Class 2 transformers: ubiquitous, hidden, and inefficient

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***Abstract*—Class 2 transformers are small line-frequency transformers that are widely used for control systems that require 24 VAC signaling, including residential and commercial HVAC systems, industrial control systems, doorbells, and much more. In this work, we sampled and tested seven Class 2 transformers, each across different operating conditions, in order to characterize their efficiencies and note their shortcomings. We also provide possible improvements and solutions. We see on average a peak efficiency of 84.43% with 5.37 W of power loss when operated at 75% (30 VA output power) of their rated power, a 1.84% efficiency drop from the temperature rise that occurs at steady state when operated with full load, 2.8 W of no-load loss at 120 VAC input, and a no-load loss contribution of over 50% when operating at less than 75% load power. With these values, there is a clear goal to strive for in order to improve or create an alternative to these Class 2 transformers.**

***Index Terms*—transformers, power supplies, HVAC systems, power electronics, magnetics**

I. Introduction

Almost no low power (< 100 W) DC power-supplies use line frequency transformers—modern power-electronic equivalents offer higher efficiencies and smaller size at low cost. But there is one common low-power application where line-frequency transformers find significant use: for control systems that use 24 VAC power and signal lines.

These transformers, which meet "Class 2" safety requirements under UL standards [1] and the National Electrical Code [2], are seen in almost all heating, ventilation, and air conditioning (HVAC) systems, industrial control systems, doorbells, garage door openers, commercial food processing and more [3]. Class 2 safety requirements include [1]–[3]:

- double insulation or reinforced insulation to prevent electrical shock hazards
- 30 V_{rms} (42.4 V_{peak}) maximum voltage output
- output current < 8 A when measured for 60 seconds under any load condition
- output power is limited
- 100 VA maximum power (10–40 VA are most common)

These devices are simple in their construction; however, this comes with disadvantages. The direct connection to the 60 Hz supply line requires a larger transformer core volume compared to high-frequency transformers used in power electronic converters for the same power level. The substantial amount of copper and steel used results in both large weight and prices ($10–60). The efficiency is low especially at light load. Lastly, with steady-state operation, the transformer reaches high temperatures that further reduce efficiency. With these devices found in residences, we see a major issue of energy loss due to this one simple but widespread device.

In this work, we sample popular Class 2 transformers across online supply sources and measure their performance. This is not primarily to act as a comparison between brands or device construction, but to show the overall problem of Class 2 transformer energy consumption. We compare weight, cost, load dependent efficiency, steady-state temperature full load efficiency, and no-load loss across input voltage variation.

We propose that power electronic solutions could be much more efficient. Solutions and alternatives to Class 2 transformers could dramatically impact the market of Class 2 transformers and could potentially reduce power losses across their many applications.

II. Transformer Selection and Testing

Transformers were selected with the following specifications: 60 Hz, 24 VAC output with a 40 VA power rating, based on this voltage and VA rating being the most commonly sold option. We also sought well-known brands and best-selling models. Table I lists all selected Class 2 transformers and their identifiers. Fig. 1 shows an image of the selected transformers.

TABLE I
Selected transformers

Identifier	Manufacturer	Number	Weight (lbs)	Price ($)
1	White-Rogers	90-T40F1	0.514	19.16
2	White-Rogers	90-T40F3	0.494	11.36
3	Packard	PF42440	0.549	12.78
4	Resideo	AT140A1000	0.452	14.10
5	Resideo	AT140A1018	0.445	18.18
6	Resideo	AT72D1683	0.675	28.54
7	Dayton	4VZE4	0.553	16.08

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Fig. 1. Image of selected transformers (ID1-ID7 from left to right)

These transformers will typically be operated across various load conditions and lengths of time. The following tests were used to measure their performance across typical operation.

A. Load dependent efficiency

To measure across the range of potential loads with which a 40 VA transformer would operate, the input of the transformer was connected to a 120 VAC 60 Hz source, while its output was connected to a specified resistance to measure at approximately 5 W, 10 W, 20 W, 30 W, and 40 W load power.

At each load condition, the efficiency and the power loss of the transformer was measured. Fig. 2 and 3 show these comparisons, and Fig 4 shows an example experimental setup.

