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Optimized Magnetic Components Improve Efficiency of Compact Fluorescent Lamps

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Abstract—**Further improvements in the efficiency of compact fluorescent lamps can be achieved by optimizing the magnetic components in the electronic ballast. Resonant inductors were evaluated in several commercial integrally ballasted lamps. Winding optimization programs were used to redesign the windings of an example inductor. Two of the proposed winding designs were built and confirmed to provide reductions in winding loss of over 40%.**

I. INTRODUCTION

COMPACT fluorescent lamps (CFLs) have played an important part in reducing the electricity demand for lighting purposes. The development of compact fluorescent lamps that use existing lighting fixtures (designed for incandescent bulbs) has allowed residential and small commercial electric customers to benefit from the energy savings offered by fluorescent lighting. CFLs use about a quarter of the energy of incandescent lamps and last 10 times longer [1]. High-frequency electronic ballasts are used to power CFLs today because they are small, light and efficient. A detailed analysis of losses show that the magnetic components are a significant source of loss in the ballast [2], [3].

The purpose of this paper is to reduce winding losses in the magnetic components of integrally ballasted CFLs. Section I-A discusses ballast topologies commonly found in CFLs. Section II reviews winding loss effects in high-frequency gapped inductors. In Section II-A, the winding optimization methods used to develop improved winding designs for the inductors are presented. The possible optimized winding designs are presented in Section III for an example inductor. Section III-A discusses the original winding design. Section III-B and III-C detail the design of two different optimized winding designs. Section III-D discusses the performance of the inductors with the optimized windings in the ballast. Section III-E compares the total cost of the original and optimized windings. The results of this work are discussed in Section IV.

A. Electronic Ballasts

There are many topologies that can be used for electronic ballasts in CFLs. A useful characterization of eight possible topologies is presented in [2] which details the performance and loss in each ballast topology. The ballasts examined had efficiencies close to and above 90%, but [2] found that the inductors are a significant source of loss and recommends reducing winding resistance to improve the overall performance of the ballast.

Ballasts that have both good load side behavior (i.e. no flicker or noise) and good input side behavior (i.e. high PF) have higher losses and component counts compared to other ballasts. Only two of the eight ballasts considered in [2] meet both these criteria and these ballasts each had three inductors. Low-cost, compact, low-loss inductors are thus important for any CFL, and are even more important for high-performance, high-power-factor CFLs.

II. WINDING LOSS EFFECTS IN GAPPED HIGH FREQUENCY INDUCTORS

The largest magnetic components found in the CFL ballasts analyzed were the resonant ballast inductors. Since the current in these inductors is purely ac, design for low ac resistance is critical, and techniques that provide reduced ac resistance can have substantial benefits. Because the inductors must be designed to avoid saturation with high resonant currents during startup, they have low flux levels and low core losses during normal operation and thus reducing winding loss is most important for improving their performance. Typical designs use solid-wire windings on gapped ferrite cores. Below we consider the ac loss effects in such windings and discuss techniques for reducing the loss.

Winding losses at high frequencies are due to eddy-current effects which consist of skin-effect losses and proximity-effect losses. Skin-effect loss results when an isolated conductor carrying a high-frequency current generates an internal magnetic field that forces the current to flow on the surface on the conductor. The skin depth is $\delta = \sqrt{\frac{\rho}{\pi \mu f}}$ where μ is the permeability (equal to the permeability of free space for most conductors), ρ the resistivity, and f the frequency. Skin effect losses can be mitigated by selecting a wire diameter that is small compared to the skin depth. The proximity-effect loss results from the extra currents induced in the conductor by an external magnetic field. Fringing fields at the air gaps in the core and current carrying conductors create the magnetic fields responsible for the proximity-effect loss. One way to reduce proximity-effect losses is to remove the winding from the regions where the field is the strongest.

In the inductors evaluated here, proximity-effect losses account for the bulk of high-frequency winding losses and result primarily from the fringing field created by the air-gap in the core. Since the wire diameter is small compared to the skin depth in all designs considered, the skin-effect losses are insignificant. Thus, the proximity effect loss in a cylindrical conductor can be calculated assuming the wire diameter is small compared to skin depth by:

$$P_{pe} = \frac{\pi \omega |B|^2 \ell d^4}{128 \rho_c} \tag{1}$$

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TABLE I

DATA FOR INDUCTORS IN COMPACT FLUORESCENT LAMPS

Manufacturer	Wattage W	Measured I_{rms} A	Measured Frequency kHz	Measured ESR Ω	Measured R_{dc} Ω	Measured L mH	Wire Size AWG	I^2_{rms}ESR W
A	24	0.206	38.7	7.19	1.70	2.33	28	0.305
B	23	0.310	47.1	2.06	1.57	1.08	39x10	0.198
C	25	0.208	45.9	4.90	3.62	1.87	33	0.212
D	26	0.211	43.3	6.48	2.96	2.10	31	0.288
E	27	0.376	52.1	1.				

where ω is the frequency in radians, ℓ is the length of the conductor, d is the diameter of the conductor, ρ_c is the resistivity of the conductor and B is the ac field, perpendicular to the axis of the cylinder [4].

