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# Comparative Study of Transformer Core Material

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**Abstract:- Most essential equipment in power distribution and transmission is Transformer. Defining a transformers is of utmost importance while specifying the requirements of power system. Understanding of the manufacturing processes and work flow to the extent that ensures the optimum, cost-effective and reliable design of transformer is required. Core of the transformers is a key part that carries the major portion of total cost and performance. Hence during the engineering of the core the material shall be chosen in such a way that it ensures the minimum loss and also low capital cost. This paper highlights the selection criteria, the evolution and standard practice that have been adopted in industry for core of transformer.**

**Basic Components of oil type Transformer:**

- **Core**
- **Winding**
- **Oil**

**The processing of these three major materials, consist of almost 70% of transformer price. 30% of total transformer weight is contributed by Core and a significant percentage of cost for total transformer. Transformer loss is having an impact on running cost in the term of revenue for its lifelong operation.**

***Keywords:-*** *Hi-B, CRGO, Eddy Loss, Hysteresis Loss, Rolled, Induction, Improved Steel, Core Loss, Electrical Steel.*

## I. INTRODUCTION

Transformer has two types of losses:

a) No Load Losses – Also known as core loss, it has two major contributors

- Hysteresis Loss – depends on steel chemistry and processing
- Eddy Loss - depends on thickness of steel, geometry, proximity to steel parts

Load Losses – Also known as Conductor loss

- $I^2R$ Loss - depends on material (Copper or Aluminium), cross sectional area and length

Where I is current flowing and R is the offered resistance

## II. TRANSFORMER CORE AND EFFICIENCY

The magnetic flux linkage between Primary and Secondary winding takes place through a low reluctance path provided by transformer core. The reluctance depends on the size, material, type and magnetic stress of the core and no-load characteristics of the transformer. The transformer performance depends on no-load loss expressed as per following formula:

$$\%EFF = \frac{100*kVA*0.5}{kVA*0.5+((NL+LL*0.91*0.5^2)/1000)}$$

Where:
%EFF = Efficiency that is the ratio of the useful power to the total power input calculated at 50% Load
KVA = Transformer rated capacity in KVA
NL = No Load Losses generally corrected to 20°C
LL = Load Losses generally corrected to 85°C
0.91 = Load Loss Temperature correction from 85°C to 55°C

No-load current, no-load loss, inrush current and magnetic noise of the transformer is expressed by the no-load characteristics. No-load loss is the most important parameter to measure transformer performance and it is of fixed kind loss.

- *Core Loss*

Core loss is expressed as follows:

$$P_{fe} = K_{fe}(\Delta B)^{\beta} A_c l_m$$

Where $\Delta B$ is the peak value of the AC component of B (t), the peak flux density. So increasing $\Delta B$ will cause core loss to increase gradually.
Core loss is made up of two components:

a) The hysteresis loss varies proportinately with the supply frequency and depends on the area of the hysteresis loop. Hysteris loop is a characteristic of the material and a function of the peak flux density

$$\text{Hysteresis loss, } W_h = k_1 f B_{max}^{\ n} \text{ watts/kg} \quad \text{--Eq. (1)}$$

b) The second is the eddy current loss which is dependent on the square of frequency but is directly proportional to the square of the core material thickness, referred as equation (2) as follows:

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

Where,
$k_1$ and $k_2$ are constants for the material
t is thickness of the material, in mm
$\rho$ is the resistivity of the material

$B_{max}$ is maximum flux density, in Tesla(T)

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

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

The core of a transformer is made up of silicon steel. This iron core has the ability to carry magnetic flux. The property of carrying flux is called permeability of that magnetic material. Modern steels materials, used for core design, have permeability in the order of 1500 compare with 1.0 for air. This means that the ability of a steel core to carry magnetic flux is 1500 times than that of air.

The first transformers manufactured in the 1880s had cores made from high grade wrought iron, there after Swedish iron was preferred. However, in about the year 1900 it was recognized that small addition of aluminium or silicon to the iron as impurity, reduced the magnetic losses. Thus journey for the specialised electrical steel making journey was started. The following type of steel are largely accepted throughout the world by all reputed transformer manufacturer for core:

a) Hot Rolled Steel
b) Cold Rolled Steel
c) High Permeability Steel
d) Domain Refined Steel

| Steel Grade | Impact on Hysteresis loss | Impact on eddy Current Loss $Note | |
|---|---|---|---|
| | | Classical*Refer Note 1 | Anomalous*Refer Note 2 |
| Hot rolled steels (thickness 0.35 mm ) | Reduce area of hysteresis loop by addition of silicon and reduction of impurities especially carbon | | |
| Cold rolled steels (thickness 0.28 mm ) | Alignment of grains within ± 6% of rolling direction reduces hysteresis | Thinner sheets of CRGO leads to reduction in eddy current loss | |
| High permeability Steel | Better alignment of grains results in 30-40% reduction in hysteresis loss | Stress coating reduces eddy-current loss and susceptibility to handling induced loss increases | |
| Domain refined steel | | | Reduced domain size reduces eddy-current loss |

