REDUCING LOSSES IN ELECTRICAL DISTRIBUTION SYSTEMS USING AMORPHOUS TRANSFORMERS

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Abstract-More than ever, electric utilities and industries today are searching for technologies that will reduce their operating costs and improve energy savings throughout their systems. New transmission and distribution technologies are now available to help utilities meet these goals.
Modern standard grain-oriented silicon steel does give low loss and this loss has been reduced substantially over the years by improvements in treatment, such as cold-rolling and laser-scribing. Future improvements in standard silicon steel losses will be relatively modest.
However, amorphous magnetic metal used for transformer cores does give the possibility of decrease core losses compared to standard core steel materials. The magnetic core of this transformer is made with amorphous metal, which is easily magnetized / demagnetized
In this paper is presented a comparison between traditional distribution transformers and amorphous distribution transformers. The advantages of amorphous distribution transformers are also investigated.

Key words: transformers, losses, efficiency, distribution systems

1. Introduction

Electric power distribution is the portion of the power delivery infrastructure that takes the electricity from the highly meshed, high-voltage transmission circuits and delivers it to customers.

The modern distribution system begins as the primary circuit leaves the sub-station and ends as the secondary service enters the customer's meter socket. A variety of methods, materials, and equipment are used among the various utility companies, but the end result is similar. More than ever, electric utilities and industries today are searching for technologies that will reduce their operating costs and improve energy savings throughout their systems. New transmission and distribution technologies are now available to help utilities meet these goals.

ANSI/IEEE defines a transformer as a static electrical device, involving no continuously moving parts, used in electric power systems to transfer power between circuits through the use of electromagnetic induction. The term *power transformer* is used to refer to those transformers used between the generator and the distribution circuits, and these are usually rated at 250 kVA and above [1]. Power systems typically consist of a large number of generation locations, distribution points, and interconnections within the system or with nearby systems, such as a neighboring utility. The complexity of the system leads to a variety of transmission and distribution voltages. Power transformers must be used at each of these points where there is a transition between voltage levels. Power transformers are selected based on the application, with the emphasis toward custom design being more apparent the larger the unit. Power transformers are available for step-up operation, primarily used at the generator and referred to as generator step-up transformers, and for step-down operation, mainly used to feed distribution circuits. Power transformers are available as single-phase or three-phase apparatus. The construction of a transformer depends upon the application. Transformers intended for indoor use are primarily of the dry type but can also be liquid immersed. For outdoor use, transformers are usually liquid immersed. It is estimated that 3% of all electricity generated is lost due to distribution transformer inefficiency. Inherent in the operation of distribution transformers are two types of energy loss: load losses that vary depending on transformer loading, and no-load losses that occur in the magnetic cores and take place over the life of the transformer regardless of the load. No-load losses represent a significant portion of the energy lost during power distribution. Using transformers with core made from amorphous material, the no-load losses can be reduced significant.

2. Transformer losses

An ideal transformer would have no power losses, and would be 100% efficient. In practical transformers energy is dissipated in the windings, core, and surrounding structures.

Transformer losses are produced by the electrical current flowing in the coils and the magnetic field alternating in the core. The losses associated with the coils are called the load losses, while the losses produced in the core are called no-load losses.
Transformer losses can be determinate with the following expression:

$$\Delta P_T = \Delta P_0 + \Delta P_S \qquad (1)$$

where:

ΔP_T - total losses in transformer;

ΔP_0 - no-load losses;

ΔP_S - load losses.

2.1 Transformer no-load losses

The no-load losses are essentially the power required to keep the core energized. These are commonly referred to as "core losses," and they exist whenever the unit is energized. No-load losses depend primarily upon the voltage and frequency, so under operational conditions they vary only slightly with system variations [2].
They include losses due to 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 can be calculated with the following mathematically expression:

$$\Delta P_0 = \Delta P_{hys} + \Delta P_{eddy} \qquad (2)$$

where:

ΔP_{hys} - hysteresis losses;

ΔP_{eddy} - Eddy current losses in core.

Hysteresis losses are caused by the frictional movement of magnetic domains in the core laminations being magnetized and demagnetized by alternation of the magnetic field. These losses depend on the type of material used to build a core. Silicon steel has much lower hysteresis than normal steel but amorphous metal has much better performance than silicon steel. Hysteresis losses are usually responsible for more than a half of total no-load losses (50% to 70%). This ratio was smaller in the past (due to the higher contribution of eddy current losses particularly in relatively thick and not laser treated sheets)
Eddy current losses are caused by varying magnetic fields inducing eddy currents in the laminations and thus generating heat. These losses can be reduced by building the core from thin laminated sheets insulated from each other by a thin varnish layer to reduce eddy currents. Eddy current losses nowadays usually account for 30% to 50% of total no-load losses. When assessing efforts in improving distribution transformer efficiency, the biggest progress has been achieved in mitigation of these losses.

