# Renco Electronics, Inc.

## *Different Ways to Increase the Efficiency of PFC Boost Inductors*

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*APN -101*

## Abstract

For the past few decades the efficiency of power supplies has been increasing steadily as semiconductor and magnetics materials have been improved and their respective losses have been reduced. Now most of this improvement in efficiency has been on a volunteer basis until a few years ago when the Energy Star (www.energystar.gov) and 80 Plus Silver (www.80pls.org) efficiency standards really started to gain acceptance. These two energy efficiency standards now set minimum efficiency requirements that must be met by certain dates.

The Power Factor Correction (PFC) boost inductor is one area where a few percentage points in efficiency can be gained. This paper discusses ways to increase the efficiency of PFC Boost inductors.

## Introduction

PFC design has been written about quite heavily for the past 5 years. As a result, there is a lot of information about designing PFC circuitry and the PFC inductor, but not much information about the subtle ways of increasing the efficiency of the PFC inductor. In order to increase the PFC circuit efficiency to meet the above mentioned standards, different ways of increasing the PFC boost inductor efficiency must be understood.

## Typical PFC Inductor

Most PFC inductor designs require that the inductor handle a large peak to peak current and this can also mean the peak current will be larger than most typical inductor designs. This large peak current requires a large gap in the center leg of the core of a ferrite based design and this is where a large percentage of the efficiency can be lost if the design engineer is not careful during the design process. Figure 1 illustrates the EF25 ferrite package that is commonly used in PFC inductors.

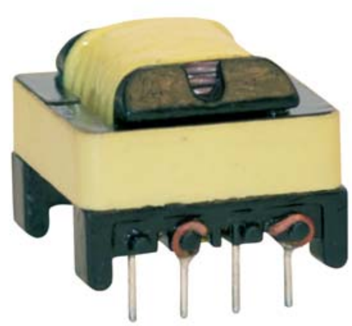

***Figure 1. EF25 PFC Inductor***

## PFC inductor Design comparison

The next section of this paper contains two real-world designs and the respective results. This will clearly show some of the issues with the PFC inductor and later on ways of correcting these issues will be discussed.

The customer contacted Renco Electronics with an urgent need for a PFC inductor with an inductance of 380 uH at a peak current of 6A in an EF25 package. The design below was wound on the EF25 bobbin using #24 AWG and samples were immediately wound and shipped out because of the urgent need. The gap size listed in Table 1 was a concern, but the design had to be completed and samples had to ship.

| | |
|---|---|
| Inductance (μH) = | 380 |
| Peak Current - Ipk (A) = | 6 |
| Frequency (Hz) = | 70000 |
| Turns = | 133 |
| Lgap(in) = | 0.125 |

***Table 1. Design #1***

A few days later, Renco Electronics was informed that with the PFC inductor that was provided the power supply efficiency at 120V input with a 100W load was only 90%. The goal for efficiency was 94%+. Upon further investigation it was determined that the initial efficiency measurement was only taken after only a few minutes of the power supply being in operation. Renco Electronics requested temperature rise test results and once those measurements were reviewed it was evident that the initial design had a problem. The temperature of the PFC inductor after only 5 minutes was 90 ºC. Clearly the PFC inductor had to be redesigned.

After further dialogue with the customer it was evident that the initial design parameters as provided by the customer were not correct. The final peak current was lower than originally specified, therefore, requiring less turns and a much smaller gap. These changes would greatly lower the temperature rise. See Table 2. Since there was no time for a third set of samples to be designed and built if the samples from Design #2 did not work, it was also decided to use the multi-stranded and strategically bundled wire known as litz. Using litz wire would ensure the Ac resistance would be as low as possible. Litz wire is commonly used to combat the skin effect and proximity losses that are commonly combined and simply known as Ac resistance losses[1]. Samples of the design listed in Table 2 were built with 25 strands of #38 SPN.

| | |
|---|---|
| Inductance (μH) = | 380 |
| Peak Current - Ipk (A) = | 4.25 |
| Frequency (Hz) = | 70000 |
| Turns = | 94 |
| Lgap(in) = | 0.06 |

***Table 2. Design #2***

Again a few days later, Renco Electronics was informed that the latest inductor samples were approved since the efficiency at 120V input with 100W load was 95%. How can a reduction in gap and the use of litz wire make such an impact? This will be covered later in this paper.

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## PFC inductor losses

Once feedback was received on the samples built per Design #1, Renco Electronics conducted a detailed analysis of the losses of the original design vs. the losses of the revised design that was eventually approved. A review of this information will be helpful in future PFC inductor designs.

