into losses in the windings, termed copper loss (or load losses), and those in the magnetic circuit, termed iron loss (or no-load losses).

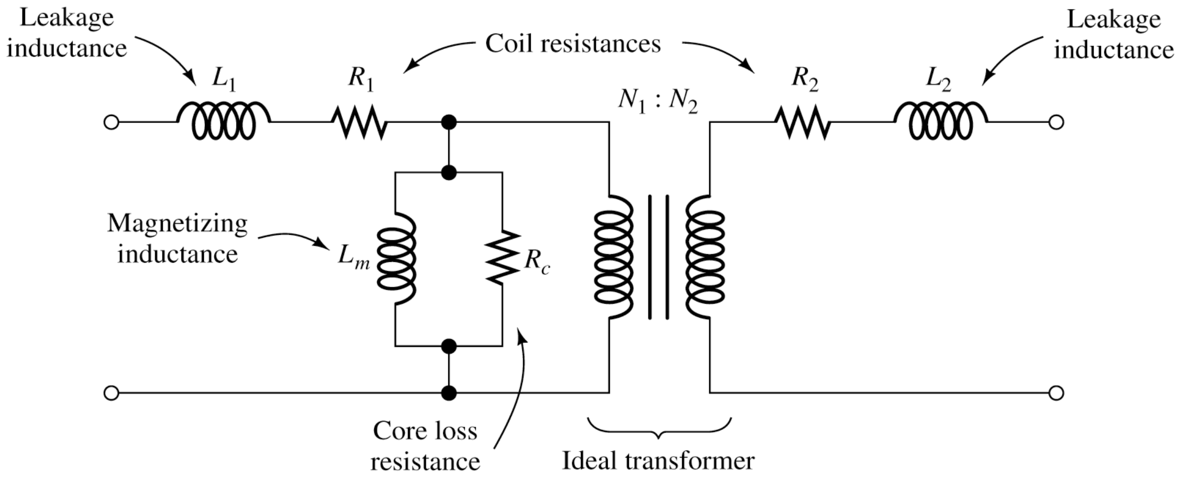

Figure 2.2: Equivalent Circuit of Practical Transformer

(subscript 1 is used for primary side while subscript 2 is used for secondary side)

Losses in the transformer arise from:

a) Winding resistance – current, I, flowing through the windings causes resistive heating of the conductors. This is proportional to the square of the current as expressed in the formula: I^2R, where R is the resistance of the windings.

b) Hysteresis losses – each time the magnetic field is reversed, a small amount of energy is lost due to hysteresis within the core.

Hysteresis loss is proportional to the frequencyand is dependent on the area of the hysteresis loop, which, in turn, is a characteristic of the material and a function of the peak flux density[3].

The relationship between magnetic flux density (B) and magnetic field intensity (H) is not linear for the types of iron core used in transformers.
This is illustrated in Figure 2.3.

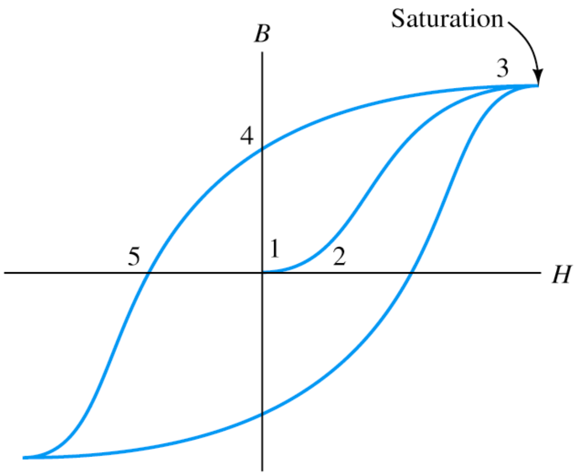

Figure 2.3: Hysteresis Loop

c) Eddy currents – ferromagnetic materials are also good conductors, and a core made from such a material also constitutes a single short-circuited turn throughout its entire length. Eddy currents therefore circulate within the core in a plane normal to the flux, and are responsible for resistive heating of the core material. The eddy current loss is dependent on the square of frequency but is also directly proportional to the square of the thickness of the material [3].

d) Magnetostriction – magnetic flux in a ferromagnetic material, such as the core, causes it to physically expand and contract slightly with each cycle of the magnetic field, an effect known as magnetostriction. This produces the buzzing sound commonly associated with transformers, and can cause losses due to frictional heating.

e) Mechanical losses – in addition to magnetostriction, the alternating magnetic field causes fluctuating forces between the primary and secondary windings. These incite vibrations within nearby metalwork, adding to the buzzing noise, and consuming a small amount of power.

f) Stray losses – leakage inductance is by itself largely lossless, since energy supplied to its magnetic fields is returned to the supply with the next half-cycle. However, any leakage flux that intercepts nearby conductive materials such as the transformer's support structure will give rise to eddy currents and be converted to heat. There are also radiative losses due to the oscillating magnetic field, but these are usually small.

Winding resistance dominates load losses, whereas hysteresis and eddy currents losses contribute to over 99% of the no-load loss (iron losses). The no-load loss can be significant, so that even an idle transformer constitutes a drain on the electrical supply and a running cost.

Minimising hysteresis loss depends on the use of a material having a minimum area of hysteresis loop, while minimising eddy current loss is achieved by building up the core from a stack of thin laminations and increasing resistivity of the material in order to make it less easy for eddy currents to flow.

The main components of core loss can be represented by the expressions [3], [4]:

Hysteresis loss, $W_h = k_1 f B_{max}^n$ watts/kg (2.4)

and

Eddy current loss, $W_e = k_2 f^2 t^2 B_{eff}^2 / \rho$ watts/kg (2.5)

Where

k_1 and k_2 are constants of the material

f is frequency, Hz

t is thickness of the material, mm

ρ is the resistivity of the material

B_{max} is maximum flux density, T

B_{eff} is the flux density corresponding to the r.m.s. value of the applied voltage

n is the 'Steinmetz exponent' which is a function of the material. Originally this was taken as 1.6 but with modern materials and higher flux densities n can vary from 1.6 to 2.5 or higher [3].

From equations 2.4 and 2.5, hysteresis and eddy current losses are material dependent. The k_1 and k_2 factors are lower for amorphous steel when compared to CRGO steel [4].

The magnetic core of Amorphous Metal Distribution Transformer is made with amorphous metal which is easily magnetized / demagnetized. Typically, core loss can be 70% less than the CRGO silicon steel (traditional) counterpart [5].

The increase in efficiency saves considerable energy and reduces CO_2 emissions [6], [7].

2.3 TRANSFORMER CORE STEELS

2.3.1 Hot Rolled Steels

Electrical sheet steels have a crystalline structure so that the magnetic properties of the sheet are derived from the magnetic properties of the individual crystals or grains and many of these are dependent on the direction in the crystal in which they are measured.

Electrical steel contains silicon which reduces hysteresis loss, increases permeability and also increases resistivity, thus reducing eddy current losses. However, the quantity of silicon is limited to about 4.5% to mitigate brittleness and ensure workability and ease of manufacture. The elimination of impurities, including carbon, also has a significant effect in the reduction of losses so that although the first steels containing silicon had specific loss values of around 7 W/kg at 1.5 T, 50 Hz, similar alloys produced in 1990s having high levels of purity have losses less than 2 W/kg at this condition.

Silicon steel laminations of thickness around 0.35 mm used in transformers until 1940s were produced by a hot-rolling process in which the grains are packed together in a random way so that magnetic properties observed in a sheet have similar values independent of the direction in which they are measured [3].

2.3.2 Cold Rolled Grain Oriented Steels

First commercial quantities of CRGO steels were produced in 1939 following development by American Rolling Mill Company in USA. It had a thickness of 0.32 mm with a loss of 1.5 W/kg at 1.5 T, 50 Hz.

In the manufacturing process, the initially hot-rolled strip is pickled to remove surface oxides and is then cold rolled to about 0.6 mm thickness from the initial hot band thickness of 2 - 2.5 mm. The material is then annealed to recrystallize the cold-worked structure before cold rolling again to the final gauge. Decarburisation down to less than 0.003% carbon is followed by coating with a thin magnesium oxide (MgO) layer. During the next anneal, at 1200°C for 24 hours, purification and secondary recrystallization occur and the magnesium oxide reacts with the steel surface to form a thin magnesium silicate layer called the glass film or Forsterite layer. Finally, the material is given a flattening anneal, when excess magnesium oxide is removed and a thin phosphate coating is applied which reacts with the magnesium silicate to form a strong, highly insulating coating [3].

2.3.3 High-Permeability Steels

High-permeability steels were introduced in 1965 by the Japanese Nippon Steel Corporation [8].

The production process (based on that of CRGO) is simplified by the elimination of one of the cold rolling stages because of the introduction of around 0.025% of aluminium to the melt and the resulting use of aluminium nitride as a grain growth inhibitor. The final product has a better orientation than cold-rolled grain-oriented steel with most grains aligned within $3^o$of the ideal (compared to 6^o for CRGO), but the grain size, average 1 cm diameter, very large compared to the 0.3 mm average diameter of CRGO steel.

At flux densities of 1.7 T and higher, its permeability is three times higher than that of the best CRGO steel, and the stress sensitivity of loss and magnetostriction lower because of the improved orientation and the presence of a high tensile stress introduced by stress coating. The stress coating imparts a tensile stress to the material which helps to reduce eddy-current loss which would otherwise be high in a large-grain material. The total loss is further offset by some reduction in hysteresis loss due to the improved coating. However, the low losses of high-permeability steels are mainly due to a reduction of 30 - 40% in hysteresis brought about by the improved grain orientation. The Nippon Steel Corporation product became commercially available in 1968, and it was later followed by high-permeability materials based MnSe plus Sb (Kawasaki Steel, 1973) and Boron (Allegheny Ludlum Steel

Corporation, 1975) [3].

2.3.4 Domain-Refined Steels

Further improvements in the production process of core steels resulted in laser-etched material with losses some 5 - 8% lower than high-permeability steel. By 1983 Nippon Steel Corporation were producing laser-etched steels down to 0.23 mm thick with losses as low as 0.85 W/kg at 1.7 T, 50 Hz [3].

Anomalous eddy-current loss arises in part due to magnetic domain wall movement during the cycles of magnetisation. Eddy current loss can therefore be reduced by subdividing the magnetic domains to reduce domain wall spacing.

