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TECHNICAL AND ECONOMIC COMPARISON OF BUTT-JOINT VS. STEP-LAP CORE FOR LV TRANSFORMERS FOR CONTINUOUS DUTY APPLICATION IN DATA CENTERS

Abstract

LV transformers designed to supply data centers generally operate in continuous duty, often in redundant configurations and with a partially loaded average operating condition. Under these conditions, no-load losses become a dominant cost factor because they depend mainly on voltage and remain almost constant over time, whereas load losses are proportional to the square of the absorbed current and therefore to the square of the load factor.

This paper compares two 250 kVA low-voltage transformers: an advanced design with a circular stepped grain-oriented core and 45° interleaved step-lap joints, and a conventional design with a 90° butt-joint. For the two units, the values considered are core (no-load) losses and load losses. The analysis shows that, in continuous service, the strong reduction in no-load losses makes the step-lap solution structurally more advantageous, especially at the partial loads typical of data centers, where transformers are usually oversized and do not operate at full load. In addition, the step-lap unit operates below the EcoDesign reference values [1]. Although EcoDesign is primarily a benchmark for medium-voltage distribution transformers rather than for this specific low-voltage data-center application, it remains a useful technical reference for highlighting the very low loss level achieved.

From an economic standpoint, the higher initial cost of the step-lap unit is discussed through a parametric return-on-investment formulation, without disclosing commercial prices, linking the higher capital cost to the greater annual energy saving as a function of the RMS load factor and the energy price. Finally, from an acoustic and mechanical standpoint, the step-lap geometry also reduces vibration and noise compared with conventional construction.

Thesis

For LV transformers intended for the continuous supply of data centers, 45° interleaved step-lap technology is technically and economically preferable to a conventional butt-joint design because it minimizes permanent losses, improves efficiency at partial load, and greatly reduces vibration and noise; consequently, the higher purchase price can be justified by a lower total cost of ownership in both energy and maintenance terms.

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1. Operating profile and loss structure

1.1 Type of duty: Continuous vs. Intermittent

The type of transformer duty is of fundamental importance, both from a sizing standpoint and from a strategic standpoint regarding losses and the cost of lost energy. The substantial differences depend on whether the transformer is *energized* or *de-energized* and on the load percentage. In intermittent-duty applications, the economic weight of no-load losses is less critical because the transformer is not permanently energized. For data-center supply, by contrast, the transformer is typically energized continuously, often within redundant architectures and with installed power intentionally higher than the effective load. In such a scenario, the loss component associated with the core is continuously present and must be treated as a structural operating cost rather than as a secondary design detail. In the following image, duty cycle S6 is shown, in which the transformer alternates a loaded operating phase with a no-load operating phase; as can be seen from the function referring to absorbed power, there are no rest conditions.

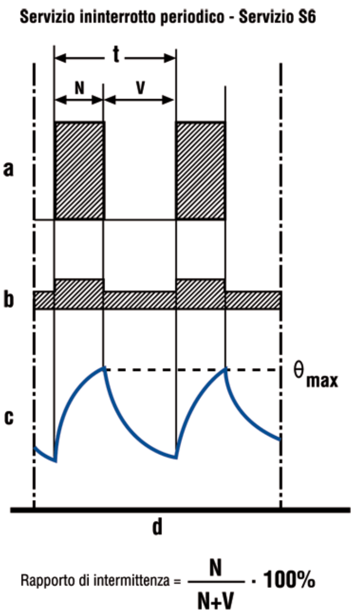

Figure 1 - Intermittent duty S6

1.2 Nature of losses

Total losses can be expressed as the sum of no-load losses and load losses. At constant and continuous voltage, core losses remain constant and persistent, whereas winding losses vary with the square of the current. For this reason, under partial and continuous load (typical of the data-center case), the relative weight of core losses becomes progressively more important.

1.3 RMS load factor

For variable load, the correct parameter is not the arithmetic average load factor, but the root mean square (RMS) load factor. This quantity depends on the square of the load, the latter being proportional to the square of the absorbed current. Any rigorous comparison of annual costs between two transformer technologies should therefore be based on the RMS load factor rather than on the average load.