Table 1

[$Note: In general the eddy current term is a complex one and can be considered to consist of following two components:

a) Classical Eddy Current Loss.
b) Anomalous Eddy Current Loss

First one can be calculated in accordance with classical electromagnetic theory. The second is dependent on the structure of the material such as grain size and magnetic domain movement during the magnetizing cycle. It is also known as residual loss.

*Note 1- Classical eddy current loss really varies as the square of supply frequency times material thickness and flux density as mentioned by the equation (2). It mainly depends on plate thickness and resistivity. Addition of silicon will increase the resistivity.

*Note 2- Anomalous eddy current loss is dependent on the structure of the material viz. grain size and magnetic domain movement during the magnetizing cycle. This can account for around half the total loss for any particular type of steel. It is this anomalous loss which can be greatly reduced by special processing of the core material as it affects significantly in controlling grain size and magnetic domain movement, so that this forms the basis of most of the modern approaches towards the reduction of core loss and development of special type advanced core for transformer.

## III. NO LOAD LOSSES

Impact of design

$$\text{Induction} = \frac{\text{Constant} \times \text{Rated voltage}}{\text{Turns} \times f \times \text{Core Area}}$$

Where

a) Rated voltage and number of turns refer to either the high voltage or low voltage side of transformer
b) Induction is a function of the electrical steel limited by its saturation value
c) f is the frequency of the supply

Every type of steel has "grains" which consist of "domains". These "domains" are orientation of electrical charges in any random direction. Therefore if a transformer core is made of Mild Steel, the core loss would be approx. 16 to 17 w/kg, at flux density 1.5T with a frequency 50Hz and the size of the transformer would be approx. 18 to 20 times the size of a transformer manufactured with grain oriented (GO) steels.

## IV. EVOLUTION OF 'GO' STEEL FROM CARBON STEEL

Before the usage of 'GO' steel, core design of transformer was governed by rectangular interleaved corners, larger yoke than core (limb) cross-section, and clamping by bolts passing through the active core area. For large power transformer, the yoke section becomes very heavy resulting in increased height of the transformer. There is a limitation gradually imposed by the loading gauge of the railways route or the road along which the transformer is to be transported. This leads to a significant increase in overall dimension for very large transformer and plant size from layout view point.

Thus it becomes necessary to reduce the transformer size to overcome the above limitations. With advent of the grain oriented steel the three limbed construction for 3-phase transformer use identical yoke and limb cross-section.

It had been identified in the early 1920s that the silicon steel crystals were themselves anisotropic, but it was not until 1934 that the American N. P. Goss patented an industrial production process, which was chiefly developed by ARMCO in the USA, that commercial use was made of this property.

In the year 1939 commercial production of grain oriented silicon steel was started. At that time the thickness was 0.32 mm and a loss of 1.5 W/kg at 1.5 T, 50 Hz was recorded. The process involved is shown in Figure 1. This is the backbone of the production of cold-rolled grain-oriented steels for many years. 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 to 2.5 mm.

Major difference between "carbon" steels and grain oriented (GO) steels are:

a) To reduce the hysteresis loss, the size of the "grains" in GO steels purposely "grown" and made bigger and are about 10 times as compared to regular steel, thereby reducing the hysteresis losses. The size of grains in CGOS is 2 mm to 5mm whereas the same is 5mm to 20mm in HGOS. In regular steels the size of a grain is less than 0.5mm.
b) In GO steels, the grains are all aligned almost parallel to the direction of rolling of the steel (i.e. the length of the steel). The angle of mis-orientation is maximum 7% for conventional GO and less than 3% for Hi-B GO steels. This reduces the hysteresis losses drastically.
c) The chemical composition of the GO steels indicates that 3.2% of Silicon as an alloy, thereby increasing, the resistivity of the steel, therefore eddy current is reduced. GO Steels are also de-carbonized and have no more than 0.06% of carbon in their chemical composition. This prevents ageing of the steel.
d) For reducing the inter-laminar Eddy-current losses a special carlite insulation coating is used in the steel.