The use of the stress coatings in high-permeability steels has the effect of subdividing magnetic domains and thus reducing core loss. The coatings impart a tensile stress into the material on cooling due to their low thermal expansion coefficient. Mechanical scribing of the sheet surface at intervals transverse to the rolling direction also serves as a means of inducing the necessary strain but this is difficult to carry out on a commercial basis and has the disadvantage that the sheet thickness at the point of the scribing is reduced, thus creating a localised increase in the flux density and causing some of the flux to transfer to the adjacent lamination with the consequent result that there is a net increase in loss.

Nippon Steel Corporation employs a noncontact domain-refining process utilising laser irradiation normally referred to as laser etching. When the high-power laser beam is trained to the surface of the sheet, the outermost layer of the sheet vaporises and scatters instantaneously. As a result, an impact pressure of several thousand atmospheres is generated to form a local elastic-plastic area in the sheet. Highly dense complex dislocations due to plastic deformation occur leaving a residual strain which produces the required domain refinement. As the laser irradiation vaporises and scatters the outermost layer of the sheet, an additional coating is necessary in order to make good the surface insulation layer.

An important aspect of the domain refinement process is that the residual strains will be removed if the material is subsequently annealed at a temperature above 500°C thus reversing the process [3].

2.3.5 Amorphous Steels

The development of amorphous steels stems from a different source than the silicon core steels described in sections2.3.1 – 2.3.4. Originally developed by Allied Signal Inc., Metglas Products in the USA, in the early 1970s as an alternative for the steel in vehicle tyre reinforcement, it was not until 1975 that the importance of their magnetic properties was recognised [8].

Amorphous metals have a non-crystalline atomic structure, there are no axes of symmetry and the constituent atoms are randomly distributed within the bulk of the material. They rely for their structure on a very rapid cooling rate of the molten alloy and the presence of a glass-forming element such as boron. Typically they might contain 80% iron with the remaining 20% boron and silicon.

The production method involves spraying a stream of molten metal alloy to a high-speed rotating copper drum. The molten metal is cooled at a rate of about 10^6degC per second and solidifies to form a continuous thin ribbon. The quenching technique sets up high internal stresses which are reduced by annealing between 200 and 280^0C to develop good magnetic properties. Earliest quantities of the material were only 2 mm wide and about 0.025 - 0.05 mm thick. By the mid-1990s a number of organisations had been successful in producing strip up to 200 mm wide [3].

The need for a glass-forming element, which happens to be non-magnetic, gives rise to another of the limitations of amorphous steels, that of low saturation flux density. POWERCORE strip (Allied Signal Inc., Metglas Products) has a saturation level of around 1.56 T. Specific loss (50Hz) at 1.35 T and 1.5T are just 0.12 W/kg and 0.28 W/kg respectively [3].

2.3.6 Microcrystalline Steels

Another approach towards the optimisation of the magnetic and mechanical performance of silicon steel, is the production of high-silicon and aluminium iron alloys by rapid solidification in much the same manner as for amorphous steels. No glass-forming additives are included so a ductile microcrystalline material is produced, often referred to as semi crystalline strip. 6% silicon iron strip has been produced which has proved to be ductile and to have losses fewer than those of commercial grain oriented 3% silicon iron.

Typical loss values are 0.56 W/kg at 1.7 T, 50 Hz. Rapidly quenched microcrystalline materials have the advantage of far higher field permeability than that of amorphous materials so far developed for power applications.

2.3.7 Standard Designations

Core steel designations are given in the International Standard IEC 60604 [9]. The document identifies particular materials by means of a code, for example 28M4 or 30M5, which are 0.28 and 0.30 mm thick, respectively. The final digit refers to the maximum specific loss value.

Figure 2.4 indicates typical loss values attainable for the range of modern core materials and shows how the non-oriented microcrystalline ribbon fits between amorphous ribbon and grain-oriented steel.

Amorphous steels have the lowest losses and the saving in no-load losses may pay off the extra cost over the CRGO type [3], [10].

2.3.8 Adoption of Improved Steels

The cold-rolled grain-oriented steels introduced in the 1940s and 1950s almost completely replaced the earlier hot-rolled steels in transformer manufacture over a relatively short timescale and called for some new thinking in the area of core design. The introduction of high-permeability grain-oriented steels some 30 years later was more gradual and, because of its higher cost, its early use tended to be restricted to applications where the capitalised cost of no-load loss was high. A gradual development in core design and manufacture to optimise the properties of the new material took place but some of these improvements were also beneficial for designs using conventional materials. In 1981 some 12% of the worldwide production of grain-oriented steel was high-permeability grade. By 1995 high-permeability material was the norm. A similar situation occurred with the introduction of laser-etched steel, which for reasons of both availability and cost, remains very much a ‘special’ material, to be used only where the cost of no-load losses is very high [3].

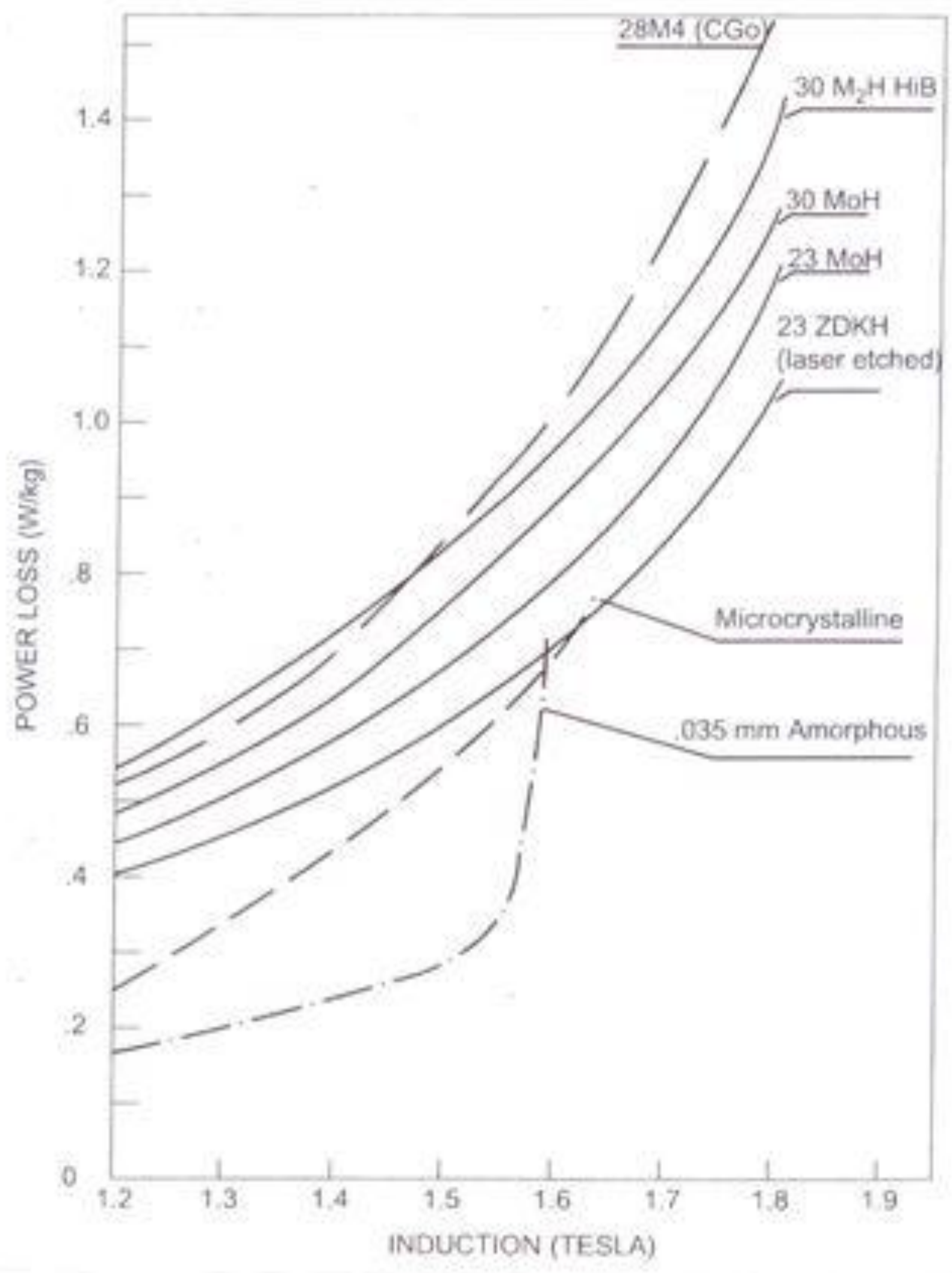

Figure 2.4: Power loss versus induction at 50Hz for various materials [3]

While the sizes of amorphous metal strip available are still unsuitable for the manufacture of large-power transformer cores, in the USA in particular, hundreds of thousands of distribution transformer cores have been built using amorphous material. In Europe, the material has been used in Holland, Sweden, Switzerland, Germany and Hungary [3]. ERDF France initiated a distribution network loss reduction process by modifying its specifications for conventional magnetic sheet transformers to amorphous sheet technology [11].

Use of amorphous metal distribution transformers is also found in Asia with Japan, India and China among the leading countries. Ghana, Nigeria, Ethiopia, Seychelles and Mauritius are some of the African countries that have embraced the technology [12].

Distribution transformers installed in KPLC network and those being procured annually are of the cold rolled grain oriented steel. A detailed comparison between the CRGO and amorphous steels is done in section 2.3.10.

2.3.9 Maintenance

The amorphous transformer core can be opened to allow insertion of coils before closing up again. This as illustrated in Figure 2.6, facilitates maintenance (replacement of failed windings) [12].

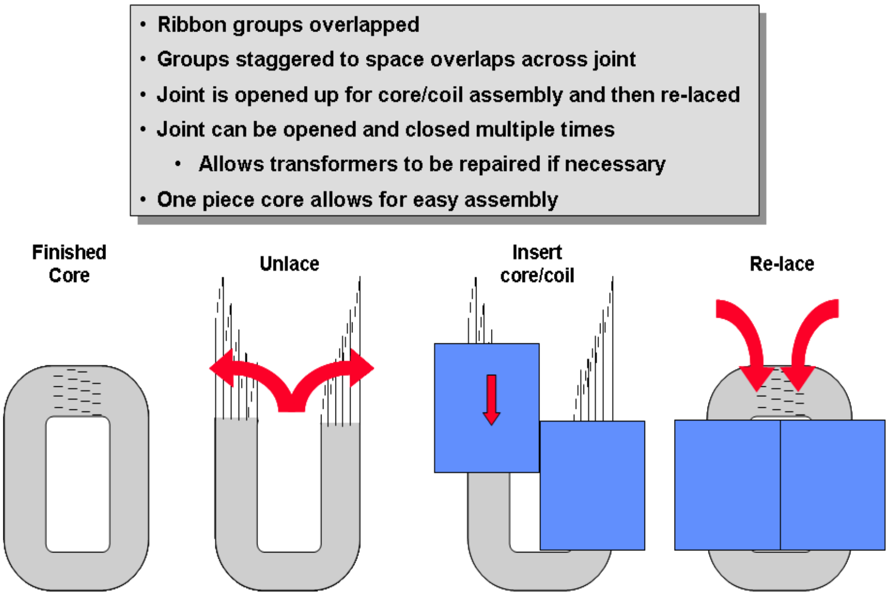

Figure 2.5: Amorphous metal distribution transformer core and coil assembly

Maintenance in CRGO transformers involves similar steps of replacing defective windings.