The formulas for calculating the RMS value and for weighing its value over time are given below:

$$x_{rms} = \sqrt{\frac{1}{T}\int_0^T x(t)^2 dt} \tag{1}$$

$$x_{rms} = \sqrt{\frac{\sum_i x_i^2 \cdot \Delta t_i}{\sum_i \Delta t_i}} \tag{2}$$

2. Case under examination and comparative equations

2.1 Measured data

Two 250 kVA transformers are compared

Core Type	No-load Losses [W]	Load Losses [W]
N.G.O. Butt-joint 90° (Rectangular)	1150	3850
G.O. Step-Lap 45° (Circular)	394	3200
EcoDesign Reference	468	3400

The key difference in favor of the step-lap solution is the large reduction in core losses, which is precisely the most valuable improvement in applications where duty is continuous. In the chart below, the area relating to the energy saved by the two solutions is highlighted in yellow, considering the full-load case:

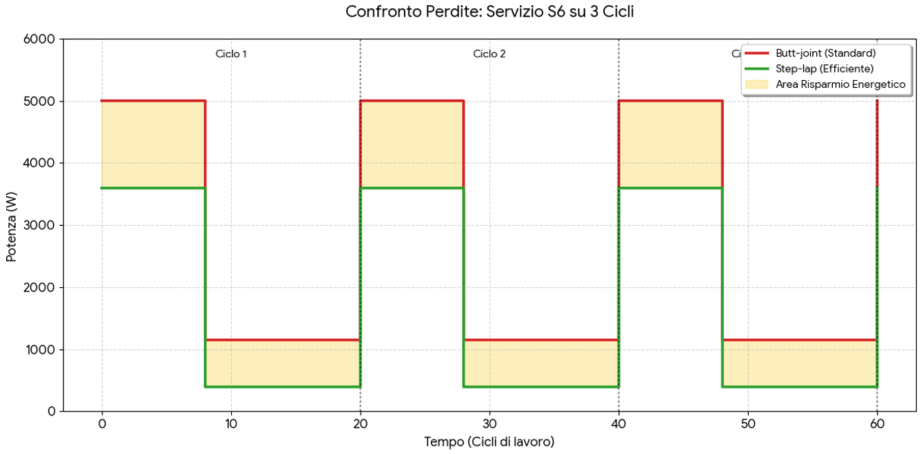

Figure 2 - Comparison between the 2 versions at full load

2.2 Comparative equations

The loss equations of the two transformers, as a function of load factor x, are reported below. The difference equation clearly shows that the advantage of the step-lap design is made up of a fixed component due to no-load losses and a variable component due to lower winding load losses.

3. Annual energy saving as a function of RMS load

3.1 General formulation

The annual energy saving is obtained by multiplying the differential loss between the two solutions by the annual operating hours. Since the transformer is assumed to remain continuously energized, the annual duration is 8760 h.

3.2 Reference values

The resulting savings are reported for representative RMS load factors. The advantage in favor of the step-lap solution remains significant under all load conditions, but it is particularly relevant at partial load because the step-lap transformer starts from a much lower no-load loss base.

4. Commercially neutral ROI formulation

4.1 Parametric formulation

A technical paper avoids disclosing transformer prices because these are commercial values that depend on the design scope, supply conditions, accessories, tests, logistics, contractual structure, and the raw-material cost at a given time. A more rigorous approach is therefore to express the payback in parametric form.

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4.2 Annual economic saving

If the average annual electricity price is denoted by C_e in €/kWh, the annual economic saving is obviously equal to the annual energy saving (kWh) multiplied by C_e. Using the Italian energy price for March 2026 [2], the PUN GME index is 114.4 €/MWh, i.e. 0.1144 €/kWh.

4.3 Simple payback and justified additional costs

If ΔC is the additional capital cost of the step-lap transformer compared with the butt-joint transformer, the payback time is ΔC divided by the annual economic saving. Equivalently, the maximum extra capital that can be supported for a target payback period T can be calculated.

5. Acoustic and mechanical implications

5.1 Why step-lap reduces vibration

The column-to-yoke joint is a critical part of the magnetic circuit. In a butt-joint configuration, the flux undergoes a more abrupt discontinuity, which increases local reluctance, leakage flux, magnetostriction-related excitation, and mechanical vibration. In a 45° interleaved step-lap joint, flux transfer between limb and yoke is more gradual and more consistent with the preferred magnetization direction of grain-oriented steel. This reduces local magnetic stress and the mechanical excitation that generates vibration.