- *Step wise Development of Steel Material for Transformer Core*

Hot rolled steel

Cold rolled Grain Oriented Steel
(Production from 1939 onwards)

High-permeability steel (production from 1965 onwards)

Domain-refined steel (production from 1983 onwards)

Amorphous steel (production started form mid-1970 onwards but till date commercial production is restricted)

Microcrystalline steel (recently developed in Japan and experimentally has been used, not under commercial use till date)

Fig 1

## V. ADOPTION OF IMPROVED STEELS

Cold rolled grain oriented (CRGO) steel came into picture in 1940s and it almost replaced the earlier hot-rolled steels in 1950s for core design of the transformer. In the year 1981 worldwide production of grain-oriented steel was high-permeability grade and it's usage was around 12%. By 1995 usage of high-permeability material for transformer core design almost became the norm.

The earliest grades of CRGO were known as M10 and M9 with flux density approx.1.00 watts/lb. and 0.90 watts/lb. respectively at 1.5T/60Hz. These were manufactured by ARAMCO in early forties. After that CRGO has been developed gradually to next higher grades. In 1955, grades M7 and M6 with approx.0.7w/lb and 0.6w/lb at 1.6T/60Hz were developed and were the most widely used grades of CRGO materials.

With further development in late sixties M3, M4 and M5 appeared.

The Hi-B Grain Oriented Steel grades (HG-OS) were developed in the early seventies and in mid eighties laser scribed material was developed.

Conventional CRGO materials (M4, M5 and M6) are regularly used core materials for Transformers. But now days to minimize core loss as well as due to energy saving issues the Hi-B (M0H, M1H, and M2H etc.) core materials are widely used and their usage is also increasing.

## VI. COMPARATIVE CORE LOSS

| Thickness | | Grade | Core Loss | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | Max. | Typical | | | | Typical |
| mm | mil | | W (W/Kg) | W (W/Kg) | W (W/Kg) | W (W/Kg) | W (W/Kg) | B (T) |
| 0.23 | 9 | 23ZDKH85 | 0.85 | 0.57 | 0.78 | 0.34 | 0.46 | 1.91 |
| | | 23ZDKH90 | 0.90 | 0.58 | 0.80 | 0.35 | 0.48 | 1.91 |
| | | 23ZDMH85 | 0.85 | 0.57 | 0.78 | 0.34 | 0.46 | 1.91 |
| | | 23ZDMH90 | 0.90 | 0.59 | 0.81 | 0.35 | 0.48 | 1.91 |
| | | 23ZH90 | 0.90 | 0.63 | 0.87 | 0.37 | 0.51 | 1.92 |
| | | 23ZH95 | 0.95 | 0.64 | 0.90 | 0.38 | 0.53 | 1.92 |
| | | 23M-OH | 1.00 | 0.66 | 0.93 | 0.39 | 0.54 | 1.92 |
| 0.27 | 11 | 27ZDKH90 | 0.90 | 0.62 | 0.84 | 0.38 | 0.53 | 1.92 |
| | | 27ZDKH95 | 0.95 | 0.65 | 0.88 | 0.39 | 0.52 | 1.91 |
| | | 27ZDMH90 | 0.90 | 0.62 | 0.84 | 0.38 | 0.53 | 1.91 |
| | | 27ZDMH95 | 0.95 | 0.65 | 0.88 | 0.39 | 0.53 | 1.91 |
| | | 27ZH95 | 0.95 | 0.69 | 0.93 | 0.41 | 0.55 | 1.91 |
| | | 27M-OH | 1.03 | 0.72 | 0.99 | 0.43 | 0.59 | 1.91 |
| | | 27M-1H | 1.09 | 0.74 | 1.03 | 0.44 | 0.61 | 1.91 |
| 0.30 | 12 | 30ZH100 | 1.00 | 0.73 | 0.98 | 0.44 | 0.58 | 1.92 |
| | | 30M-OH | 1.05 | 0.74 | 1.01 | 0.44 | 0.60 | 1.91 |
| 0.35 | 11 | 35M-1H | 1.16 | 0.85 | 1.13 | 0.52 | 0.68 | 1.92 |
| | | 35M-2H | 1.22 | 0.90 | 1.19 | 0.54 | 0.73 | 1.92 |