It is therefore expected that no appreciable increase in maintenance cost will arise when the existing CRGO transformers are replaced with AMDT type.

2.3.10 Comparisons between Amorphous and CRGO Steels

2.3.10.1 The differences in atomic arrangement, core thickness and hysteresis loss curve between CRGO and AMDT are illustrated in Figures 2.6 to 2.8.

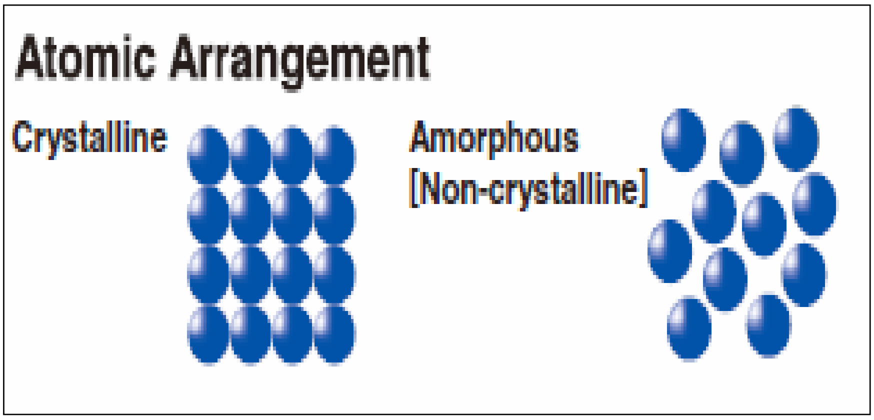

Figure 2.6: Atomic arrangement (crystalline & non-crystalline) [13]

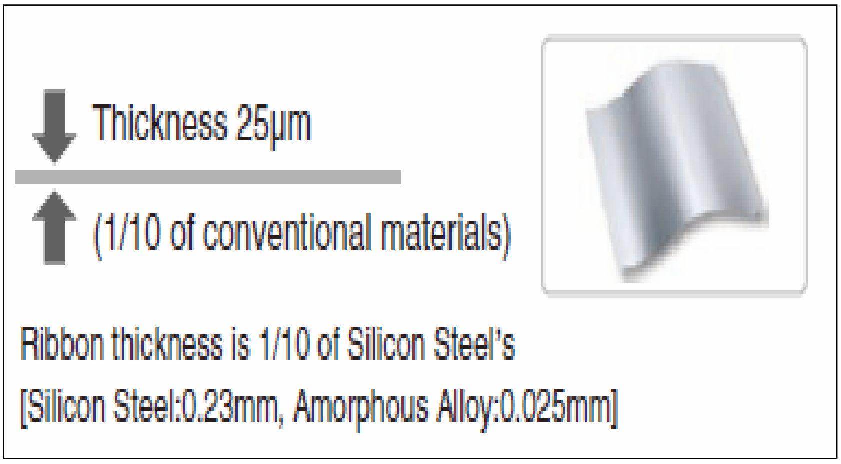

Figure 2.7: Core Thickness [13]

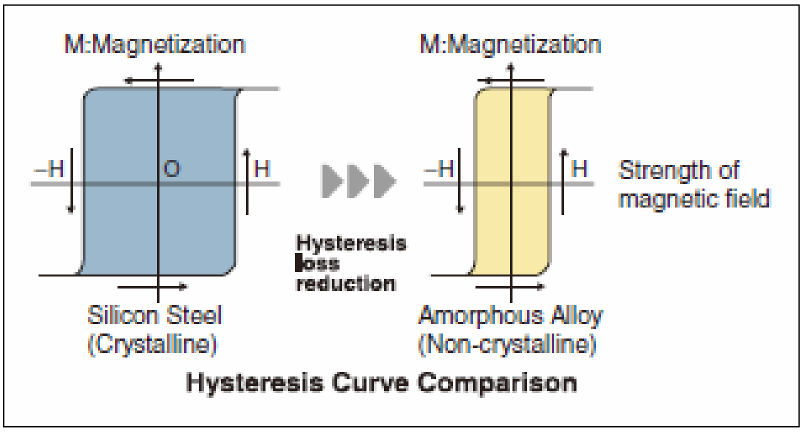

Figure 2.8: Hysteresis Curve Comparison [13]

Figure 2.9 shows typical construction of amorphous metal distribution transformer.

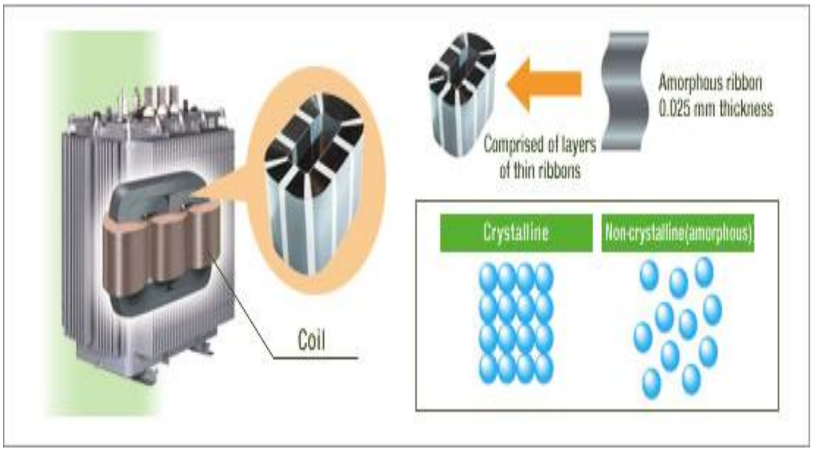

Figure 2.9: AMDT construction [13]

2.3.10.2 Characteristics that favor the use of amorphous steels are:

a) Amorphous steel is non-crystalline and has thinner hysteresis loop resulting in lower hysteresis losses when compared to CRGO.

b) Amorphous metals are available in very thin sheets and have higher resistivity resulting in lower eddy current losses when compared to CRGO.

c) Amorphous metal distribution transformers have lower no-load losses when compared to CRGO transformers.

2.3.10.3 Challenges in using amorphous steels are:

a) Amorphous steels are available in limited sizes that are unsuitable for large power transformers. Their use is limited to distribution transformers of ratings of typically up to 2.5MVA.

b) Amorphous steels have lower saturation flux density which results in limited overload.

c) Amorphous steel has poor stacking factor which results from a combination of the very large number of layers of ribbon needed to build up the total required iron section and the relatively poor flatness associated with this very thin ribbon.

d) Amorphous steels are more expensive than CRGO steels.

2.3.10.4 The challenges identified above regarding the use of amorphous transformers are not expected to hinder the implementation of the project for the following reasons:

a) The research proposes amorphous distribution transformers; the limitation on power transformers is therefore not applicable.

b) The company (KPLC) has over the last few years been reinforcing the distribution network, overloading distribution transformers is therefore unlikely.

   Reinforcement schemes of distribution transformers target ideal loading of 60%. As indicated in Figure 2.10 and Figure 2.11, the performance of amorphous transformers at such loadings is superior to CRGO.

c) The poor stack factor and poor flatness of amorphous steels leads to shell type construction which results in increase in widths for AMDT when compared to CRGO transformer. This however, is not a major problem since the transformer structures in use in KPLC are standardised at 2.2m width and will accommodate shell type constructions for pole mounted transformers of ratings up to 315KVA. The larger sizes of 630KVA and 1000KVA are mounted on the ground, adequate for shell type construction as well. The shell type construction as shown in Figure 2.5 above is repaired in similar way as the core type construction currently in use.

Figure 2.10: Efficiency vs loading [12]

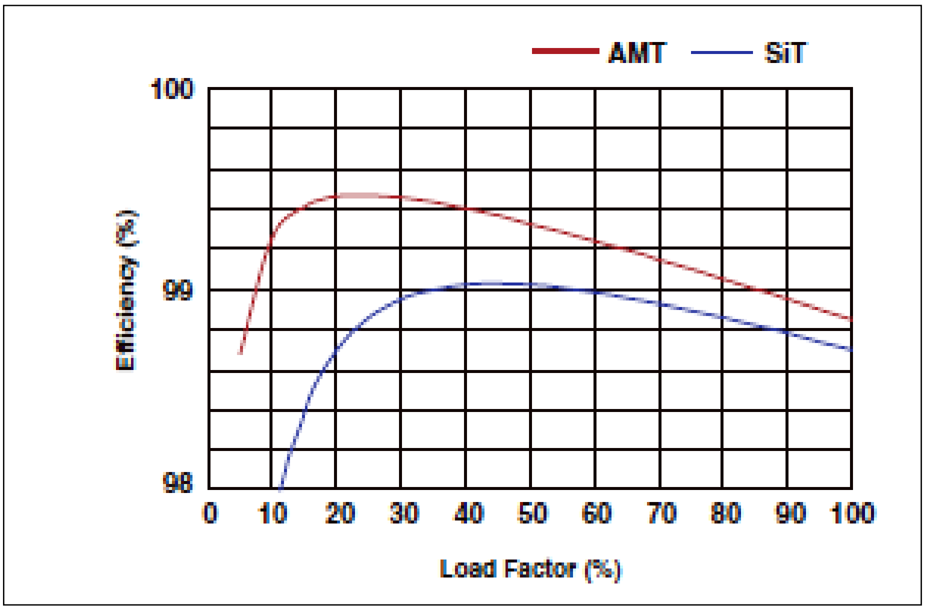

Figure 2.11: Efficiency vs Load factors (50KVA AMDT & SIT/CRGO) [13]

d) The benefits in energy cost savings and CERs resulting from reduction in carbon dioxide emissions will pay for the high cost of AMDT over the CRGO.