2.2 Transformer load losses

Load losses, as the terminology might suggest, result from load currents flowing through the transformer.
Transformer load losses include I^2R losses in windings due to load current (ohmic losses), eddy losses due to leakage fluxes in the windings, stray losses caused by stray flux in the core clamps, magnetic shields, tank wall, etc., and losses due to circulating current in parallel windings and parallel conductors within windings [3].

$$\Delta P_S = \Delta P_{RI} + \Delta P_{EC} + \Delta P_{SL} \qquad (3)$$

where:

ΔP_{RI} - losses due value of the current and resistance of the transformer;

ΔP_{EC} - Eddy Current Losses;

ΔP_{SL} - Stray Losses.

Ohmic heat loss, sometimes are referred as copper loss, since this resistive component of load loss dominates. This loss occurs in transformer windings and is caused by the resistance of the conductor. The magnitude of these losses increases with the square of the load current and is proportional to the resistance of the winding.

Conductor eddy current losses. Eddy currents, due to magnetic fields caused by alternating current, also occur in the windings. Reducing the cross-section of the conductor reduces eddy currents, so stranded conductors are used to achieve the required low resistance while controlling eddy current loss.
Stray loss occurs due to the stray flux which introduces losses in the core, clamps, tank and other iron parts. Stray loss may raise the temperatures of the structural parts of the transformer.

To reduce losses in transformers, two elements can be adapted: core and windings. Transformer design is complex, with many of the characteristics of distribution transformers specified in national or international standards. In the following, is meant to reduce no-load losses (transformer core losses).

3. Amorphous transformers

While modern standard grain-oriented silicon steel does give low loss and this loss has been reduced substantially over the years by improvements in treatment, such as cold-rolling and laser-scribing, future improvements in standard silicon steel losses, while achievable are not likely to give any significant step decrease in loss: any improvements in losses in traditional core steel will be relatively modest.
Amorphous magnetic metal used for transformer cores does give the possibility of decrease core losses compared to standard core steel materials. The magnetic core of this transformer is made with amorphous metal, which is easily magnetized / demagnetized.[4]

3.1. Amorphous metal advantages

Amorphous metal is a unique alloy whose structure of metal atoms occurs in a random pattern as opposed to conventional Cold-Rolled Grain-Oriented (CRGO) silicon

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steel, which has an organized crystalline structure. The higher resistance to magnetization and demagnetization through the crystalline structure leads to higher core losses in CRGO.
Amorphous metals are made of alloys which have no atomic order. The lack of systematic structure has given them the additional name metallic glasses.
Rapid cooling of molten metals prevents crystallization and leaves a vitrified solid with structure in the form of thin strips – a perfect energy saving substitute for CRGO.
The random molecular structure of amorphous metal causes less friction then SiFe when a magnetic field is applied. This unique property allows for greater ease of magnetization and demagnetization and significantly lowers hysteresis losses in amorphous metals. In addition, amorphous metals have very thin laminations, resulting in lower eddy current losses.[4]
A comparison between amorphous metal and CRGO steel in terms of properties is presented in Table 1.

Table1. Comparison of properties

Properties	Amorphous metal	CRGO steel
Density, [g/cm^3]	7.15	7.65
Specific resistance	130	45
Saturation flux density, [Tesla]	1.56	2.04
Thickness, [mm]	0.025	0.27
Space factor	0.86	0.97
Brittleness	Higher	Lower
Annealing temperature, [^{o}C]	360	810
Annealing atmosphere	Inert gas	Inert gas
Special annealing requirement	Magnetic field annealing	-
Coefficient of rolling	94.8 %	82 %
Available form	Ribbon/foil	Sheet/ Roll
Typical core loss, [W/kg] (at 50Hz, 1.4 Tesla)	0.20	0.90