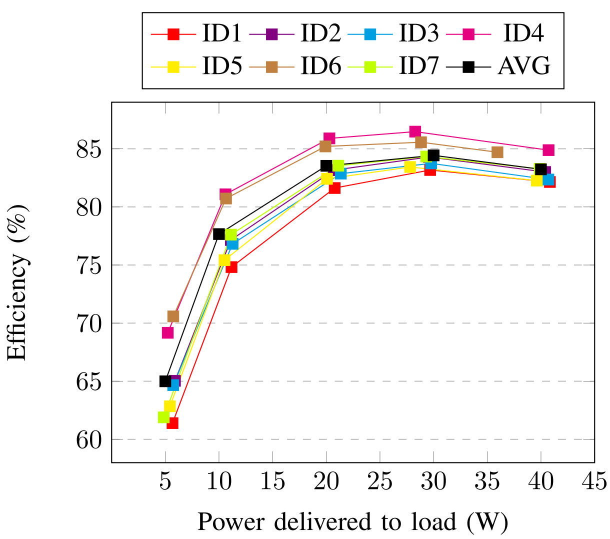

Fig. 2. Efficiency versus load power

These results show an average peak efficiency of 84.43% with 5.37 W of power loss when operated at 75% (30 VA) of rated power. At full load (40 VA) there is an average efficiency of 83.23% with 8.02 W of power loss. There is also a significant roll off towards the lower rated power points, with an average efficiency of 65.09% (2.95 W of power loss) when operated at 12.5% (5 VA) of rated power.

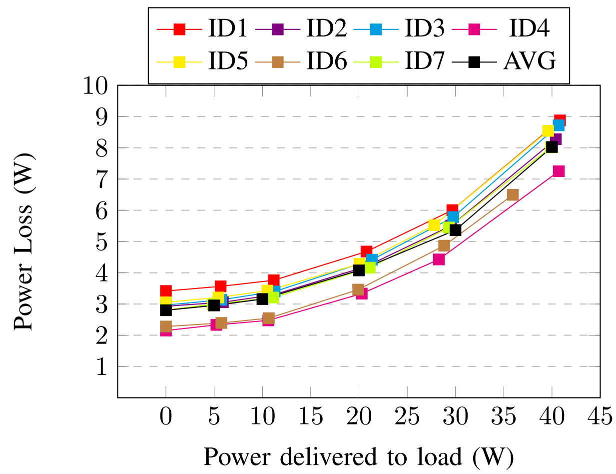

Fig. 3. Power loss versus load power

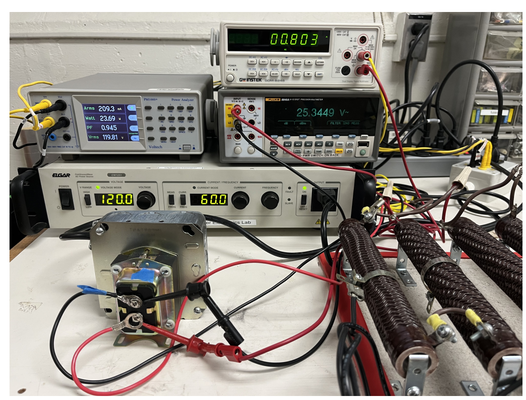

Fig. 4. Example experimental setup for measuring load dependent efficiency, measurement equipment includes Fluke 8846A 6.5 Digit Precision Multimeter, GDM-8245 Dual Display Digital Multimeter, and Voltech PM1000+ Power Analyzer

B. Steady-state temperature full load efficiency

For applications where the transformer is on for long time periods, its power losses will cause the transformer to heat up and will reduce its efficiency. To measure this effect, the

