



## **Facility Electrical Losses: Proximity Effect, Skin Effect, and Eddy Current Losses**

### **Introduction**

There is much confusion about calculating the wattage losses within an operating AC facility power distribution system. Despite large bodies of published knowledge to the contrary, many facility and utility engineers persist in performing simple line loss calculations based upon known wire conductor specifications and published DC resistance values. Consequently, when discussions of possible energy usage reduction measures are raised, these same personnel frequently cause substantially beneficial projects to go unimplemented.

EASI specializes in identifying and eliminating or reducing AC distribution losses in fully operational, fully loaded commercial and industrial power systems.

This paper is our simple statement that all of our work is based upon standard, published calculative methods, and considers long acknowledged and quantified phenomenon contributing wattage losses to operating AC power systems. The particular focus herein is upon proximity effect losses and eddy current losses in magnetics and distribution wiring.

### **Proximity Effect**

The AC current in two round, parallel wires is not distributed uniformly around the conductors. The magnetic fields from each wire affect the current flow in the other, resulting in a non-uniform current distribution, which in turn, increases the apparent resistance of the conductors. In parallel round wires, we call this the proximity effect.

EASI applies proprietary mathematics routines to identify the distribution losses associated with proximity and skin effects. EASI quantifies the AC losses in conductors, switchgear, protective systems, and the windings of any magnetic device within a closed facility electrical distribution system. Without proximity analysis the actual distribution losses can be much higher than the predicted DC losses.

### **Proximity Losses in AC Conductors and Magnetic Devices**

Proximity effect is an AC power system phenomenon that can greatly increase magnetic losses over DC resistance or skin effect values alone. Closed form analysis in the form of a set of hyperbolic equations is possible without resulting to 3-D finite analysis programs. However, a full harmonic analysis must be used on the governing equations or loss estimates may be off by orders of magnitude. As a result, EASI uses a proprietary computer program in order to quickly calculate the results of design changes upon facility distribution system losses.

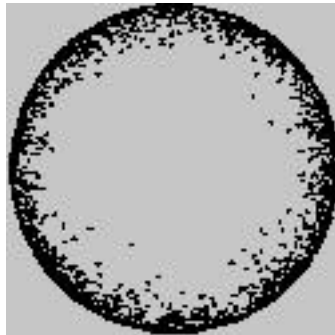
### **What is Proximity Effect?**

Most power engineers are familiar with the tendency of a current to flow on the outside of a conductor at higher frequencies. With skin effect, the current distribution is affected by the conductor's own magnetic field, increasing the losses. Proximity effect is similar, but is the mutual influence of multiple current carrying conductors. Their interaction causes uneven current distribution in the conductors, again increasing losses.

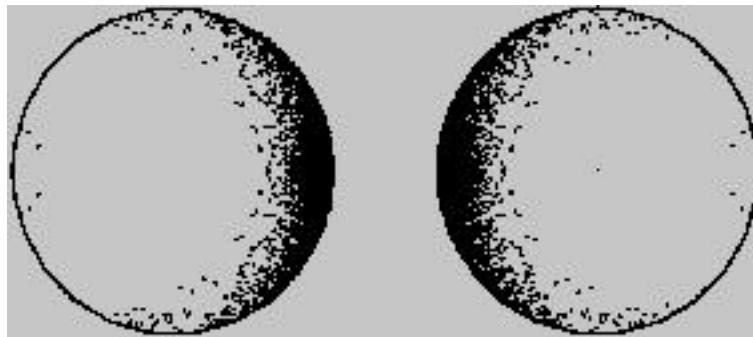
Proximity and skin effects are major source of losses in transformer and inductor designs, as well as in AC power distribution systems composed of separate, round wire conductors, applied within enclosed pipe conduit. Whether the effect is visualized as induced circulating (eddy) currents, or as a redistribution of the current to meet boundary conditions, the result is a non-uniform current distribution with an increase in loss over what the DC resistance alone would suggest. Figures 1-3 show typical current distributions for skin effect, and proximity effect with current flow both in the same direction and in opposite directions.

Proximity effect is especially onerous. More serious than skin effect, the analysis of proximity current losses is obscure and mathematically difficult. Because of this, proximity effect is one of the most neglected magnetic design areas. It can be argued that core loss and proximity effect are the two most important considerations in magnetic design for AC power distribution systems. Just as operating flux density is core loss (and not saturation) limited at high frequencies, so wire current density is limited by proximity effects, and not DC resistance.