As shown in (1), the proximity-effect loss is proportional to the square of the ac field, B. There are many ways to calculate the two-dimensional field [5] in the winding window of a gapped inductor. When an accurate model of the two-dimensional field is used with (1), an accurate prediction of winding loss can be obtained.

A. Winding Optimization

We believe we can reduce winding losses through two different strategies. One way to reduce proximity-effect loss is through the use of smaller diameter wire. In some cases, the increase in dc resistance is offset by the reduction in proximity-effect loss, such that total loss in reduced. Or, smaller-diameter strands can be combined in parallel litz-wire constructions. We used the method described in [6] to obtain optimized litz-wire designs. The method is capable of taking into account non-sinusoidal waveforms, two-dimensional field effects and wire cost. Since the lowest-loss litz-wire design is typically very expensive [7], one must consider the relative cost of different litz-wire designs in order to choose a good practical design [8]. The optimization method used [6] finds the lowest loss design for each of various cost levels. The loss is calculated using (1) and a two-dimensional model of the field in the winding window.

Another way to reduce proximity effect losses is to space the winding away from the gap as shown in [9]. This will reduce the proximity effect losses by removing the winding from the area with strongest field. We used the method described in [10], [11], [12] to determine the area of the winding window that should contain wire for the lowest total winding loss. This method is effective at determining the lowest-loss winding shape because it considers the two-dimensional shape of the field, the effect of the winding shape on the shape of the field and the effect of the winding shape on total winding loss by accounting for both resistive and eddy current effects.

III. OPTIMIZING THE MAGNETIC COMPONENT

Five different commercial CFLs with integral electronic ballasts were disassembled and analyzed for this study. Table I lists the lamps along with the measured resonant ballast inductor parameters. A wideband current probe was used to measure the inductor current; for example, Fig. 1 shows the waveform in the inductor of CFL A. An impedance analyzer (Agilent 4294A) was used to measure the complex impedance of the inductor at the operating frequency. Two of each lamp type were purchased so that the inductor from one could be taken apart to measure the core size, the wire size and the number of turns, while retaining the other intact for measurement and comparison with the optimized designs.

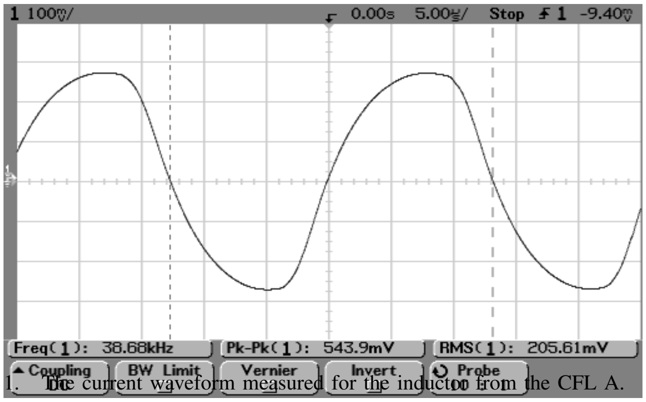

Fig. 1. The current waveform measured for the inductor from the CFL A.

A. Original Winding Design: CFL A

The electronic ballast found in CFL A contained 26 components. Two of the three magnetic components were inductors. The inductor considered was made with an EE core (approximately an EE19), it had a 1.1 mm gap in the center leg and the winding consisted of 226 turns of 0.31 mm wire. The packing factor for the design was estimated from the measured wire diameter and measured winding area.

Because the goal of this investigation is to reduce winding loss, we sought to keep the core loss constant. Thus, all measurements were done with the same core (an EE19 of TDK PC40 material). The component of the effective series resistance (ESR) appearing in small-signal measurements of the inductor that was due to core loss was determined from a two-winding small-signal measurement of core loss, using a 1:1 transformer on an ungapped core. This ESR was subtracted from the total measured ESR to find the ac winding resistance, R_{ac}

The winding loss of the original design was predicted by the method outlined in Section II. The calculated loss for the original winding design was 0.356 W. The current waveform used by the optimization program was a sinusoidal waveform based on the rms current measured in Fig. 1. The loss calculated from the field analysis (0.356 W) is larger than the loss calculated from the measured ac resistance and rms current (0.301 W) of the original winding but the results were reasonably close.

