Reducing Building Factor by Using Step Lap (SL) Laminations

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Summary:

A proper value of the Building factor (BF) is important while calculating the No-Load Loss (NLL) of any power or distribution transformer. It is an empirically derived factor which is based on the experience of the Transformer Manufacturer (TM) and ranges from 1.08 to 1.35 for three phase, three limb cores. Step Lap (SL) construction of transformer core instead of conventional but type construction (or Non Step Lap (NSL) type) which is still widely used by TMs in India, has been successfully used by various TMs world over, to reduce the Building factor in Transformer cores by 5 to 8%, reduce the No Load current and the noise level relative to conventionally stacked NSL cores. This paper explains how SL laminations reduce the No Load Loss in a transformer by considering the specifics of magnetic Flux transfer in joints areas of a SL core versus a NSL transformer core.

The magnetic circuit is one of the most important active parts of any transformer. While the basic principle of transformation of energy has remained the same for over a century, since the first transformer was built, transformers have become more efficient due to improvements in materials and more sophisticated production processes (better manufacturing technology).

This paper examines one such production process which reduces the NLL, No Load current and noise level of a transformer and hence improves its efficiency.

BF is a non dimensional parameter defined as the Ratio of (No Load Loss of a transformer / core weight) in watts per kg to the Epstein or Single Sheet watt loss (in watts per kg).

Therefore $BF = \frac{(\text{NLL measured on transformer in watts per kg})}{(\text{Epstein or Single Sheet Test loss in watts per kg})}$

BF ensures that the NLL of a transformer does not equal to the core weight of the transformer multiplied by the Single sheet loss as defined by the producing Mill at the particular operating flux density. For example, if the core weight is 200 kgs for a 100 KVA transformer, manufactured from M4 grade material and operating at 1.7 Tesla, if the material used is C 120 27 (i.e conventional M4 grade GO having a core loss of 1.2 Watts per kg at 1.7 Tesla) then the Maximum NLL should simply be 200 kgs x 1.2 w/kg = 240 watts. However, in practice it is never so for a three phase, three limb core due the BF.

BF depends on various factors, some of the major ones being the following:

1. **Core Geometry**: BF is directly proportional to the Area of Proportion of Corner Joints to the total core area, kinds of joints (SL or NSL), Air gaps, overlap area at joints, etc.
2. **Quality of workmanship of Core**: Burrs in Laminations, Accuracy of dimensions especially at the corner joints (precision of angles), flatness of the laminations, dust particles in between laminations, skills in core building (squareness of the core), clamping pressure on the core etc.
3. **Grade of Material Being used**: Whether material used is Hi-B Grain Oriented (HGO) or Conventional Grain Oriented (CGO) which affects the stacking factor of material, Insulation resistivity
values of material (IR values of coating on GO), Permeability of the material, thickness of the lamination (which effects eddy current losses).

However the major reason contributing to BF is Core Geometry, i.e the Area of Proportion of Corner joints to the total area of the core. Therefore in a smaller rating core (like 25 kva to 100 kva- varies from 1.25 to 1.35 ) where the BF is much higher compared to a Power transformer core like 25 MVA and above (varies from 1.08 to 1.15) where it is comparatively lower.

As it is not possible to examine all these factors in a single paper, we shall only examine the most important one, which can directly reduce the NLL significantly- using SL laminations for making transformer core and understanding the reasons for the same, mainly the advantages in flux transfer in SL over NSL joints.

Both Hysterisis and Eddy Current losses when added make up the NLL of a transformer. Due to the complexity of determining each individually, generally designers use either of the following two equations while calculating the NLL in a transformer:

(1) \[ NLL = Wt \times Kt \times w \]

OR

(2) \[ NLL = (Wt - Wc) \times w + Wc \times w \times Kc \]

Where \( w \) is core loss in Watts per kg of the CRGO material used in core.

\( Wt \) is the total weight of the core

\( Wc \) is the weight of the core at Corner joints.

\( Kt \) is the Building factor of the total core and

\( Kc \) is the Building factor of the core at the corner joints.

A Cross sectional view of behavior of Flux in a Conventional NSL Core stack is shown in Figure 1 below. It has mitred joints and is usually built two laminations at a time with an off-centre overlap of around 10 mm in the centre leg. As can be seen from the diagram, the joints are staggered one on either side 5 mm around the centre point.
Figure 1- A cross sectional view of the Conventional Non Step Lap (NSL) type joints and behaviour of flux in it, which is mostly used in India.