Amorphous metal material allows the construction of a low-loss core. Amorphous metal is extremely thin, has high electrical resistivity, and has little or no magnetic domain definition. Cores made from this material can exhibit 60–70 percent lower core losses than one made of conventional steels. However, amorphous metal material does have some drawbacks: It saturates at a lower flux level of 1.56 Tesla versus 2.04 Tesla for conventional materials, and it has higher excitation requirements. Amorphous metal material is also fragile and requires special handling during the construction process. Additionally, these designs cannot be “packed” as effectively into the winding window, causing the designs to have a space factor of 85 percent versus 95–98 percent for steel core materials, which increases losses. The net effect of the lower flux density and higher space factor is a larger core with greater winding (conductor) losses and higher production costs.
Amorphous metals exhibit[5]:
- easier magnetization (low coercivity and high permeability);
- lower magnetic loss (low coercivity, high permeability and high resistivity);
- faster flux reversal (as a result of low magnetic loss)
-versatile magnetic properties resulting from post-fabrication heat-treatments and a wide range of adjustable chemical compositions.

3.2. Comparison of no-load losses in CRGO and AMDTr

Losses of the electricity network world-wide can be estimated at 1 279 TWh, or 9.2% of electricity use. These are technical losses, including losses in power cables and lines, power and distribution transformers, metering loss. Non-technical losses are not included[6].

Traditional distribution transformers are contributing to important energy losses across diverse distribution networks. Core losses are present in the transformers even when they are under no-load conditions; in addition, the load factor is very low. Put together up to 3% of all electrical power generated is wasted through transformer losses worldwide.
In selecting the material for core, we say that amorphous metal core outflanks in reducing the no-load losses. This can summate immense economic savings to the electric utilities since they are one of the highest energy efficient transformers rated so far.
In amorphous metal core transformers, core losses can be reduced by up to 75% compared with CRGO transformers assuming that performance parameters like load loss (copper loss), impedance and temperature rise remain constant[7].
The core loss is voltage-dependent and also slightly temperature dependent. Thus, if the distribution grid voltage level changes, the core loss will also change. A higher voltage will generate higher losses and a lower voltage lower loss. The temperature dependence is complex in that the hysteresis loss will increase slightly with increased temperature but the eddy current loss will decrease with temperature increase because of increase of resistance with temperature.

The Figure 1 illustrate typical losses of a 1000 kVA standard CRGO transformer, low loss CRGO transformer and the amorphous transformer.

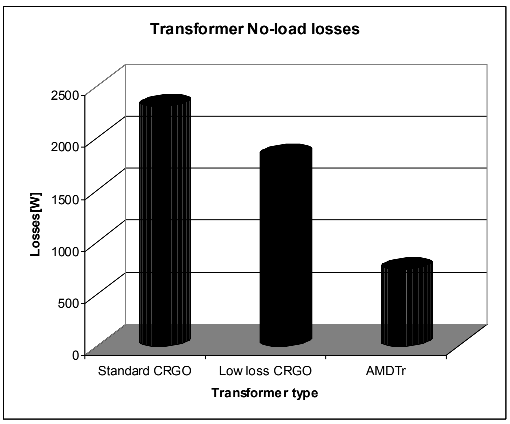

Figure 1 Transformer no-load losses

In the following it is presented variation of no load losses for dry-type transformers. The primary voltage is 20 kV and the secondary is 0.4 kV. It is taking in consideration transformers which are found in distribution systems.

Table 2 No-load Losses

Rated Power (kVA)	Standard CRGO (W)	Low loss CRGO (W)	AMDTr (W)
100	560	443	179
160	870	689	278
250	1100	871	352
630	2000	1585	640
1000	2300	1822	736
1600	3500	2773	1120
2500	5000	3962	1600

In figure 2, no-load losses are presented for 3 construction types of transformer core for different rated powers.