Table 2

➢ *Figure Between Crgo And Hi-B Steel*

During over-excitation the operating flux density of core material carries a significant impact on the overall size and material cost. The more improved quality of core materials than CRGO however does not have higher saturation level though they have lesser loss and magnetizing VA. The saturation flux density gets limited by the over-excitation conditions specified by users. The slope of B-H curve of CRGO material significantly worsens after about 1.9 T (for a small increase in flux density, relatively much higher magnetization current is drawn). In case of simultaneous overvoltage and under frequency the flux density increases to high level in core. Hence, under above said condition if over-excitation is a%, general guideline can be used for operating peak flux density of [1.9/(1+a/100)]. For a power system, in which a voltage profile is well maintained, a continuous over-excitation condition of 5% considered. In this case operating flux density will be of 1.8T.

| USA | | | | | | | |
|---|---|---|---|---|---|---|---|
| AISI ( 1983 ) | | | | | | | |
| MAXIMUM CORE LOSSES - Electrical Steels Grain Oriented Full Processed ASTM A665 | | | | | | | |
| ASTM Type | Former AISI Type | Thickness | | Maximum Core Loss at 15 kg (1.5 T) | | | |
| | | | | W / lb | | W /kg | |
| | | Inch | mm | 60Hz | 50Hz | 60Hz | 50Hz |
| 27G053 | M-4 | 0.0106 | 0.27 | 0.53 | 0.40 | 1.17 | 0.89 |
| 30G058 | M-5 | 0.0118 | 0.30 | 0.58 | 0.44 | 1.28 | 0.97 |
| 35G066 | M-6 | 0.0138 | 0.35 | 0.66 | 0.50 | 1.46 | 1.11 |

Table 3

## VII. NO LOAD MATERIAL IMPACT

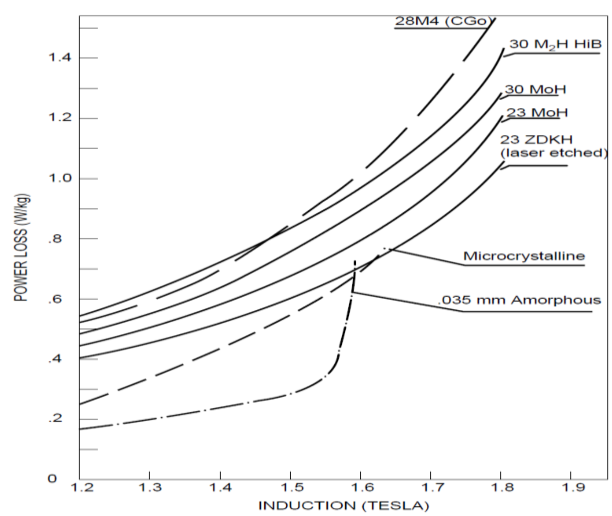


Fig 2:- Power loss versus induction at 50 Hz for various materials

## VIII. WORLD INSTALLED PRODUCTION OF GRAIN ORIENTED SILICON STEEL (Data Courtesy of Sumitomo Corporation) As of 2007

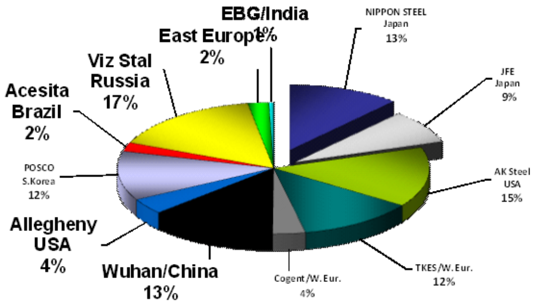


Fig 3

## IX. WORLD INSTALLED PRODUCTION OF HI B SILICON STEEL* - As of 2007

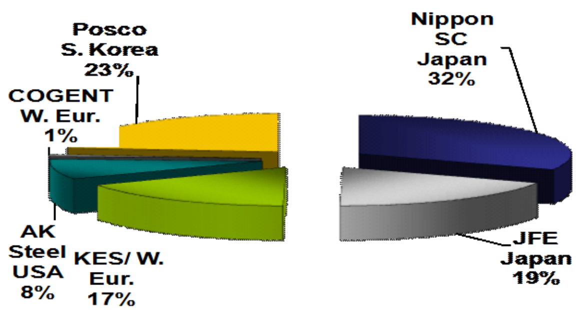


Fig 4:- *- Data Courtesy of Sumitomo Corporation

The availability of high grade steel is much lesser than the actual requirement. Now a days with trend of super critical (660 MW) and Ultra Critical (800 MW) Power plant, the large power transformer (especially GT and ST) manufacturing have been increased in a significant amount. Hence, the availability of Hi-B and CRGO steel should be more in modern days.