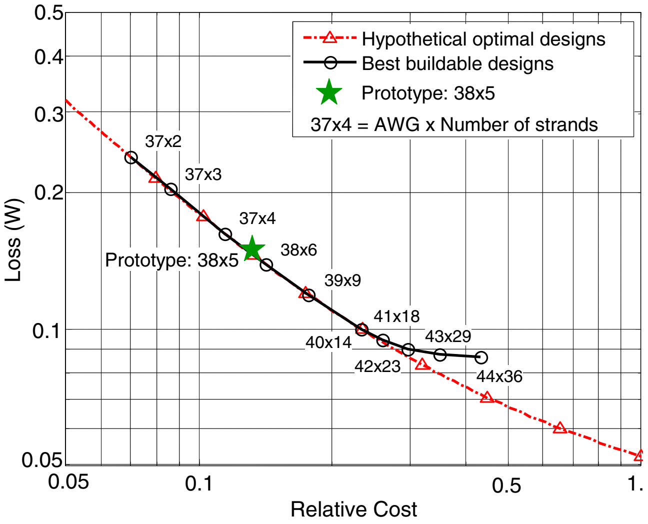

Fig. 2. The optimal design curve is a plot of relative cost verses loss for a ra of different optimal stranding configurations. This curve is for the inductor f CFL A. All buildable designs are marked with a circle and labelled with AW number of strands for that design.

B. *Litz-Wire Winding Optimization Results*

We used the implementation of the litz-wire winding optimi tion method presented in [6] and available at [13] to produ the design curve shown in Fig. 2 for the inductor winding fr CFL A. The design curve is a plot of relative cost versus l Each circle on the curve represents a specific design, a wire s and number of strands, that gives the lowest loss for any given cost or lowest cost for any given loss. The dashed line indicates the hypothetical optimal designs that may not fit in the winding window or may not use an integer number of strands. The solid line shows the possible optimal designs that are buildable; that is, these designs are the optimal stranding that will fit in the winding window as determined by the packing factor.

The method presented in [6] predicts that the use of a single strand of AWG 32 would reduce loss by 24%. In this example, the use of a single strand of smaller diameter wire can provide a reduction in winding loss. If 6 strands of AWG 38 were used, the loss would be reduced by 48%. The design composed of 14 strands of AWG 40 might be the best design for this ballast because the winding loss is reduced by 54%. The winding designs using AWG 42, 44 and 46 might provide a slightly greater reduction in loss, but at a considerable increase in cost as the designs call for more strands of fine wire.

A litz-wire prototype for this ballast was built with 5 strands of AWG 38 to confirm the winding loss predicted by the method outlined in Section II. The predicted loss is shown in Fig. 2. The measured performance listed in Table II confirms the accuracy of the loss calculation and shows that the loss can be cut nearly in half.

TABLE II

WINDING RESULTS: INDUCTOR, CFL A

Winding Design	Winding Loss, predicted W	Winding Loss, measured* W
Original design	0.356	0.301
Litz-wire 38x5	0.1639	0.1633
Shape Optimized AWG 30	0.177	0.176

*The winding loss, P_w was calculated by $P_w = I_{rms}^2 R_{ac}$ where R_{ac} is the measured ESR of the component minus the ESR of the core.

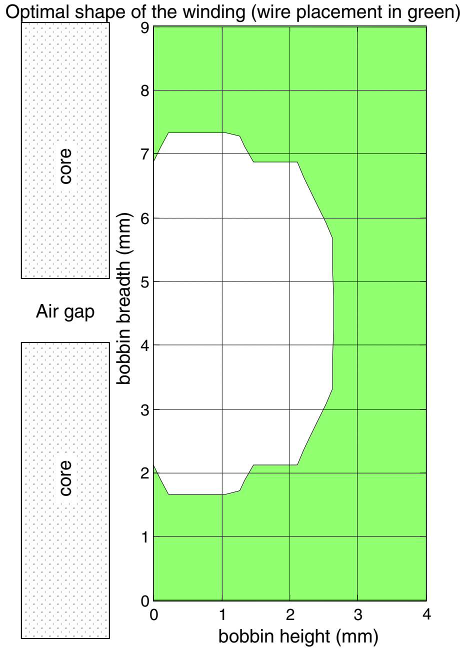

Fig. 3. Optimum wire placement for the inductor from the CFL A. The shaded area shows where the winding should be located in the winding window. The dotted region indicates the center leg of the core and the air gap is labelled.