2.4.10.4 The physical characteristics of amorphous in comparison with CRGO steel are summarised in Table 2.1.

Table 2.1: Physical Characteristics of Amorphous compared to CRGO steels [12]

	Description	Unit	Amorphous steel	CRGO steel
1.	Density	g/cm^3	7.15	7.65
2.	Electrical resistivity	μΩ-cm	130.00	45.00
3	Saturation flux density	Tesla	1.56	2.03
4.	Typical core loss (50 Hz, 1.4 T)	Watt/kg	0.20	0.90
5.	Thickness	mm	0.025	0.27
6.	Space factor	-	0.86	0.97
7.	Brittleness	-	Higher	Lower
8.	Available form	-	Ribbon/Foil (142.2, 172.2& 213.4 mm)	Sheet/roll
9.	Annealing temperature	^0C	360	810

2.4 MEASUREMENT OF NO-LOAD LOSSES OF A TRANSFORMER

2.4.1 Test Method

The no-load loss is measured on one of the windings at rated frequency and at a voltage corresponding to rated voltage if the test is performed on the principal tapping or to the appropriate tapping voltage if the test is performed on another tapping. The remaining winding or windings are left open-circuited [14].

In the standard procedure, high voltage terminals are kept open circuited, and as far as is possible, asymmetrical and sinusoidal voltage is then applied to the low voltage winding.

The test voltage is adjusted according to a voltmeter responsive to mean value of voltage but scaled to read the r.m.s. voltage of a sinusoidal wave having the same mean value. The reading of this voltmeter is taken as U_C.

At the same time, a voltmeter responsive to the r.m.s. value of voltage is connected in parallel with the mean-value voltmeter and it’s indicated voltage U is recorded.

When a three-phase transformer is being tested, the voltages are measured between line terminals, if a delta-connected winding is energized, and between phase and neutral terminals if a star or zigzag connected winding is energized.

The test voltage wave shape is satisfactory if the readings U_C and U are equal within 3%

The measured no-load loss is Pm, and the corrected no load loss, Po, is taken as Po = Pm [1 + d] with d = [U_C - U] / U_C [13].

Voltmeter readings of average volts, rms volts, no-load loss, excitation current and frequency are usually recorded from the power analyser. The voltage and current input to power analyser is through voltage and current transformer.

2.4.2 Typical No-load Losses for existing CRGO Transformers in KPLC Network

2.5.2.1 The typical no-load losses (as per Rating Plate) for 11/0.433kV CRGO distribution transformers in KPLC network are shown in Table 2.2.

Table 2.2: Typical No-load losses for existing CRGO Transformers

RATING 11/0.433kV, KVA	Manufacturer A, W	Manufacturer B, W
50	162	160
100	254	300
200	432	435
315	610	570
630	895	1,100
1,000	1,470	1,800

The above data when plotted on a scatter diagram shows that no-load losses increase with KVA rating. The results are shown in Figure 2.12.

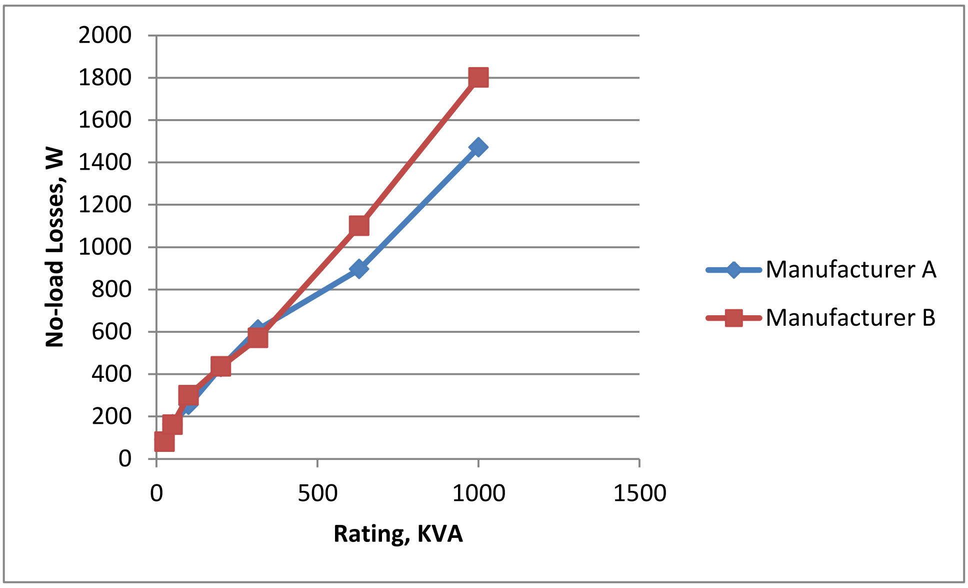

Figure 2.12: Variation of No-load losses with KVA Rating

No-load losses are therefore dependent on the KVA rating and vary among manufacturers. In the example shown in Figure 2.12, the no-load losses for both manufacturers A and B are equal for KVA ratings of up to 315KVA. However, for higher KVA ratings, manufacturer B has higher no-load losses when compared to manufacturer A.

As indicated in section 2.6, most regulations give the minimum efficiency standards allowed for transformers. This in effect implies maximum total losses allowed, and a manufacturer with high no-load losses ensures lower load losses so as to meet the requirement on minimum efficiency.

2.5 CARBON TRADING

The United Nations Framework Convention on Climate Change (UNFCCC) agreed in 1992 places most of the responsibility for taking action to limit greenhouse gas emissions on the developed countries, which are referred to collectively as Annex I countries. Annex I countries are required to report each year on the total quantity of their greenhouse gas emissions and on the actions they are taking to limit emissions [15].

The UN identified a cluster of greenhouse gases as the causes of global warming and therefore Climate change. These gases include: Carbon Dioxide (CO_2), Methane (CH_4), Nitrous Oxide (NO_2), Sulphur Hexafluoride (SF_6), Hydro-Fluorocarbons (HFC-23) &Per-Fluorocarbons (PFCs).

The Kyoto Protocol to the UNFCCC places a legally binding obligation on Annex I countries to limit their average annual greenhouse gas emissions during the “first commitment period” 2008 – 2012 to agreed targets, expressed as a proportion of their 1990 emissions. Non Annex 1 countries (includes Kenya) have no emissions reduction targets.

The Clean Development Mechanism (CDM), defined in Article 12 of the Kyoto Protocol, allows a country with an emission-reduction commitment under the Protocol to implement an emission-reduction project in developing countries. The emission reductions resulting from such projects, known as Certified Emission Reductions (CERs) can be traded and sold, and used by Annex I Parties (industrialized countries) to meet a part of their emission reduction targets under the Kyoto Protocol. Parties not included in Annex I will benefit from project activities resulting in certified emission reductions.

Examples of CDM projects include rural electrification project using solar panels or the installation of more energy-efficient equipment. Carbon credits are created by implementing a project that reduces the emission of carbon dioxide into the atmosphere. 1 ton reduced = 1 carbon credit created, officially known as CER or compliance credits.

The Grid Emission Factor (GEF) is the amount of carbon dioxide (CO_2) emissions associated with the generation of 1 unit of electricity i.e. tons of carbon dioxide per MWh of electricity generated (tCO_2/MWh).The Grid Emission Factor is key to determining the carbon revenue that grid connected renewable energy and energy efficiency projects can generate through the Clean Development Mechanism.

Through the assistance of United Nations Development Program, KPLC has developed a tool for the calculation of the GEF which is availed to CDM project proponents in the country. The tool uses the hourly dispatch data for all the generating plants in the country to calculate the GEF.

Kenyan GEF value as calculated for 2010 using the Dispatch Method with Option A1 (using actual fuel consumption) used to determine the CO_2 emission factor of the thermal power units is 0.6499tCO_2/MWh [16].

2.6 MINIMUM EFFICIENCY STANDARDS

Throughout the world, electrical utilities are adopting various energy efficiency standards. The drive is towards energy efficient transformers.

In Australia, utilities have set up Minimum Energy Performance Standards (MEPS) and High Energy Performance Standards (HEPS). Similarly, India has set up Bureau of Energy Efficiency (BEE) and Central Electricity Authority (CEA) standards to regulate the electrical utilities in that country. European countries have set up EN/IEC (International Electro-technical Commission) standards while Japan has Top-Runner Program addressing energy efficiency standards [12].

The Department of Energy (DOE) in USA has implemented Energy Conservation Standards for distribution transformers. The standards established are minimum efficiency levels. The standards apply to distribution transformers manufactured for sale in USA or imported on or after January 1, 2010. The minimum efficiency levels are at 50% loading [17].

Currently KPLC standards for distribution transformers specify CRGO steel and gives maximum total losses allowed at full load. When compared with the DOE Standards, the maximum losses set by KPLC are quite high, up to five times those set by DOE. This calls for a review of the KPLC standards towards higher efficiency.

2.7 ECONOMIC CONSIDERATIONS

2.7.1 Net Present Value

In terms of benefits and costs, NPV = B – C [18], where B is the present value of the benefits and C is the present value of the costs, NPV is the Net Present Value of the investment.

2.7.2 Payback Period

In terms of Benefits, B and Costs, C: Payback period = C/B [18]

2.7.3 Total Ownership Cost (TOC)

TOC considers: Initial Capital Cost i.e. purchase price of transformer and the Operating Cost i.e. cost for supplying the No- Load and Load losses over the life span of transformer.

TOC = Initial Cost of Transformer + Cost of the No-load Losses + Cost of the Load Losses [3] (2.6)

Cost of No Load loss = A*(No Load losses) (2.7)

Cost of Load Losses = B* (Load losses) (2.8)

A and B are called the Capitalization factors and are given by [19]:

$$A = Ec * H * [(1+r)^n – 1] / r(1+r)^n \quad (2.9)$$

$$B = A * (I_L/I_R)^2 \quad (2.10)$$

Where

Ec=Cost of Energy (Ksh/kWh)

H=Number of Hours of Operation

r =rate of Interest (%/Year)

n=Number of Years of Transformer Operation (life time of transformer)

I_L=Loading Current

I_R=Rated Current

When compared to CRGO, the amorphous metal distribution transformer will result in lower total cost of ownership.

Capitalization of losses has the following advantages:

- Enable the purchaser to evaluate the transformer cost taking into consideration loss values over the life span of the transformer.

- Enable the manufacturer to design the transformer with low losses to reduce the total life cost of transformer.

- A transformer with lower losses (both core and winding) reduces the amount of power generation needed to accommodate the losses.