## X. IMPACT ON MATERIALS

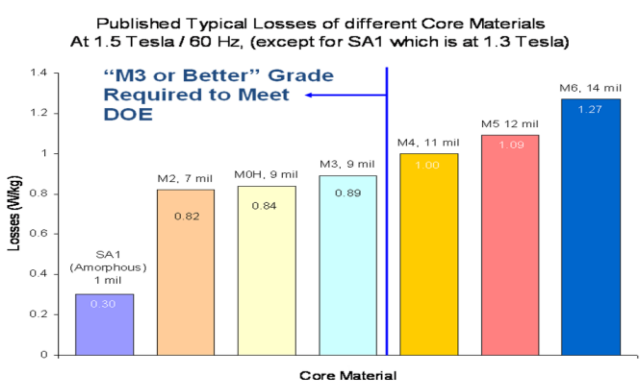


Fig 5

Even M3 and higher grade shall be used for distribution transformer also.

## XI. INCLUSION OF ADVANCED CORE MATERIAL IN SPECIFICATION OF POWER PROJECTS

Reputed Consultants and utility company often generalize the clause of the core material instead of writing any specific materials. But some utility is very specific generally for 400 KV and above for the use of Hi-B as core materials.

## XII. PRACTICE OF REPUTED MANUFACTURER

Now a day's most reputed manufacturer of EHV grade transformer are using Hi-B grade Steel as core material. Siemens, ABB , Alstom/GE etc. have adopted the practice of using Hi-B as core material for large power transformer. Distribution transformer with higher size is usually adopting high grade CRGO like M4, M5.

## XIII. HANDLING OF TRANSFORMER CORE MATERIAL

The transformer core selection alone can't give the desired result regarding improvement of transformer performance. The core material needs to be carefully handled also and following are the main areas of consideration:

- The gross cross sectional area of core is=l*b (where l=length and b=breadth and include the cross sectional area of core material & insulating material). But the net cross sectional area is only considered as effective path for magnetic circuit.

Net cross sectional area:

Net cross sectional Area = Stacking factor (also called Iron factor) (Ks) * gross cross sectional Area
Where always Ks <1

The stacking factor is always near to unity. If it decreases the net cross sectional area decreases which leads to increase in density and core losses.

Now in order to keep the stacking factor to near unity, the core material needs to be shaped very carefully during giving it to required shape. Also reputed transformer core manufacturer have faced difficulties in this point even if after high technologies and machines take charge of workmanship.

- Slitting, shearing, notching, holing etc. are the processing operations which all damage the grain structure of the GO material around the area of fabrication and working. Most of these induced stresses can be removed by stress relief annealing. To determine the effect of annealing, two stacks of Epstein samples measuring 30 mm x 305 mm were

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fabricated from M4 grade CRGO steel coils. Stack 1 was cut and annealed in a fast single sheet roller hearth annealing furnace at a temperature of around 820ºC and stack 2 was left un-annealed

| | Core loss at 1.5T/50Hz (w/kg) | Core loss at 1.7T/50Hz (w/kg) |
|---|---|---|
| Stack 1(annealed) | 0.82 | 1.36 |
| Stack 2(un-annealed) | 1.00 | 1.61 |

Table 4

This experiment has been conducted later on various higher grade steel. However the results are similar. So, this annealing is considered as extra requirement and hence increases the cost.

## XIV. COMMERCIAL IMPLICATION OF CORE MATERIAL IN MEDIUM AND LARGE SIZE POWER TRANSFORMER

As per the available data from standard manufacturer the difference of price between M5 or M6 GRGO Steel and Hi-B steel is nearly INR 30, 000/kg. So, the requirement of specified core material shall be mentioned in pre-bid stage of a project, because it has a huge commercial implication on overall price of transformer. However using higher grade of Steel increases the capital cost and also makes the stacking of core difficult as higher grade steel needs to be handled very carefully.

## XV. CONCLUSION

The core material of transformer is a very critical item in terms of performance and stability of overall power generation and distribution system. So, the successive research work shall be done to develop cost effective but high quality core material (steel) generation and availability of the same at manufacturer workshop in time to meet up the delivery schedule of large power transformer.

## REFERENCES

[1]. By Carlos Gaytan Manager of Engineering Distribution Transformers April 29, 2008.
[2]. J&P Transformer Handbook.
[3]. Website of KRYFS: Manufacturers of CRGO Strips, CRGO Transformer Laminations and CRGO Core in Mumbai, India.
[4]. High Voltage Engineering and Testing by Hugh Mclaren Ryan (Institution of Electrical Engineers).
[5]. Transformer Engineering by S.V Kulkarni and S.K Khaparde.