C. *Shape-Optimized Winding Results*

We used the implementation of the shape-optimized winding design method presented in [14] and available at [13] to produce the winding design shown in Fig. 3. In this example, the lowest-loss, single-strand shape-optimized winding used AWG 30 wire. The loss was predicted to be 0.177 W. The winding cross section shown in Fig. 3 was constructed by building up the bobbin with polypropylene tape to approximate the proposed winding shape. The winding loss was calculated to be 0.172 W using the ac resistance and the operating current, 0.206 A$_{rms}$. The measured winding loss matched the predicted loss well even though the exact winding shape predicted was only approximated during construction. The shape-optimized winding reduced the winding loss from 0.301 W for the original full-bobbin design to 0.172 W, thus providing a 42% reduction in winding losses. The use of a slightly smaller wire diameter combine with spacing the wire away from the air gap in the core was extremely effective at lowering the winding loss.

TABLE III

CFL A: POWER CONSUMPTION FOR GIVEN LIGHT OUTPUT

Design	Light lux	Power watts
Original Winding	528	21.94
Litz-wire 38x5	528	20.98
Shape Optimized AWG 30	528	20.99

D. Performance of Prototype Windings in the Ballast

The performance of CFL A was measured with each of three inductor windings: the original design, AWG 38 × 5 litz wire, and the AWG 30 shape-optimized design. The tests all used the same core (EE19 of TDK PC40 material). The input voltage was adjusted to achieve the same light output with each inductor, as measured using a digital light meter (ExTec model 403125). The input power was calculated from the input voltage and current waveforms after allowing the lamp and ballast at least 30 minutes to stabilize. The results are summarized in Table III. The ballasts with the optimized windings used almost a watt less power, which corresponds to a 4.3% reduction in power consumption, while producing the same light output.

The measured reduction in power consumption was much greater than the predicted reduction in winding loss. Some of this might be explained by a small reduction in power loss leading to a lower temperature in the inductor and other parts of the ballast, which in turn could further reduce the loss and temperature. For example, the core loss in PC40 ferrite is minimized between 80° C and 100° C; at higher temperatures the core loss starts to increase more and more rapidly. The resistance of the winding, as well as copper traces on the circuit board, is decreased at lower temperature, as are the on resistances of the MOSFETs. The lamp temperature could also be affected. Further study would be needed to verify and identify such additional loss reductions.

E. Cost Comparison

Although the method used to optimize litz-wire designs [6] provides approximate comparisons between the costs of different litz-wire configurations, the cost model used does not predict the cost difference between litz and single-strand windings. Thus, in order to assess the economic viability of the different designs we propose, we obtained quotes for the various wire types from several manufacturers. Quotes were based on quantities sufficient for about 50 000 inductors. The present value of the energy consumption cost was calculated based on a lamp life of 10 000 hours, with the lamp operated 2000 hours per year for five years; an electricity price of $0.10/kWh, and an annual discount rate of 6%. The energy savings calculation included only the direct improvement in winding loss based on measured room temperature winding resistance and did not include the additional energy savings found in system measurement.

The wire costs, energy costs, and sum of these two are listed in Table IV. The costs of the winding process and the core are not included because they are assumed to be invariant. The AWG 38 × 5 litz wire is much more expensive than the original 0.31 mm wire. However, the energy savings are sufficient to easily justify its use. But the single-strand shape-optimized design offers a reduction in both winding cost *and* energy cost, and has by far the lowest total cost. We assume that in mass production the cost the special bobbin shape would not add significant extra cost.

TABLE IV

COST COMPARISON

Winding Type	Measured Winding Loss	Present Value of Energy	Wire Cost	Total Cost
0.31 mm solid	0.301 W	$0.264	$0.077	$0.341
AWG 38 × 5 litz	0.163 W	$0.143	$0.161	$0.304
Shape optimized AWG 30	0.176 W	$0.154	$0.052	$0.207

IV. RESULTS AND CONCLUSIONS

Both winding optimization methods used here showed a reduction in winding loss is possible through proper design. The litz-wire winding prototype reduced the winding loss by 48%. The shape-optimized winding reduced the loss by 40%. The in-ballast performance of each prototype was investigated and initial results showed that the optimized winding reduced the power consumption of the lamp-ballast by 4.3% for the same light output as the original winding design. More investigation into ballast performance is needed to fully characterize improved ballast performance.

The design of magnetic components for high-frequency applications is difficult because the loss effects at high-frequencies are complicated and not easily understood. The winding design tools used to optimize the windings considered here are easy to use and available for free at [13]. High-frequency magnetic design tools are essential to improving the efficiency of power conversion systems in a variety of applications. Accurate winding loss methods have been shown to reduce losses in the magnetic components of electronic ballasts in CFLs.

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