- Enable the transformer manufacturer to use superior grade of materials (core and conductor) to meet the required low losses.

3. CHAPTER THREE: METHODOLOGY

3.1 RESEARCH DESIGN

The study utilized a descriptive research design with one stage of the study involving measurements.

Descriptive research involves gathering data through observations, schedules, questionnaires, interviewing or observation of records and then organizing, tabulating, depicting, and describing the data collected [20]. Descriptive research is concerned with specific predictions, narrations of facts and characteristics concerning individual, group or situation. This design was most appropriate since the aim of the study was to assess the no-load losses in CRGO distribution transformers used in KPLC network.

On the other hand, experimental research involves measurement of the effects of an experiment which the researcher conducts intentionally [20]. In this study, measurements were made to determine the typical no-load losses of representative size of existing CRGO distribution transformers. The test was carried out in accordance with IEC 60076 [14].

The overall research design specified the following:

a) The methods of data collection,
b) Selection of sample,
c) Collection of data,
d) Processing and analyzing of data,
e) Reporting of findings.

3.2 TARGET POPULATION

Data on quantities of each KVA rating of the existing CRGO distribution transformers in the KPLC distribution network was collected from all the six KPLC regional offices in the country.

Transformers for testing and details on nameplate were collected from Nairobi region. All KPLC distribution transformers are of the same specification throughout the country.

Corresponding data on amorphous distribution transformers was collected from the manufacturers.

3.3 SAMPLING PROCEDURE AND SAMPLE SIZE

The Drawing Offices in each of the six KPLC Regions maintain data on distribution transformers and carried out compilation of data on each KVA rating of existing distribution transformers. The purposive sampling technique, also called non-probability sampling, deliberate sampling and judgment sampling is the deliberate choice of an informant due to the qualities of the informant [20]. It is a non-random technique that does not need underlying theories or a set number of informants. The researcher simply decides what needs to be known and sets out to find people willing to provide the information by virtue of knowledge or experience. The research for data on quantities of each KVA rating therefore involved 6 respondents.

Samples for testing and details on rating plate were collected from new transformers. During sampling, the researcher purposively chose representative of the whole. There is advantage of time and cost inherent in this method of sampling [20].

The average KVA rating for the KPLC distribution network was computed by dividing the total installed capacity (KVA) by the total number of existing distribution transformers.

Samples of the average KVA rating were tested from the manufacturers that have supplied the largest quantity of distribution transformers to KPLC in the last ten years. Purposeful sampling needs a minimum of fifteen samples to generalize in terms of averages [21]; the study therefore covered sixteen samples.

3.4 DATA COLLECTION

Methods used in data collection include observation, questionnaires, schedules, interviewing and observation of records [20]. The researcher used observation (during testing/ measurements), schedules and observation of records in collecting primary data. The data was collected in five different categories as follows:

3.4.1 Quantities and Type of existing Distribution Transformers in KPLC Network

Primary data on quantities of existing CRGO transformers of each KVA Rating per region in the KPLC network was collected through schedules. In designing the schedule, fixed alternative (closed) questions were used to limit bias and aid in data analysis. The respondents were asked to fill in data for fixed (pre-determined) sizes. The schedule used is attached at Annex 1.

Information on type and ratings of distribution transformers in use was established by observation of records at the company's Research and Development Department which sets standards/specifications for transformers in KPLC.

To obtain data free from errors introduced by those responsible for collecting them, the researcher travelled to the six regional offices to explain and have the Drawing Office managers enter accurately the required data in the schedules.

3.4.2 Quantities and Unit costs per Manufacturer

Data on previously supplied quantities of CRGO distribution transformers per manufacturer and unit costs were obtained by observation of records at KPLC Procurement Department. Collection of data on quantities covered the last ten years while data on cost covered the last most recent tender.

3.4.3 Typical No-load Losses of existing CRGO Distribution Transformers

Samples of the average KVA rating were tested in accordance with International Standard for Power Transformers, IEC 60076 [14].

Observations were made and results recorded while the testing staff made the necessary test set-ups and measurements.

Calibrated test and measuring equipment were used during the tests.

3.4.4 Typical No-load Losses and Unit Cost of AMDT

Typical no-load losses and unit cost of amorphous metal distribution transformers were collected from three manufacturers through schedules sent by e-mail and visit by the researcher to one of the factories. In designing the schedule, fixed alternative (closed) questions were used to limit bias and aid in data analysis. The respondents were asked to fill in data for fixed (pre-determined) sizes. The schedule used is attached at Annex 2.

3.4.5 Energy Purchase Costs to KPLC

Data on energy purchase costs to KPLC were obtained from records at KPLC Planning Department. The data covered the period January to March 2012.

3.5 DATA PROCESSING AND DATA ANALYSIS

3.5.1 Descriptive Techniques

The data collected was quantitative in nature. Descriptive statistics and content analysis techniques were applied. This was done with the aid of Microsoft excel worksheet. Frequency graphs, tables and charts were used to illustrate degree of influence of certain variables to the outcome of the study.

3.5.2 Calculations

3.5.2.1 Calculation of Total Annual Energy Cost Savings

Total annual energy cost savings E_{cs} arising from the change of existing CRGO distribution transformers to amorphous type was worked out as:

$$E_{cs} = W_T(kW)*24h/day * 365days/year * A_v * \text{unit cost per kWh} \tag{3.1}$$

Where:

W_T = Total savings in no-load losses (kW) when existing CRGO distribution transformers are replaced with amorphous metal distribution transformers,

A_v = System availability factor, takes into account periods that distribution transformer is off supply due to outages/maintenance.

Unit cost per kWh was worked out based on energy purchase costs from the various generating stations.

3.5.2.2 Calculation of Reduction in CO_2 Emissions

Reduction in CO_2 emissions, $CO_{2(R)}$, was worked out using the formula:

$$CO_{2(R)} = \{W_T(MW)*24h/day*365days/yr*A_v\}*GEF\ (tCO_2/MWh) \quad (3.2)$$

3.5.2.3 Calculation of NPV, Payback Period and Total Ownership Costs

The researcher made use of standard formulae in determining net present value, payback period and total ownership costs of AMDT over the CRGO distribution transformers.

3.6 REPORTING THE FINDINGS

The researcher made use of frequency tables, graphs, charts, percentages and calculations to present the findings.

4. CHAPTER FOUR: RESEARCH RESULTS AND ANALYSIS

4.1 RESEARCH RESULTS

4.1.1 Response Rate

Drawing Office managers in the six regional offices of KPLC were the primary staff for compiling data on existing CRGO distribution transformers.

Data on amorphous distribution transformers was received from three respondents out of the four who had previously supplied CRGO distribution transformers to KPLC.

The high response rate of above 75% was attributed to the administration of schedules by researcher who made visits to explain and have the respondents fill-in and return the schedules.

4.1.2 Total number of each KVA rating of existing CRGO distribution transformers

Data collected from the six regions in KPLC were compiled and are shown in Table 4.1. The quantity for each KVA rating per region is shown before summing the figures to get the total number of existing CRGO distribution transformers for the existing network as on 31st May 2012.

Table 4.1: Total number of existing CRGO distribution transformers in KPLC

VOLTAGE RATIO	**KVA RATING**	**Total number of existing CRGO distribution transformers in service**						**Total**
		Region 1	**Region 2**	**Region 3**	**Region 4**	**Region 5**	**Region 6**	
11/0.250 kV	**5**	6	19	13	11	4	28	**81**
	15	48	380	156	104	40	189	**917**
	25	84	402	251	189	46	156	**1,128**

Table 4.1 continued

VOLTAGE RATIO	KVA RATING	Total number of existing CRGO distribution transformers in service						Total
		Region 1	Region 2	Region 3	Region 4	Region 5	Region 6	
11/0.433 kV	**50**	271	1,431	891	748	241	628	**4,210**
11/0.433 kV	**100**	292	945	452	749	249	333	**3,020**
	200	224	319	189	972	272	253	**2,229**
	315	189	179	113	935	309	152	**1,877**
	630	34	79	27	321	111	34	**606**
	1,000	10	35	52	227	75	24	**423**
33/0.250 kV	**25**	93	382	392	12	36	38	**953**
33/0.433 kV	**50**	98	1,265	685	42	84	97	**2,271**
	100	118	598	301	19	35	48	**1,119**
	200	86	195	80	10	38	28	**437**
	315	42	40	33	10	27	17	**169**
	630	15	14	11	1	7	2	**50**
	1,000	17	15	10	5	4	3	**54**
Total number of existing CRGO distribution transformers in the system								**19,544**

4.1.3 Quantities Supplied per Manufacturer

From records of supply to KPLC, the manufacturers who have supplied the largest quantity of distribution transformers in the last ten years were identified. This was necessary so as to compare no-load losses of existing CRGO transformers with AMDT from these same manufacturers. The manufacturers were coded as A, B, C and D for ease of reference in this report and also to safeguard business interests.

4.1.4 No-load Loss Measurements

Combining the quantities of the existing CRGO distribution transformers on both the 11kV and 33kV systems gives the results in Table 4.2.

The total quantities per rating as well as total capacity per rating are shown graphically in the charts in Figure 4.1 and Figure 4.2.

Table 4.2: Total quantities and capacity of existing distribution transformers per size

KVA RATING	Total number of 11kV & 33kV Transformers	Total Capacity, KVA
5	81	405.00
15	917	13,755.00
25	2,081	52,025.00
50	6,481	324,050.00
100	4,139	413,900.00
200	2,666	533,200.00
315	2,046	644,490.00
630	656	413,280.00
1,000	477	477,000.00
	19,544	2,872,105.00

The data in Table 4.2 and Figure 4.1 shows that the most prevalent rating is the 50KVA rating. However, in terms of installed capacity, the average rating is equal to the total installed capacity divided by the total number of distribution transformers giving a result of 146.96KVA. The nearest standard rating is 200KVA.

In addition, Figure 2.12 shows that no-load losses increase with KVA rating. No-load losses of 50KVA transformer cannot therefore be representative of the network since the average rating of 146.96KVA is larger than the 50KVA.