A Cross sectional view of SL Laminations (6 steps) and the behavior of flux is shown in Figure 2. As can be seen the joints are staggered 3 on either side, around the centre point.

Figure 2: Behavior of Flux in the 6 SL joint.
Similar to an electrical circuit where, 

Electric current follows the path of least resistance, in a magnetic circuit, 
Magnetic flux follows the path of least reluctance (which corresponds to Highest Magnetic Permeability). In fact, the situation in an electric circuit and a magnetic circuit are analogous. Like Resistance \( R = \frac{V}{I} \) in any electric circuit, 

\[ \text{Reluctance, } R = \frac{F}{\Phi} \]

Where \( R \) is the Reluctance of the Magnetic Circuit in ampere turns/ weber

\( F \) is the Magnetomotive Force in Ampere – turns and

\( \Phi \) is the Magnetic flux in webers.

As we see above in Figures 1 and 2 above, when the Flux in the transformer core approaches the air gap at the corner joint in the core, it has two options – Either to cross the Air gap at the joint (where the Magnetic Permeability is much lower (=1), as the Magnetic Reluctance of Air is much higher.

The second option for the flux is to cut across the insulation layers of the laminations and move to the overlapping laminations in the vertical direction (the direction perpendicular to the rolling direction of the laminations) above or below where the Magnetic Permeability is of the order of \(10^4\) and as a result the Magnetic Reluctance is much lower.

Obviously the flux will choose option 2 i.e to cut across insulation layers and transfer to the laminations overlapping above or below it. However as CRGO saturates at a flux density of approximately 2 Tesla this is the constraining factor for the “ready to transfer flux” approaching the air gap at the corner joint.

Let us consider a core which is operating at a flux density of 1.7 Tesla. As the flux approaches the “air gap” at the corner joint, it has to decide between option 1 and 2 above. If all the flux transfers to the overlapping laminations above or below, in a NSL type joint where there are just two overlapping laminations, then the flux in the overlapping laminations will be 5.1 Tesla/ 2 = 2.65 Tesla per lamination which creates “overcrowding of flux” and also much over the saturation limit of the CRGO (which is approx 2 Tesla). Thus in a NSL type joint, some of the flux will get transferred to the adjoining overlapping laminations, however some part of the flux will also have to jump across the air gap (which is option 1). This is what is shown in Figure 1 above. Even the flux which gets transferred to the adjoining laminations in a NSL, increases the flux density in the lamination above the saturation level which automatically contributes to the saturation of the material at joints and therefore higher NLL.

The flux which crosses the air gap contributes to “wasting of flux” and therefore requires a higher no load current to achieve the required calculated flux density. Further the over-saturation of flux at the corner joints also leads to higher magnetostriction of the core which is the main cause of noise level in a transformer. This transfer of flux in a Conventional type (NSL type) core is more explicitly shown below once again for better understanding in Figure 3:

![Figure 3: Diagrammatic representation of flux transfer to overlapped sheets in a Non Step Lap joint](image-url)
However the situation is different for SLcore. The “ready to transfer flux” approaching the air gap has many more options as can be seen in figure 2 above, simply because there are more layers of laminations “available” for distributing this “ready to transfer flux”. As can be seen in the diagrammatic representation of the 6 Step Lap core, the flux has six options to jump instead of just two and therefore there is a more balanced distribution of flux over the adjoining laminations which results in very little flux jumping the air gap thereby also contributing to lower losses at the corner joints, as the flux density of the corner joints remains around the saturation flux density of 2 Tesla. This is explained diagrammatically below in Figure 4:

![Figure 4: Diagrammatic representation of flux transfer to overlapped sheets in a Step Lap joint.](image)

It has been determined by Mechler and Girgis in (1) that the Flux density in NSL joints at the air gap is high as compared to in a SL joint and the flux density in the adjoining laminations in a NSL joint is much higher, as compared to SL joint which is discussed more in detail below with the help of diagrams and plots.
The distribution of this flux in NSL is represented below in Figures 5, 6, 7 and 8.

**Figure 5:** Magnetic flux lines in a NSL core joint at 1.7 T induction.

**Figure 6:** Corresponding Sketch of Figure 5 to identify lines for line plots (not to scale).
As can be clearly seen from the above, the flux density in the steel laminations along line 1 after the Air Gap reaches 2.7 Tesla and this is approximately the same amount of flux found along line 3 (which is normal or perpendicular to the direction of rolling) in the steel laminations. It should also be noticed that the Flux density in the air gap is as high as 0.7 Tesla.