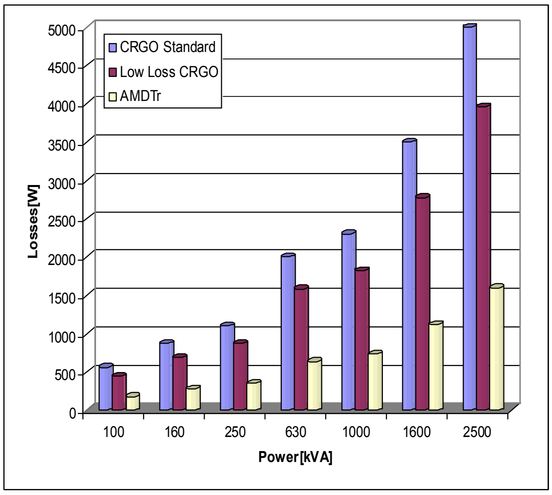

Figure 2 No-load losses for different rated powers of transformers

3.3. Losses reduction due to non-linear loading (i.e. harmonic distortion)

The transformers operation in non-sinusoidal conditions produces supplementary power losses in its components: windings and magnetic circuits.
Both components of core loss (hysteresis and eddy current losses) are dependent on the AC frequency at which the magnetic field alternates, so that when frequency increases, the core loss will increase. Hysteresis loss increases linearly with frequency but eddy current loss scales as the square of frequency. Thus any higher harmonic components in the exciting voltage will cause increased core loss [8].
Use of best quality core material like Amorphous Magnetic alloy offers great advantage not only at fundamental frequency but, the advantage increase manifold as the distortion in both load current and supply voltage increases. There is increase in total loss and decrease in efficiency with higher distortions, but this phenomenon is affecting this core material much less as compared to transformer with poor quality core.
Smaller thickness and higher resistivity lead to lower magnetic loss at higher frequencies in amorphous transformer cores.
Before the excess losses can be determined, the harmonic spectrum of the wave must be known.
The harmonic content for a Total Harmonic Distortion of 25 % is presented bellow:

Table 3 Harmonic Spectrum

Harmonics	Content	Harmonics	Content
1	100 %	11	9 %
3	1 %	13	6 %
5	20 %	15	1 %
7	10 %	17	5 %
9	1 %		

A 3 phase, 250 kVA Transformer was tested under non-harmonic and harmonic conditions and the values noted down for losses are as follows:
- without harmonic distortion (Table 4);
- with total harmonic distortion of 25% (Table 5).

Table 4 Losses without harmonic distortion

Losses	**AMDTr**	**CRGO**
Hysteresis (A)	99	155
Eddy Current (B)	33	311
Total Core Loss (C)= (A+B)	132	466
Load Loss (D)	966	1084
Loading	55%	58%
Total Loss (C+D)	1098	1550

Table 5 Losses with THD of 25%

Losses	**AMDTr**	**CRGO**
Hysteresis (A)	99	155
Eddy Current (B)	74	698
Total Core Loss (C)= (A+B)	173	853
Load Loss	1553	1671
Loading	55%	58%
Total Loss (C+D)	1726	2524

A comparison chart for losses, when transformer is working in sinusoidal state and also in polluted harmonic state is presented in following figure:

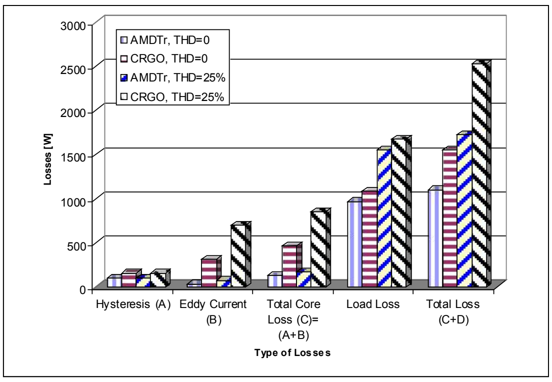

Figure 3 Losses in CRGO and AMDTr transformers without/with harmonic distortion

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Thus, it is very evident form above tables that AMDTr (Amorphous Metal Distribution Transformers) are no doubt superior and offer a better technology at our disposal.

4. Transformer efficiency

Transformers which are connected to the power supplies and loads and are in operation are required to handle load current and power as per the requirements of the load.
An unloaded transformer draws only the magnetization current on the primary side, the secondary current being zero. As the load is increased the primary and secondary currents increase as per the load requirements. The volt amperes and wattage handled by the transformer also increases. Due to the presence of no load losses and I^2R losses in the windings certain amount of electrical energy gets dissipated as heat inside the transformer. This gives rise to the concept of efficiency.

Efficiency of power equipment is defined at any load as the ratio of the power output to the power input. Distribution transformers are very efficient electrical machines reaching maximum efficiency at the level of 97,5% to 99,4%. Operating efficiency is smaller because transformers do not operate at maximum efficiency all the time.

This maximum efficiency point is at the point where load losses proportional to square of transformer load are equal to the no load losses which are constant and appear all the time when the transformer is energized (usually between 40% and 50% loading).
The efficiency for transformers with rated power of 2000 kVA is presented in figure 4; it is taking in consideration 2 types of cores for transformers: cold rolling grain oriented steel and amorphous metal. The load of transformers takes values between 0 and 100 %.