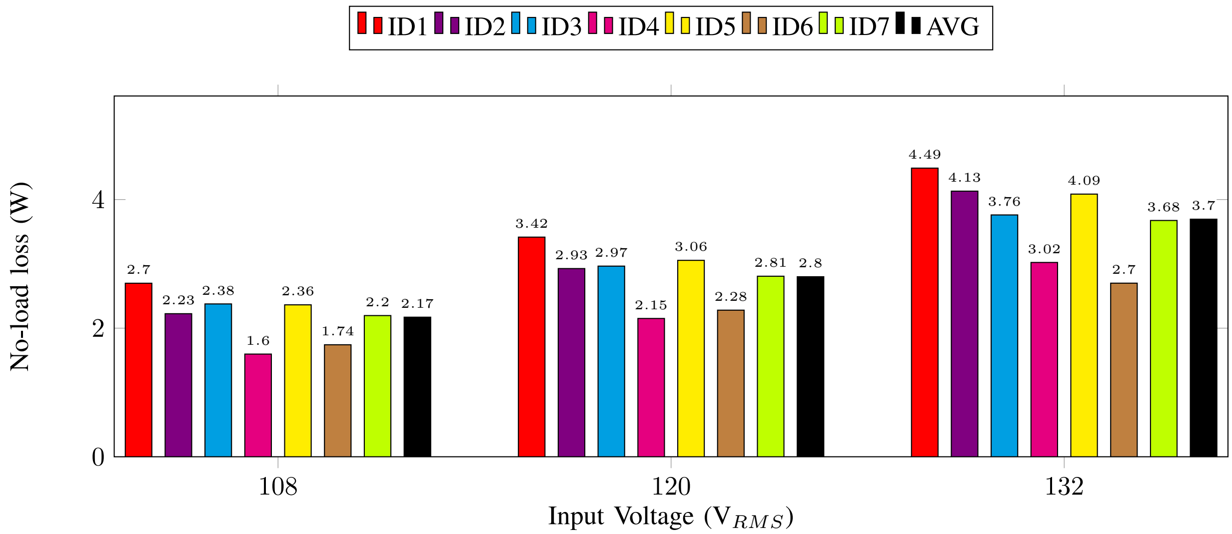

Fig. 5. No-load loss measured across input voltage variation for each selected transformer

transformer's input was connected to a 120 VAC 60 Hz power supply while the output was connected to a specified resistance at full load (40 VA). The transformer is then run for several hours to allow it to reach its steady-state temperature (T_{ss}).

At the steady state temperature, its efficiency and the DC resistance of the primary winding are measured, in order to infer the temperature. Results are shown below in Table II.

TABLE II
TRANSFORMER PERFORMANCE AT T_{ss}.
RESISTANCE MEASURED IS OF THE PRIMARY WINDING.

ID	$R_{25°C}(\Omega)$	$R_{T_{ss}}(\Omega)$	Eff$_{25°C}$(%)	Eff$_{T_{ss}}$(%)	T_{ss}(°C)
1	18.37	23.01	82.4	80.3	91.0
2	18.56	24.49	83.3	81.4	106.4
3	19.32	25.02	83.9	82.4	98.1
4	21.08	25.85	84.9	83.2	83.9
5	20.20	24.82	82.2	80.5	83.1
6	21.88	26.34	82.7	80.5	77.1
7	18.77	22.59	83.2	81.4	76.4

The trend of increased R$_{DC}$ explains the decrease of efficiency as we approach the T_{ss}, as well as being useful to determine the temperature.

On average, there is a 1.84% drop in efficiency from the room temperature measurement to the T_{ss} measurement, with an average full load efficiency of 81.4% at T_{ss}.

C. No-load loss across input voltage variation

Next we measure non-load loss across different input voltages. This is the baseline power loss that will be seen across all load conditions.

The input of each transformer is connected to a 120 VAC 60 Hz power supply, while the outputs are left open-circuited. Once energized, the power loss associated with this conditions was measured through the input-connected power analyzer. Also, comparisons across input load variation (±10% of 120 VAC) are included. Fig. 5 shows these comparisons.

These results show that on average there is 2.8 W of baseline power consumption at 120 VAC. The losses go up rapidly at high line voltage, on average by 32% for a 10% line voltage increase, or proportional to voltage to the 2.9 power, reflecting the nonlinear core loss characteristics [4]. They also drop rapidly at low line, but not as rapidly: by 22.5%.

III. DISCUSSION

A. Results

Through all tests performed on the transformers, each transformer shows similar results with no significant outliers. However, among the transformers sampled, transformer ID4 had the highest efficiency across most operating conditions, with one of the lower weights and the lowest no-load loss at nominal line voltage. However, its no-load loss increased disproportionately at high line, going up by 40%. ID6 had similar performance with slightly higher losses for most operating conditions, but only increased by 18% at high line, such that it offered the best performance in this condition.