While the comparison, in Table 3, is not an apples to apples comparison since the design was changed after Design#1 was tested, it does provide valuable information. In Design #1 the largest contributor to the total losses is the loss directly related to the Ac resistance of the winding. Almost 17 watts of Ac resistance loss is the main contributor to the estimated 230 ºC temperature rise. Design#1 would easily have gone into thermal runaway if allowed to operate for more than 5 minutes.

Using litz wire in Design #2 reduced the Ac resistance losses to 1.4W. More importantly the combination of the reduction of the gap size by more than half and the use of litz wire reduced the estimated temperature rise to 39 ºC. The measured temperature rise was 45 ºC.

It can be clearly seen, in Table 3, how the transformer efficiency is increased by the reduction in total inductor losses.

| | Design #1 | Design #2 |
|---:|:---:|:---:|
| Core loss of inductor (W) = | 0.637 | 0.237 |
| Pdcr (W) = | 1.023 | 0.725 |
| Pacr (W) = | 15.227 | 1.401 |
| Total Inductor Losses (W) = | 16.888 | 2.363 |
| **Estimated Temperature rise (ºC) =** | **230.183** | **39.240** |
| $\eta$Transformer (%) = | 83.604 | 97.706 |

***Table 3. Inductor Losses for Design #1 and Design #2***

## Resistance vs. Frequency Losses

When reviewing Table 3 it is evident that the use of litz wire greatly reduced the Ac resistance, the total losses, and ultimately the temperature rise. This reduction in temperature rise does come with a price. Magnetics designs that utilize litz wire can easily cost 30%+ more than designs that utilize solid copper wire. Some options to possibly still use solid wire will be discussed later on.

For cost purposes it would be ideal to use solid copper wire, but the Ac resistance does increase as the frequency is increased. In the case of the above mentioned designs, the inductors are operated at 70 kHz. In Figure 2 it is clear that after 20 kHz the Ac resistance of the solid wire increases substantially. The Ac resistance of the litz wire on the other hand stays reasonably flat from 60 Hz to 80 kHz.

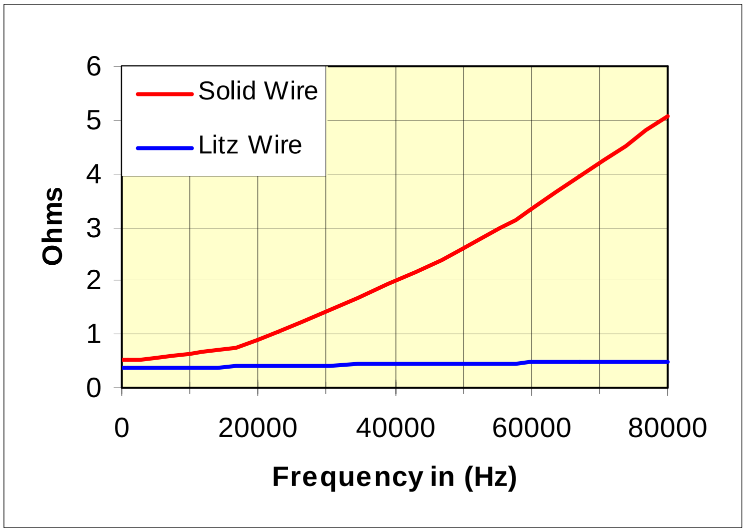


***Figure 2. Winding Resistance vs. Frequency for EF25 PFC Inductor***

At 70 kHz the Ac resistance for the solid wire is more than 4 ohms vs. the ½ ohm of Ac resistance measured on the design using the litz wire. When calculating the $I^2R$ losses directly related to theses Ac resistances, the Irms value of the peak-peak ripple current must be used.

Could the solid wire still be used in this type of design? Yes, but the peak current, inductance, or both have to be reduced in order to reduce the turns, the number of layers of the winding, and ultimately the Ac resistance. Another option is to select a different inductor package that will allow more turns per layer and thus, fewer layers. The above mentioned designs both had windings with approximately 6 layers. Design #1 would have had much less Ac resistance if there would have been only two layers or less of solid wire. Taking a close look at Figure 3, it is evident that as the numbers of layers are reduced the Ac resistance is also reduced. Furthermore, at 70 kHz the Ac resistance is reduced by 75%, to approximately 1 ohm, by simply reducing the number of layers of solid wire to 3. Comparing Figure 2 to Figure 3 it is also evident that the inductor with 2 layers of solid wire has an Ac resistance, at 70 kHz, which is less than the Ac resistance of the 6 layers of litz wire. Therefore, if the Ac resistance is a concern and costs must be kept low, by avoiding litz wire, try reducing the layers of the winding to two or less. This may be enough to meet the efficiency requirements while also keeping costs low.