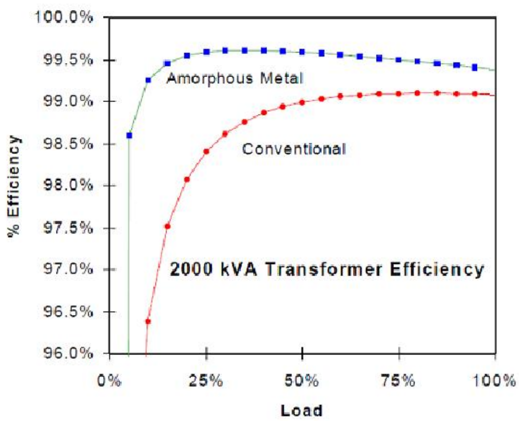

Figure 4 Transformer efficiency (Conventional and Amorphous)

The efficiency for amorphous transformers, as it can be seen, is higher than conventional transformer. AMDTr is the ideal solution in case the loading of transformer is very low.

5. Saving potential

Transformer losses represent power that can not be delivered to customers and therefore have an associated economic cost to the transformer user/owner.
To determinate the saving potential by using amorphous transformers against steel core transformers, it is necessary to calculate the annual energy losses.
The annual energy losses of a transformer can be estimated from the following expression [2]:

$$W_{loss} = (P_0 + P_S \cdot L^2) \cdot 8760h \qquad (4)$$

in which:

W_{loss} - is the annual energy loss in kWh;
L – is the average per-unit load on the transformer;
8760 – number of hours in a year [h/year].

To calculate the losses cost, it is necessary to establish their value (in prices) at the moment of transformer purchase, trough capital values. This is called the Total Capitalized Cost of the losses, TCC_{loss}. This can be calculated using the following formula (5):

$$TCC_{loss} = W_{loss} \cdot \frac{(1+i)^n - 1}{i \cdot (1+i)^n} \cdot C_{kWh} \cdot 8760 \qquad (5)$$

where:

i – is the estimated interest rate[%/year];
n – is the expected life time of the transformer [years];
C_{kWh} - kWh price [EURO/year].

Total Capitalized Cost of the no load losses for transformers taking in consideration (1000 kVA standard CRGO, low loss CRGO and AMDTr), when lifetime of transformers take values from 1 to 30 years, is presented in figure bellow:

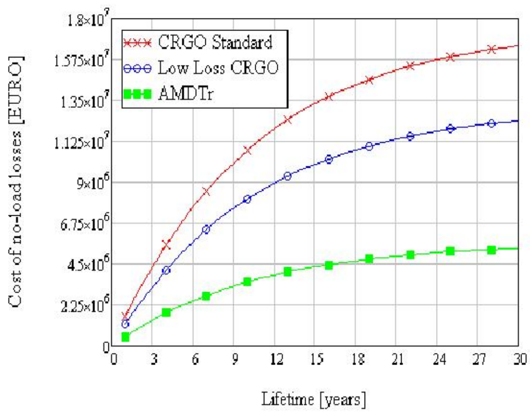

Figure 5 Total Capitalized Cost of no-load losses in CRGO versus AMDTr

Total capitalized cost of no-load losses in case of using amorphous transformers is less than other two cases (CRGO Standard and Low Loss CRGO).

6. Conclusions

Several studies have compared CRGO and amorphous transformers in terms of energy efficiency and profitability, and all conclude that amorphous transformers are the most energy efficient options.

There are very little differences in production techniques between AMDTr and CRGO steel wound core transformer, mostly to do with material handling.

Due to lower design inductions and lower space factors than CRGO steel, amorphous cores are heavier.

Loss benefits of material are being caring over into no-load losses of distribution transformers.

In case of amorphous transformers no-load losses are with 60-80 % less than cold rolled grain oriented transformers. Efficiency of AMDTr transformers is higher (range between 0.5 – 1 %) than CRGO transformers.

Under pure sinusoidal excitation, amorphous metal-based transformers exhibit about ¼ of the no-load loss of a high-grade silicon-steel. This corresponds to an annual worldwide potential savings of about 125 TWh and annual reduction of CO_2emission of about 100 million tons.

Under harmonic conditions which are the actual conditions we are in, potential energy savings are considerably higher than the above. The energy savings is estimated at ~220 TWh.

Worldwide use of amorphous metal-based transformers, therefore, will help us reduce fossil-fuel dependency and create cleaner environment with higher air quality.

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