5.2 Consequences on noise

Lower vibration translates directly into lower emitted sound power and lower sound pressure levels. This aspect is particularly valuable in data-center applications, where acoustic quality, installation refinement, and reduction of parasitic mechanical transmission are relevant design objectives. In practical terms, step-lap construction offers very low noise levels, whereas butt-joint constructions tend to become acoustically more penalizing as transformer size increases.

6. EcoDesign reference as a performance benchmark

6.1 Correct interpretation of the benchmark

The losses of the step-lap transformer are lower than the EcoDesign reference. This does not mean that the EcoDesign regulatory framework applies exclusively and fully to the current category of low-voltage transformers for data centers. However, EcoDesign remains a credible benchmark for highlighting the low level of losses achieved.

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7. Conclusion

7.1 Final assessment

The comparison between a step-lap transformer and a butt-joint transformer shows that, for data-center operation with continuous and long-term supply, the decisive issue revolves not only around the initial investment but also around the total cost of ownership. Consequently, the annual energy saving remains substantial regardless of power rating and is already significant in absolute economic value even at modest RMS loads. The parametric ROI formulation shows how this benefit can justify a higher initial investment.

At the same time, better management of the magnetic flux in the 45° internal joint reduces vibration and therefore noise, providing an additional application advantage with lower maintenance requirements, which is particularly relevant for data-center environments.

Overall, the step-lap solution should not be seen simply as a high-end option, but as the technically consistent choice for continuous high-efficiency duty.

Analytical formulas

This paragraph sets out the formulas used in the analysis. With regard to losses, as mentioned, we can consider a constant part P_{fe} and a part dependent on the load factor P_{cu_n}

$$P_{tot}(x) = P_{fe} + P_{cu\_n} \cdot x^2 \tag{3}$$

Therefore, for the two step-lap and butt-joint solutions, the following was considered:

$$P_s(x) = 394 + 3200x^2 \tag{4}$$

$$P_b(x) = 1150 + 3850x^2 \tag{5}$$

The variation in losses between the two solutions can therefore be expressed as:

$$\Delta P(x) = P_b(x) - P_s(x) = 756 + 650x^2 \tag{6}$$

From this variation, the annual energy saving can be evaluated as:

$$E_{sav}(x) = \Delta P(x) \cdot \frac{8760}{1000} \tag{7}$$

$$E_{sav}(x) = (756 + 650x^2) \cdot 8{,}76 \tag{8}$$

$$E_{sav}(x) = 6623 + 5694x^2 \left[\frac{kWh}{anno}\right] \tag{9}$$

Through the cost of energy, the saving in euro/year can be evaluated as:

$$S(x) = E_{sav}(x) \cdot C_e \tag{10}$$

$$S(x) = (6623 + 5694x^2) \cdot 0{,}11441 \tag{11}$$

$$S(x) = 757 + 652x^2 \left[\frac{€}{anno}\right] \tag{12}$$

The investment payback times were evaluated using the following formulas:

$$T_{PB}(x) = \frac{\Delta C}{S(x)} \tag{13}$$

$$\Delta C_{max}(x, T) = S(x) \cdot T \tag{14}$$

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Table 1. Differential losses and annual savings with respect to RMS load factor

RMS load factor	ΔP(x) [W]	Esav(x) [kWh/year]	Annual saving S(x) at 0.1144 €/kWh [€/year]
0.25	797	6978	798
0.50	918	8046	921
0.75	1122	9825	1124
1.00	1406	12317	1409

Table 2. Maximum justified additional cost $\Delta Cmax$ for selected payback targets

RMS load factor x	S(x)[€/year]	Max extra Capex with breakeven 3 years [€]	Max extra Capex with breakeven 5 years [€]	Max extra Capex with breakeven 10 years [€]
0.25	798	2394	3990	7981
0.50	921	2762	4603	9206
0.75	1124	3372	5619	11239
1.00	1409	4227	7045	14089

This table provides a commercially useful criterion because it establishes, based on the selected breakeven time, the load factor, and the delta energy saving versus the butt-joint solution, how much of an incremental price for the step-lap transformer versus the butt-joint transformer is sustainable.

Notes
[1] Ecodesign regulation
[2] PUN GME

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