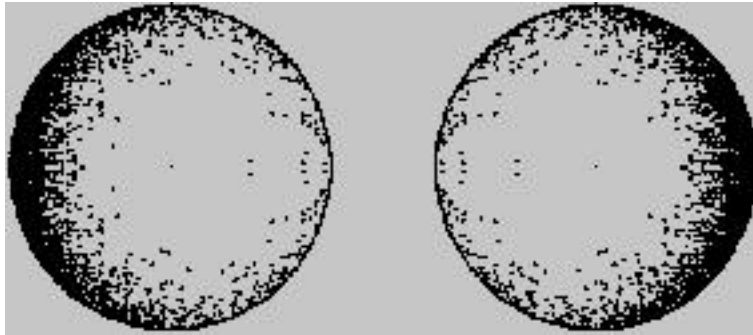
EASI has conducted substantial research into the anticipation, analysis and calculation of proximity and skin effect losses, and has long incorporated these findings into all of our energy efficiency design calculations.



**Figure 1** - Current distributions for skin effect



**Figure 2** - Current distributions for proximity effect with current flow both in the same direction



**Figure 3** - Current distributions for proximity effect with current flow both in opposite directions

### Eddy Current Losses Aren't Just for High Frequencies

Eddy current effects aren't just limited to high frequency designs. Proximity effects can occur whenever the conductor thickness is a significant fraction of the skin depth. A large, high power 60 Hertz transformer or wire conductor pair will suffer from proximity losses, while a very small high frequency transformer or wire pair might not.

Even non-current carrying conductors experience eddy current losses when immersed in an external AC magnetic field. These might be a shield, adjacent conductors within a distribution panel, or even a transformer or motor winding that is not conducting at a given point in time. Skin and proximity effects are important in every conductive element inside transformers, inductors, groups of wire conductors, or any AC magnetic device.

### Terminology

One skin depth (SD) is the equivalent current penetration depth into a conductor that all current would have to flow for an equivalent loss. Skin depth is only a function of frequency and conductor properties. Measuring dimensions in skin depths eliminates frequency as a parameter.

DC resistance ( $R_{dc}$ ) is the base resistance ignoring high frequency effects. The AC resistance ( $R_{ac}$ ) is the total effective resistance for a given waveform, and may be used to find the actual loss. How much the resistance or loss increases is given by the  $R_{ac}$  to  $R_{dc}$  ratio.

A winding is a set of turns or group of adjacent conductors that share the same current and waveform. A winding section is the portion of a winding that is uninterrupted by any other conductors. The portion of a winding or pair of conductors that exists in a single physical plane is a layer.

An individual winding element (wire) is a conductor. The conductor or winding height is measured at right angles to the axial center of the core.

The tangential magnetic field is the field that goes across the winding surface. It is assumed to be uniform. The field ratio is the ratio of the tangential fields at the top and bottom surfaces of the conductor.

## Proximity Effects Can Dramatically Increase Losses

Follows is a discussion relevant specifically to transformer design. The same principles apply equally to multiple wire conductors in close proximity to one another, as in a long conduit run, a crowded junction box, or within a well filled breaker panel.

For one winding layer one skin depth high, proximity and skin effect calculated losses have roughly the same magnitude. By definition, skin effect does not change with winding construction. For proximity effect, multiple winding layers increase the magnetic field buildup and hence losses. Proximity effect may not be noticed until a multi layer design is attempted.

Suddenly, losses may increase by orders of magnitude over a skin effect based prediction! Consider the following cases for a bipolar PWM drive with a duty cycle (DU) of 0.5, where  $R_{ac}/R_{dc}$  is the resistance loss increase (all waveform frequencies are at 100 KHz):

### $R_{ac}/R_{dc}$ at One Skin Depth Increases with Layers

Waveshape	Layers	$R_{ac}/R_{dc}$	Comments
Bipolar 0.5 DU	1	1.17	good design!
Bipolar 0.5 DU	10	19.5	disaster strikes!
Bipolar 0.5 DU	100	1860	hopeless!