## Gap Size

If the Ac resistance can be kept low by simply using two layers or less of solid wire then the only other area of concern is the gap size. The fringing flux that surrounds a large gap will intersect with the eddy currents in the windings and cause localized heating. See Figure 4. In other words, melted bobbins and fused copper. If the gap size is large and solid wire is used in more than two layers the design can easily go into thermal runaway as was the case with Design #1.

Now if the gap size is large, but solid copper wire is still the desired choice then the winding has to be kept at a safe distance from the fringing flux that is radiated by the gap. There are different techniques used to keep the winding away from the fringing flux or to reduce the amount of flux that is fringing in ferrite based designs. Renco Electronics' Design Engineering Team would be happy to assist with your PFC inductor designs and can discuss the various ways to keep the windings away from the gap.

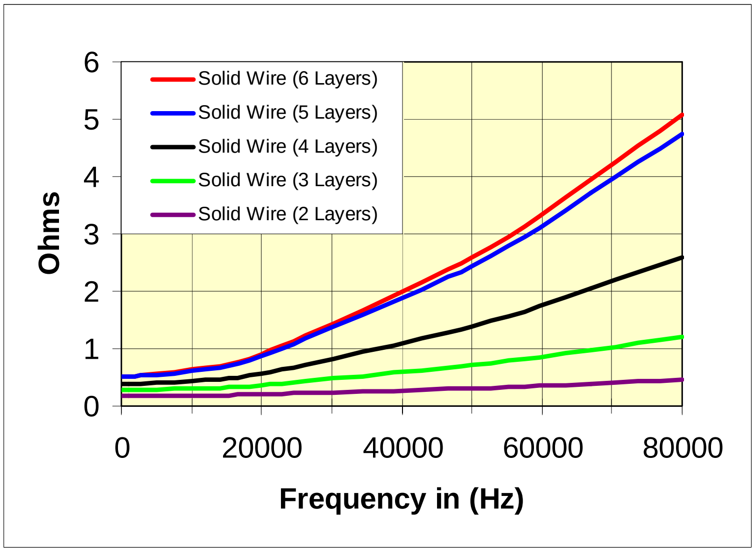


***Figure 3. Winding Resistance - Various layers for EF25 PFC Inductor***

One option available to eliminate the fringing flux and the related consequences is to use a powder core made of Kool Mu, MPP, or Hi-flux materials manufactured by Magnetics, Inc. These powder cores do not require a physical gap in the center of the core since the gap is distributed throughout the material. The downside is that powdered cores are more expensive than ferrite cores and have higher core losses. The trade-offs should be investigated carefully.

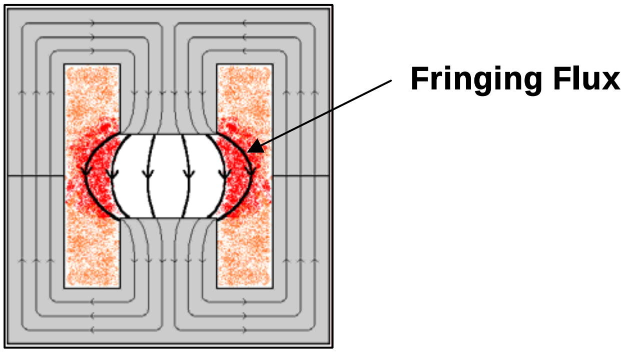


***Figure 4. Fringing Flux – Courtesy of Magnetics, Inc.***

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## Conclusion

This paper has compared two real world PFC inductor designs in detail. Furthermore, it was discussed how the inductor losses can be reduced and the efficiency increased by switching to litz wire, reducing the turns, and reducing the gap size. Finally, it is clear that in order to increase the efficiency of PFC inductors or any magnetic component a careful review of the magnetics design must take place.

If you need assistance with your PFC inductor design or other custom magnetics designs contact Renco Electronics' Design Engineering team at Engineering@rencousa.com or call the Engineering hotline: 1-800-645-5828

[1] For more discussion on Skin Effect and Proximity Effect refer to the application note - APN-100 titled, *The Effects of Increasing Frequency on Magnetic Components.* Available at www.rencousa.com