Mechler and Girgis then repeated the same experiment with a SL core and the results are shown below in Figures 9, 10, 11 and 12.
Figure 9: Flux lines in step-lap core joint at B (overall) = 1.7 T.

Figure 10: Sketch for identification of lines in a Step Lap Joint
As can be seen from the above, the flux density across the air gap in a Step Lap joint is as low as 0.04 Tesla (as compared to 0.7 Tesla for a NSL joint) and the flux density across the six steps is at the saturation level of approximately 2.028 to 2.035 Tesla (as compared to over saturated level of 2.7 Tesla for a NSL joint).

Therefore it is clear that the SL construction facilitates a much more efficient way of core building and empirically has been found to reduce the No Load losses of a transformer by 5 to 8 % over NSL cores which is a significant reduction in NLL.

Of course, there are various parameters in a SL core which have to be optimized four of the important ones being the Number of steps in a SL joint, the distance of overlap between the steps, number of laminations per lay and the air gap. Best results with a SL lamination can only be achieved when all these parameters are at an optimum level. However it is not within the scope of this paper to discuss optimization of these parameters here.

There are two types of SL laminations that can be manufactured. Horizontal step lap and vertical step lap. These are shown in Figures 13 (Vertical Step Lap) and 14 (Horizontal Step Lap) below for better understanding. It is the designer’s choice which one to use as there is no significant difference in performance of the core as long as the four optimization factors mentioned in the previous paragraph are taken care of.
The variables while designing step lap laminations are the following:

1. No. of steps per book
2. No of laminations per step
3. Amount of overlap (shift) in the book between different steps
4. Type of step lap to be used – Vertical or Horizontal step Lap.

Ideally, if a core designer is not comfortable converting the existing NSL core drawing to SL core drawing, the Lamination manufacturer or processor should have the capability to do so given the parameters of core diameter, window height and cross sectional area of the core.

SL laminations are nothing new. They have been used in Europe, USA and many other countries for more than a decade now. Some Multinational transformer manufacturers in India too use these kind of cores as they significantly reduce the BF by 5 to 8 %, thereby significantly reducing the NLL of the transformer, reduce the No Load current and also reduce the Noise level of a transformer. However it has not been popularized in India because SME transformer manufacturers using their existing designs were comfortable with the NSL joint design. Also if some of them did try to migrate to the SL design, the manufacturing facilities were not available in India till some years ago. Manufacture of SL laminations is a precision job that can only be done on high precision Automatic cut off lines (like Heinrich Georg) using only Prime CRGO coils, which involves installing expensive capital equipment. As most of the core processing in India till a few years ago was done on manual treadle shears, it was not possible to manufacture SL laminations even if the designers wanted these type of laminations. So the designers did not change
over to the more efficient SL design as the manufacturing capability was not available within the country specially with the lamination manufacturers. Also the lamination manufacturers never bothered to invest in expensive capital equipments as few Indian TMs used SL design laminations which would be the major reason to invest in an expensive cut to length line. This was a classical chicken and egg situation.

However now many lamination manufacturers and transformer manufacturers have installed CNC lines and it is possible for step lap cores to be now manufactured in India, which can only be done from Prime CRGO coils as CNC machines don’t accept second grade material. Therefore use of step lap core not only ensures more efficient transformers, it also ensures use of Prime material, which has been the demand of ITMA for a long time. Thus it is strongly recommended that TMs should take advantage of this advancement in manufacturing technology to reduce the BF and as a result the NLL and make their transformers more efficient.

Conclusions:

1. The NLL in a transformer is dependant on the BF which is dependant on various factors like Core Geometry, Quality of workmanship of laminations or core and the grade of material being used.
2. The Area of the joints to the area of the entire core has a major role to play in the BF increasing.
3. The BF can be reduced by using SL Laminations instead of NSL laminations, by a factor of 5 to 8%.
4. SL Laminations distribute the flux around the corner joints more effectively than non SL Laminations as the flux has more options to choose from.
5. SL Laminations thereby reduce NLL, No Load current, Noise level (due to lower magnetostriction of core ) and help productivity as they make core building faster and more efficient.
6. Step Lap Laminations are of two types, Horizontal Step Lap and Vertical Step Lap.
7. SL laminations can only be manufactured with Prime material on Automatic cut off lines having the capability to do so.

References:

3. N.Hihat, E.Napieralska-Juszczak, J.Ph. Lecointe, J.K Sykulski, “Computational and experimental verification of the equivalent permeability of the step lap joints of transformer cores”
4. Vladimir Segal, “Effects of Joint design and some other parameters on Build factor of a 3 phase stacked core”, Proprietary report.