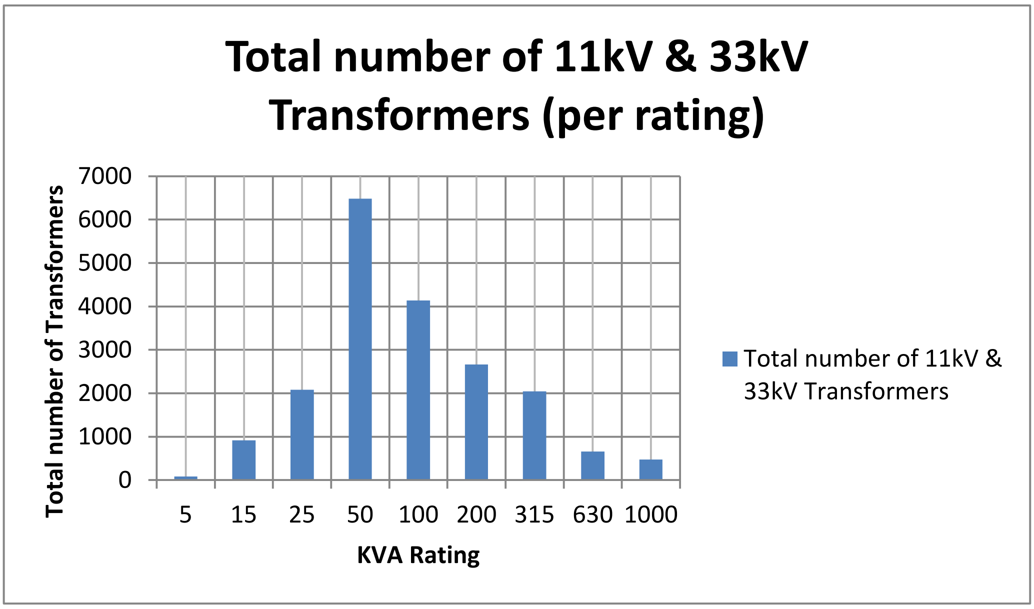

Figure 4.1: Total Number of 11kV & 33kV Transformers as per KVA Rating

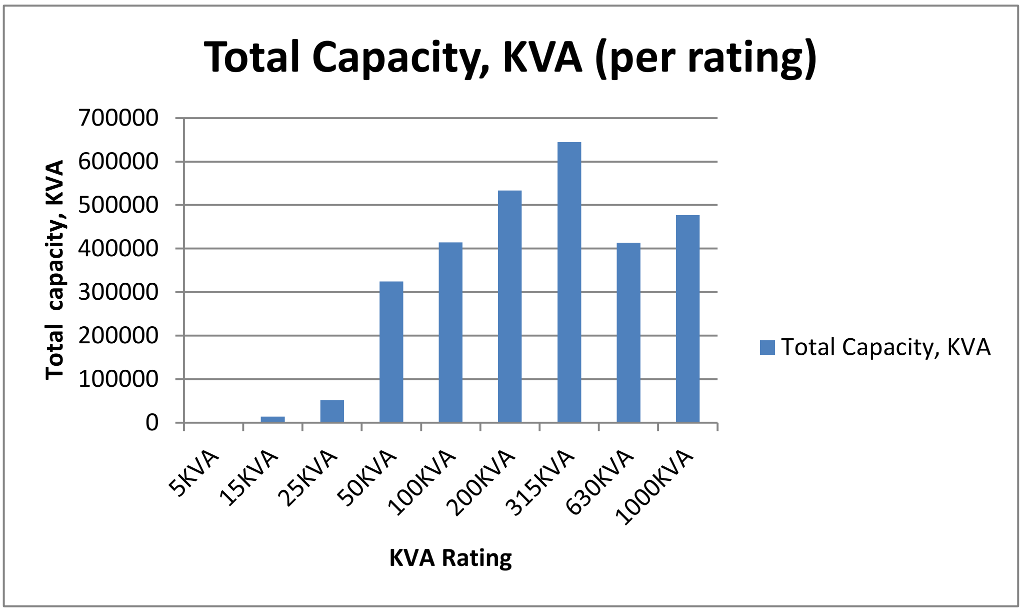

Figure 4.2: Total Capacity as per KVA Rating

The 50KVA rating constitutes 33% of all the existing distribution transformers but in terms of capacity they constitute only 11% of the installed capacity. No-load losses are capacity dependent; the average rating of 200KVA was therefore used as representative for no-load loss analysis. No-load loss measurements were therefore for samples of new 200KVA 11/0.433kV transformers, this being the average size for the installed capacity of CRGO distribution transformers (sample test reports are attached at Annex 3).

Table 4.3: Test Results of No-load Losses

	Manufacturer	**Transformer Sample Number**	**Measured Value of No-load Losses, W**
1	A	A1	324
2		A2	318
3		A3	334
4		A4	318
5	B	B1	476
6		B2	475
7		B3	468
8		B4	467
9	C	C1	631
10		C2	644
11		C3	619
12		C4	659
13	D	D1	470
14		D2	485
15		D3	452
16		D4	481
Average no-load losses, W			476

The average No-load Losses for existing CRGO distribution transformers is 476W.

4.1.5 Unit cost of CRGO transformers

For purposes of carrying out cost benefit analysis, the current unit cost of 200KVA 11/0.433kV distribution transformer to KPLC was obtained from supply records. This formed the baseline data against which the cost of the proposed AMDT is to be compared.

The most resent tender cost to KPLC of 200KVA 11/0.433kV CRGO transformer is USD 3,426 (CIF Mombasa).

4.1.6 Typical no-load losses and unit costs of 200KVA 11/0.433kV AMDT

The average no-load losses and unit cost of corresponding size of AMDT were obtained from the manufacturers who have previously supplied CRGO distribution transformers to KPLC.

The data is presented in Table 4.4:

Table 4.4: No-load losses & unit costs of 200KVA 11/0.433kV AMDT transformers

Description	Manufacturer A	Manufacturer B	Manufacturer C	Average
No-load Losses, W	173	120	120	137
Unit Cost, USD (CIF Mombasa)	3,397	6,637	7,571	5,868

4.1.7 Comparisons between CRGO and AMDT for 200KVA11/0.433kV Rating

The typical no-load losses of AMDT were compared with the corresponding CRGO distribution transformers. The differences in no-load losses between the two types were computed. The data is presented in Table 4.5.

Table 4.5: Difference in No-load Losses between 200KVARating CRGO and AMDT

Description	CRGO, x	AMDT, y,	Difference = x-y	Total savings in no-load losses= (x-y)*19,544
No-load Losses (W)	476	137	339	6,625,416

Note: The total number of existing distribution transformers as per Table 4.1 is 19,544.

The data in Table 4.5 shows that the total savings in no-load losses when all the existing CRGO transformers are replaced with the AMDT type will be 6,625,416W.

4.1.8 Energy purchase costs to KPLC

Data was collected from KPLC on total energy purchased and total payments made between January and March 2012 so as to work out the average cost per unit of electrical energy in Ksh/kWh. The data covered all the sources of energy to KPLC within the period of January to March 2012.The results are presented in Table 4.6.

Table 4.6: Energy Purchase Costs to KPLC (Jan – March 2012)

Generator (types)	**Total Energy purchased (GWh)**	**Total cost (Ksh, Billion)** (covers energy cost, fuel cost, capacity cost and forex adjustment)	**Average cost per unit (Ksh/kWh)**
Hydro, Diesel, Geothermal, Steam and Imports	1,930	20.6	10.7

The data in Table 4.6 show that the average cost per unit of electricity to KPLC is Ksh 10.7 per kWh.

The pass through costs (fuel cost and forex adjustment) are included in the unit cost to KPLC since the study covers no-load losses. The no-load losses are not recovered from the customers.

4.2 ANALYSIS

4.2.1 Total annual no-load energy losses for existing CRGO distribution transformers

The total number of existing CRGO distribution transformers is 19,544. The average KVA rating of 200KVA typically has no-load losses of 476W. The total no-load losses for the existing CRGO distribution transformers are therefore computed as 19.544*476 = 9,302,944W. This is equivalent to 81.5GWh of no-load losses per year.

As per Section 1.3, total system losses in KPLC stand at 1,071 GWh. Therefore Total No-load Losses of existing CRGO distribution transformers represent 7.6% of the system losses {(81.5/1071)*100% = 7.6%}.

The results are presented in the chart in Figure 4.3.

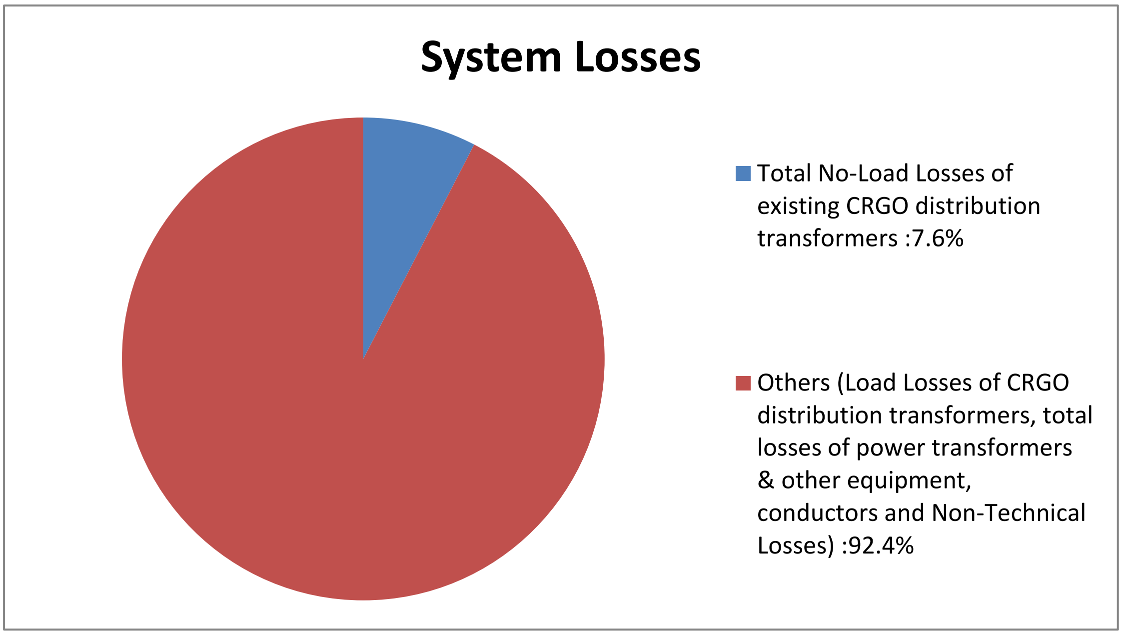

Figure 4.3: No-load losses of existing CRGO transformers against total system losses

The remainder of system losses is made up of load losses in existing CRGO distribution transformers, load and no-load losses in power transformers, transmission line losses, interlink losses, I^2R loss in distribution lines, losses due to poor power factor and harmonic currents and non-technical losses [22].