Although ID4 was the highest efficiency Class 2 transformer tested, it only reached a peak efficiency of 86.47%, low compared to the efficiencies ($>$ 90%) of many power electronic power supplies on the market.

All transformers achieve peak efficiency at about 75% of their rated power, and decreased efficiency at higher operation temperatures; both conclusions expected of most power supply devices. However, these devices showed large no-load losses, meaning that if they are just left connected to the power supply while the load is off or disconnected, this will contribute a large share of power consumption. In most applications, these transformers are connected to line voltage continuously, since their function is to provide power to the control systems that power up additional equipment when needed.

To further show the impact of the no-load loss, we can combine the data presented in Fig. 3 and Fig. 5, to see how much of the total power loss is the no-load loss in each load condition. This is shown in Fig. 6.

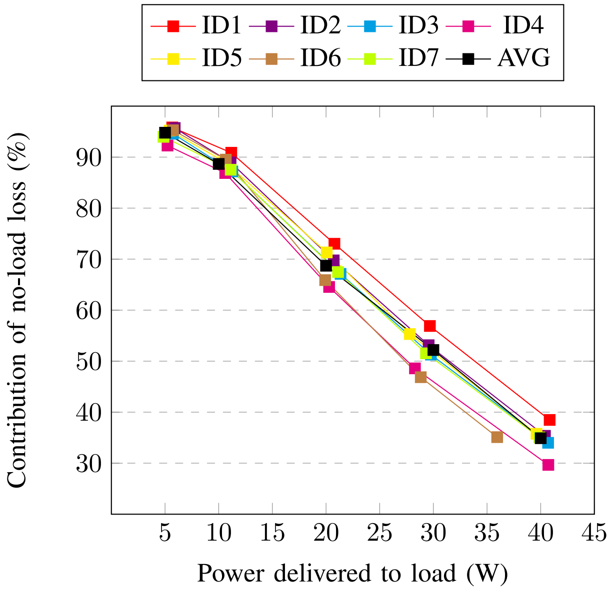

Fig. 6. Contribution of no-load loss to the total measured power loss across load variation

These results show that the no-load loss is the main culprit for low efficiencies across the different load powers. At less than 75% of load power, the no-load loss contributes to more than 50% of the total power loss. Even at the full load condition this no-load loss is 34.9% of the total power loss.

Reducing this no-load loss is critical for improving efficiencies across all load power ranges.

B. Potential solutions

No-load losses are dominated by core loss [4]. Lower loss core materials are available and could be substituted [5]–[8], and larger core area and more winding turns could be used to reduce flux. Thus, it is possible to reduce losses with similar technology by adjusting designs and materials, but with increases in cost. DOE regulations to require improved efficiency for AC-to-AC "external power supplies" are under consideration [9], but many Class 2 transformers do not fit in this category.

An alternative is to implement an isolated AC-to-AC switching power converter, also known as a solid-state transformer [10]–[13]. This approach uses power semiconductors to create a waveform at a frequency orders of magnitude larger than the line frequency to allow using a much smaller and more efficient transformer. The hope is that, as in AC-to-DC switching power supplies, the cost savings from using a smaller transformer make up for the higher cost incurred by the power semiconductors.

Modern high-efficiency AC to DC power supplies use a variety of techniques to achieve low no-load or light-load loss [14]–[16]. These techniques often involve holding a dc output voltage on a capacitor between intermittent operation of the power conversion hardware to maintain the voltage as needed. This type of strategy is not directly applicable when an ac output is needed, making the design of an electronic replacement for Class 2 transformers with very low standby power a challenge that will need a concerted effort to address.

IV. Conclusion

Class 2 transformers are the standard transformers for various applications that require 24 VAC power and signal lines. However, typical Class 2 transformers have large weights, low efficiencies across all loads, large steady-state temperature rise at full load and a large no-load loss contribution compared to the total power loss, especially considering that the transformer is energized continuously in a typical application.

Improvements are technically feasible, and our future work will explore alternatives that can provide lower no-load loss, with an emphasis on low cost.

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