Replacing all the existing CRGO distribution transformers with AMDT type will result in total no-load losses of 19,544*137 = 2,677,528W which result in 23.5GWh per year.

When compared to the existing system losses, the no-load losses for AMDT will be 29% of the total no-load losses of CRGO transformers.

The chart in Figure 4.2 shows the comparison in total no-load losses between AMDT and CRGO distribution transformers.

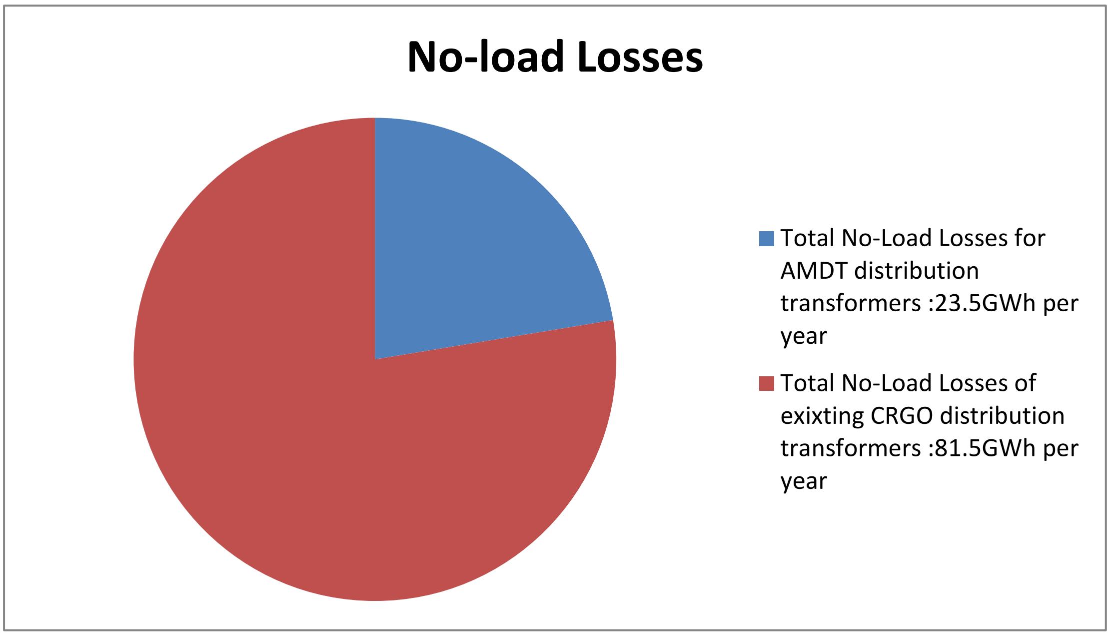

Figure 4.4: Comparison of total no-load losses between AMDT and CRGO

Saving in No-load Loss units when all the existing CRGO distribution transformers are replaced with amorphous metal distribution transformers will be (81.5 – 23.5) GWh = 58GWh per year.

The total system losses will therefore reduce by 58GWh to 1013GWh per year

As a percentage, the system losses will therefore be 15.1% of the total energy purchased by KPLC as compared with current value of 16%. This will represent a reduction of 0.9% in system losses, and will be in line with the requirements of The Energy Regulatory Commission which has set targets for KPLC requiring reduction in system losses since these are considered when setting tariffs.

The target system loss factor was 16.4% in 2008/09, 15.9% in 2009/10 and 15.4% in 2010/11 [23].

Transformers with lower losses in effect reduce the amount of power generation needed to accommodate the losses.

4.2.2 Total annual energy cost savings

As per Equation3-1, $E_{cs} = W_T(kW)$* 24h/day * 365days/year * A_v x unit cost per kWh

Where W_T = Total savings in no-load losses when existing CRGO distribution transformers are replaced with amorphous metal distribution transformers.

A_v = System availability factor, takes into account periods that distribution transformer is off supply due to outages/maintenance. In the absence of accurate data, this factor was taken as 1.

Unit cost per kWh (to KPLC) was worked out based on energy purchase costs by KPLC from the various generating stations.

As per Table 4-5, W_T = 6,625,416W

Therefore;

E_{sc}= 6,625.4kW* 24h/day* 365days per year*Ksh10.7/kW

= Ksh 621 million per year.

The total annual energy cost savings to be realized by KPLC when all the existing CRGO distribution transformers are replaced with amorphous metal distribution transformers will be Ksh 621 million per year at the current average cost per unit.

Replacing all the 19,544 existing CRGO distribution transformers at once is not practical given that the transformers are spread countrywide and logistical challenges as well as service interruptions to customers will results in huge losses.

Replacement in phases at the rate of 5,000 units being procured per year would result in total annual energy cost savings of ¼ *Ksh 621 million per year = Ksh 155 million per year.

4.2.3 Reduction in CO_2 emissions

As per Equation 3-2, $CO_{2(R)}$ = {W_T (MW) * 24h/day * 365days/year * A_v} * GEF (tCO_2/MWh).

Where: GEF is the amount of carbon dioxide (CO_2) emissions associated with the generation of 1 unit of electricity i.e. tons of carbon dioxide per MWh of electricity generated (tCO_2/MWh), given as 0.6499 tCO_2/MWh by KPLC.

Other parameters are as defined in 4.2.2 above.

As per Table 4-6, W_T = 6,625,416W

Therefore

$CO_{2(R)}$=6.6MW* 24h/day* 365 days/year* 0.6499 tCO_2/MWh

= 37,575 tCO_2 per year

At the current rate of 7.0 Euro per ton of CO_2 emission reduction, the benefit to the company will be: Ksh37,575* 7*109 = Ksh29 million per year (at current exchange rate of Ksh 109 per Euro)

4.2.4 Cost Benefit Analysis

Cost benefit analysis was done for 200KVA 11/0.433kV distribution transformer, this being the average size in terms of installed capacity in the KPLC network.

Table 4.7 shows the typical data for 200KVA 11/0.433kV distribution transformers:

Table 4.7: Unit cost data for 200KVA 11/0.433kV distribution transformer

Voltage Ratio	**KVA Rating**	**Indicative Unit Cost, AMDT** (USD)	**Unit Cost, CRGO** (USD)	**Difference in unit cost between AMDT & CRGO** (USD)
11/0.433 kV	200 KVA	5,868	3,426	2,442

As per Table 4.5,

Savings in no-load losses for each existing 200KVA 11/0.433kV distribution transformer is: $W_{200KVA11/0.433kV}$ = 339W.

4.2.4.1 Net Present Value

NPV = KshB_x.PVIFA(i,n) – C_x.

Where B_x = Ksh (W_{TX})*(24)*(365)*(unit cost per kWh) per year and C_x is the difference in price between CRGO and AMDT transformers of Size X.

Therefore for 200KVA 11/0.433kV and based on Tables 4-3, 4-5,4-6, 4-7 and Present Value Interest Factor of Annuity standard tables:

$NPV_{200KVA11/0.433kV}$ = [0.339*24 * 365 * 10.7* 6.811] – [(2442)*83]

= Ksh(216,421 – 202,686) = Ksh 13,735

The NPV is positive; this favours the undertaking of the project (of replacing all existing CRGO distribution transformers with AMDT type).

4.2.4.2 Payback Period

Payback period = C_x/B_xyrs = 202,686/216,421 = 0.94 years = 11.2 months.

The Payback Period is less than one year, this favours the undertaking of the project (of replacing all existing CRGO distribution transformers with AMDT type).

4.2.4.3 Total Ownership Cost

As per Equations 2-8 to 2-12(with parameters already defined):

TOC = Initial Cost of Transformer + Cost of No-load Losses + Cost of Load Losses.

= Initial Cost of Transformer + A*(No Load losses) + B* (Load losses)

From Table 4-7 and discount rate of 12% (r = 0.12) for n = 15yrs, A = Ksh Ec * H * $[(1+r)^n - 1] / r(1+r)^n$ =10.67*24*365 $[(1+0.12)^{15} -1]/0.12(1+0.12)^{15}$

= Ksh 637,234.6 per kW= USD 7,677.53 per kW

B = $A*(I_L/I_R)^2$ = USD7,677.53*$(0.6)^2$ per kW = USD 2,763.91 per kW, with a load factor of 0.6.

For 200KVA 11/0.433kV and with data given in Tables 4-3, 4-4, 4-5 & 4-6, the TOC for each type is:

CRGO transformer: TOC_{CRGO} = USD 3,426 + 7,677.53(0.476) + 2,763.91(Load Losses)

= USD 7,080.5 + 2,763.91(Load Losses)

AMDT transformer: TOC_{AMDT} = USD 5,868 + 7,677.53(0.137) + 2,763.91(Load Losses)

= USD 6,919.8 + 2,763.91(Load Losses)

Therefore assuming equal Load Losses between the 200KVA 11/0.433kV CRGO and AMDT transformers, then the Total Ownership Costs of CRGO transformer are higher than the AMDT type.

5. CHAPTER FIVE: DISCUSSIONS AND CONCLUSIONS

5.1 DISCUSSIONS

1) The total annual no-load energy losses for entire network of existing CRGO distribution transformers in KPLC network is 81.5GWh.

   The total system losses reported for 2010 were 1071GWh. This means that the total no-load losses of existing CRGO distribution transformers are 7.6% of the total system losses in the network. The remainder of system losses are due to the load losses of the distribution transformers, no-load and load losses of power transformers, transmission line losses, interlink losses, I^2R loss in distribution lines, losses due to poor power factor and harmonic currents and non-technical losses.

2) The total no-load losses for equivalent number of amorphous metal distribution transformers are 29% of the total no-load losses of existing CRGO distribution transformers.

3) Total annual cost savings (to KPLC) in no-load energy losses if all existing distribution transformers were replaced by amorphous metal distribution transformers would be Ksh 621Million per year.

   The savings reduce to Ksh 559 Million per year if a system availability factor of 90% is applied. However, replacing all the 19,544 existing CRGO distribution transformers at once is not practical given that the transformers are spread countrywide and logistical challenges as well as service interruptions to customers will result in huge losses and customer dissatisfaction.

   It is therefore recommended that replacement be done in phases at the rate of the 5,000 units being procured per year resulting in total annual energy cost savings of Ksh 155 million per year.

4) The reduction in CO_2 emissions resulting from the energy savings would be 37,575 tCO_2 per year, which at the current market rate of Euro 7 per tCO_2emission reduction translates to a benefit (under CDM) to KPLC of Ksh29 million per year.

5) Cost-Benefit analysis of replacing existing distribution transformers with the amorphous metal distribution transformers reveals positive Net Present Values, Payback Periods of less than one year and reduction in Total Ownership Costs. All these favour the undertaking of the project (of replacing all existing CRGO distribution transformers with AMDT type).

6) Maintenance of AMDT follows the same principles as CRGO distribution transformers. The core is opened and windings replaced in a similar manner. However, familiarisation with the new technology will be necessary in the initial stages especially for the maintenance staff. Training is therefore recommended for the maintenance staff.

5.2 CONCLUSIONS

The use of amorphous metal distribution transformers will reduce the no-load losses in KPLC distribution network and result in cost savings of Ksh 621 million per year and reduction in CO_2 emissions of 37,000 tons per year. The system losses will reduce by 0.9% to 15.1% and help KPLC achieve target system loss factor set by the regulator (Energy Regulatory Commission, Kenya).

6. CHAPTER SIX: REFERENCES

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ANNEX 1: Schedules (1 to 6)

STATION/REGION ……………………………………………..

Voltage Rating	KVA Rating	Total number of distribution transformers in service
11/0.250 kV	5	
“	15	
“	25	
11/0.433 kV	50	
“	100	
“	200	
“	315	
“	630	
“	1,000	
33/0.250 kV	25	
33/0.433 kV	50	
	100	
	200	
	315	
	630	
	1,000	

ANNEX 2

1. **Data received from Manufacturer A for AMDT transformers**

Voltage Ratio	KVA Rating (KVA)	Specific core loss (W/kg)	No load loss, amorphous transformer (W)	Indicative Price (CIF Mombasa) (USD)
11/0.25kV	5	0.201	11	339
	15	0.204	20	557
	25	0.204	28	803
11/0.433kV	50	0.204	50	1,376
	100	0.204	87	2,035
	200	0.204	173	3,397
	315	0.204	245	5,036
	630	0.204	350	10,206
	1,000	0.204	480	13,062
33/0.25kV	25	0.204	38	1,227
33/0.433kV	50	0.204	66	2,080
	100	0.204	114	2,876
	200	0.204	195	4,220
	315	0.204	310	6,283
	630	0.204	460	11,690
	1,000	0.204	625	15,070

2. Data received from Manufacturer B for AMDT transformers

Voltage Ratio	KVA Rating (KVA)	Specific core loss (W)	No load loss, amorphous transformer (W)	Indicative Price (CIF Mombasa) (USD)
11/0.25kV	5	-	-	-
	15	-	-	-
	25	-	-	-
11/0.433kV	50	-	43	4,184
	100	-	75	4,814
	200	-	120	6,637
	315	-	170	9,852
	630	-	320	15,186
	1,000	-	450	27,350
33/0.25kV	25	-	-	-
33/0.433kV	50	-	85	5,670
	100	-	120	6,507
	200	-	175	9,192
	315	-	245	12,535
	630	-	420	21,020
	1,000	-	590	35,681

3. Data received from Manufacturer C for AMDT transformers

Voltage Ratio	KVA Rating (KVA)	Specific core loss (W)	No load loss, amorphous transformer (W)	Indicative Price (CIF Mombasa) (USD)
11/0.25kV	5	0.22	18	1,855
	15	0.22	25	2,661
	25	0.22	32	2,903
11/0.433kV	50	0.22	43	3,575
	100	0.22	75	5,230
	200	0.22	120	7,571
	315	0.22	170	10,184
	630	0.22	320	16,488
	1,000	0.22	450	20,935
33/0.25kV	25	0.22	55	5,161
33/0.433kV	50	0.22	75	7,079
	100	0.22	110	9,675
	200	0.22	158	14,007
	315	0.22	240	18,840
	630	0.22	390	30,007
	1,000	0.22	580	37,684

ANNEX 3: Sample Test Results of No-load Losses (CRGO)

Product Specification

Rated Capacity 200 kVA Phase number 3

Frequency 50 Hz Connection symbol Dyn11

Ratings:HV:11000V±2×2. 5%, 10. 5A;LV:433V, 266. 7

Test Result

1、D.C. resistance Temperature 21.0 ℃

Item NO.	H.V. (Ω)				
	I	II	III	IV	V
AB	8.170	7.951	7.733	7.517	7.299
BC	8.163	7.945	7.727	7.511	7.297
CA	8.168	7.950	7.731	7.516	7.297

L.V. (Ω)	ao	bo	co
	0.004231	0.004230	0.004276

2、Measurement of voltage ratio and check of connection symbol

The tolerances of voltage ratio: 0.4 % , Connection symbol: Dyn11

3、Insulation Resistance Temperature 21.0 ℃

.HV.-L.V. 2000 MΩ H.V-earth 2000 MΩ L.V-earth 2000 MΩ

4、Separate-source voltage withstand test

Connection of experiment	Pressure-proof kV	Time s	Conclusion
H.V.- L.V. and earth	38	60	Pass
L V.-. H.V and earth	5	60	Pass

5、Induced H.V. imposed voltage by L.V. side 200%, 100 Hz, 60 Seconds pass.

6、No-load experiment : No-load loss 318 watt, No-load current 2.16 %

7、Short circuit Test: Load loss(75℃) 2397 Watt., impedance voltage (75℃) 4.22 %

8、 Transformer Oil: 25# Breakdown Voltage 45 kV

Result of Authentification

Each test item, in pursuant to IEC-60076 , of this product has passed the examination, It could be put into service.

Testing assistant: 沈涛 Review: 2011.10.20

Product Specification

Rated Capacity 200 kVA Phase number 3

Frequency 50 Hz Connection symbol Dyn11

Ratings:HV:11000V±2×2. 5%, 10. 5A;LV:433V, 266. 7A

Test Result

1、D.C. resistance Temperature 21.0 ℃

Item NO.	H.V. （Ω）				
	I	II	III	IV	V
AB	8.115	7.896	7.678	7.463	7.242
BC	8.112	7.893	7.675	7.461	7.240
CA	8.106	7.887	7.669	7.455	7.235
L.V. （Ω）	ao		bo		co
	0.004337		0.004345		0.004382

2、Measurement of voltage ratio and check of connection symbol

The tolerances of voltage ratio: 0.4 %, Connection symbol: Dyn11

3、Insulation Resistance Temperature 21.0 ℃

.HV.-L.V. 2000 MΩ H.V-earth 2000 MΩ L.V-earth 2000 MΩ

4、Separate-source voltage withstand test

Connection of experiment	Pressure-proof kV	Time s	Conclusion
H.V.- L.V. and earth	38	60	Pass
L V.-. H.V and earth	5	60	Pass

5、Induced H.V. imposed voltage by L.V. side 200%, 100 Hz, 60 Seconds pass.

6、No-load experiment : No-load loss 324 watt, No-load current 2.00 %

7、Short circuit Test: Load loss(75℃) 2399 Watt., impedance voltage（75℃）4.19 %

8、 Transformer Oil: 25# Breakdown Voltage 45 kV

Result of Authentification

Each test item, in pursuant to IEC-60076 of this product has passed the examination, It could be put into service.

Testing assistant: 汪凡 Review: 2011.10.20

Product Specification

Rated Capacity 200 kVA Phase number 3

Frequency 50 Hz Connection symbol Dyn11

Ratings:HV:11000V±2×2.5%, 10.5A;LV:433V, 266.7A

Test Result

1、D.C. resistance Temperature 21.0 ℃

Item NO.	H.V. (Ω)				
	I	II	III	IV	V
AB	8.168	7.948	7.730	7.514	7.292
BC	8.195	7.976	7.758	7.542	7.320
CA	8.169	7.950	7.732	7.517	7.296

L.V. (Ω)	ao	bo	co
	0.004236	0.004248	0.004276

2、Measurement of voltage ratio and check of connection symbol

The tolerances of voltage ratio: 0.4 % , Connection symbol: Dyn11

3、Insulation Resistance Temperature 21.0 ℃

.HV.-L.V. 2000 MΩ H.V-earth 2000 MΩ L.V-earth 2000 MΩ

4、Separate-source voltage withstand test

Connection of experiment	Pressure-proof kV	Time s	Conclusion
H.V.- L.V. and earth	38	60	Pass
L V.-. H.V and earth	5	60	Pass

5、Induced H.V. imposed voltage by L.V. side 200%, 100 Hz, 60 Seconds pass.

6、No-load experiment : No-load loss 334 watt, No-load current 2.54 %

7、Short circuit Test: Load loss(75℃) 2392 Watt., impedance voltage (75℃) 4.14 %

8、Transformer Oil: 25# Breakdown Voltage 45 kV

Result of Authentification

Each test item, in pursuant to IEC60076, of this product has passed the examination, It could be put into service.

Testing assistant: 沈鸿l Review: 2011.10.20

试验站

Product Specification

Rated Capacity 200 kVA Phase number 3

Frequency 50 Hz Connection symbol Dyn11

Ratings:HV:11000V±2×2. 5%, 10. 5A;LV:433V, 266. 7

Test Result

1、D.C. resistance Temperature 21.0 ℃

Item NO.	H.V. (Ω)				
	I	II	III	IV	V
AB	8.170	7.951	7.733	7.517	7.299
BC	8.163	7.945	7.727	7.511	7.297
CA	8.168	7.950	7.731	7.516	7.297

L.V. (Ω)	ao	bo	co
	0.004231	0.004230	0.004276

2、Measurement of voltage ratio and check of connection symbol

The tolerances of voltage ratio: 0.4 %, Connection symbol: Dyn11

3、Insulation Resistance Temperature 21.0 ℃

HV.-L.V. 2000 MΩ H.V-earth 2000 MΩ L.V-earth 2000 MΩ

4、Separate-source voltage withstand test

Connection of experiment	Pressure-proof kV	Time s	Conclusion
H.V.- L.V. and earth	38	60	Pass
L V.-. H.V and earth	5	60	Pass

5、Induced H.V. imposed voltage by L.V. side 200%, 100 Hz, 60 Seconds pass.

6、No-load experiment: No-load loss 318 watt, No-load current 2.16 %

7、Short circuit Test: Load loss(75℃) 2397 Watt., impedance voltage (75℃) 4.22 %

8、 Transformer Oil: 25# Breakdown Voltage 45 kV

Result of Authentication

Each test item, in pursuant to IEC-60076, of this product has passed the examination, It could be put into service.

Testing assistant: 沈彪 Review: 2011.10.20

25/10/11