Simply increasing the wire size won't help; unlike skin effect, a larger than optimum wire size can dramatically increase the losses, especially for multiple winding layers. Litz wire is not a panacea and may also increase losses. Consider a unipolar drive with a duty cycle of 0.25, and different conductor heights:

### $R_{ac}/R_{dc}$ Increases with Conductor Thickness or Height

Conductor Height	$R_{ac}/R_{dc}$ @ 1 Layer	$R_{ac}/R_{dc}$ @ 10 Layers
0.1 SD	1.0	1.013
0.2 SD	1.0	1.19
0.5 SD	1.04	5.35
1.0 SD	1.23	26.5
2.0 SD	2.05	110
5.0 SD	4.88	314

Increasing the conductor thickness can sharply increase the resistance. Too thin a conductor is better than too thick for multiple layer designs. For one layer, larger wire sizes are "safe" in that losses never increase with wire diameter. Skin effect losses are also always "safe."

## A Waveform's Harmonics Must be Considered for Proximity Effect.

If a proximity effect loss analysis was based on a sine wave approximation the winding or conductor grouping losses would be off by almost 300% for a typical PWM waveform. For typical high input line conditions, the losses would be off by 500%, or more. For a short circuit condition with a narrow pulse, winding loss estimates would be off by 12:1!

## How is Proximity Effect Analyzed?

As shown, proximity effect totally dominates wire losses for many common cases. Oddly enough, there is little obtainable literature on proximity effect. An examination of many magnetic and power supply books, and programs revealed absolutely no coverage. As a result, even experienced magnetic and power engineers do not consider proximity effects.

Closed form eddy current loss equations can not be obtained for arbitrary conductor placements. Dowell (reference 1) noticed that for most designs the magnetic field varies only in the radial or height direction, and not in the axial or horizontal direction. These assumptions allowed the desired closed form loss equations to be derived. Not meeting these assumptions usually increases the losses over predicted and can be considered a "bad" design. EASI's calculative methodology encompasses both Dowell's findings, as well as our own empirically derived transforms in determining accurate proximity effect losses.

Two other key papers extended Dowell's work. The next (reference 2) applied harmonic analysis to the equations and applied the results to a broad range of practical situations. A set of normalized graphs were produced, allowing analysis without a computer (which weren't that common before 1986). Since most of EASI's systems applications are into industrial facilities with substantial PWM and other nonlinear loading, we have carefully extended our calculative systems for skin effect, proximity effect and eddy current efficiencies to properly factor higher than line frequency currents, and to base these determinations upon field gathered harmonic data. Dowell also assumed that the fields were uniform to the winding surface. The third paper (reference 3) showed that the losses in a single layer could be found if the tangential field amplitude on either side of the layer was known. Simplified magnetic field plots, showing the change in field strength in the height direction, were used to visualize the required amplitudes. (EASI has established a correlation between Dowell's tangential field amplitude based predictors, originally intended for modeling single layer transformer windings, and the modeling of multiple wire conductors in very close proximity in AC distribution arrangements.)

Even with the aid of all referenced papers, the analysis is not straightforward. Using concepts developed from the third paper, the following equation governs the losses in an individual layer at one frequency:

$$Loss = Area \frac{H^2}{2\delta\sigma} \left[ (1 + H_r M_n) - 4H_r D_n \right]$$

**Area** is the total conductor surface area = (winding width) (winding length)

**H** is the high side magnetic field intensity (in ampere turns per length)

**H<sub>r</sub>** is the field ratio for one winding (high side to low side)

***Mn*** and ***Dn*** are defined, using the skin depth, conductor thickness and standard hyperbolic identities, as:

$$Mn \equiv \frac{\text{SINH}(2\Phi) + \text{SIN}(2\Phi)}{\text{COSH}(2\Phi) - \text{COS}(2\Phi)}$$

$$Dn \equiv \frac{\text{SINH}(\Phi)\text{COS}(\Phi) + \text{COSH}(\Phi)\text{SIN}(\Phi)}{\text{COSH}(2\Phi) - \text{COS}(2\Phi)}$$

and:

$$\Phi \equiv \frac{H_t}{\delta}$$

is the layer or conductor height in skin depths (for copper wire at 100 KHz the skin depth is approximately 0.0084")

and finally:

$$\delta \equiv \sqrt{\frac{2}{2\pi F \mu_0 \sigma}}$$

the skin depth constant at any frequency where:

**$\mu_0$**  is the material's permeability

**$\sigma$**  is the material's conductivity

This loss equation must be applied to every layer of a transformer winding, considering the net magnetic field build up; or must be applied to every pair of wire conductors being evaluated. Worse yet, for a non-sinusoidal waveform this equation must be evaluated at every significant harmonic. For a 100 KHz pulse at a 50% duty cycle with 50 nS rise times, about 200 harmonics should be analyzed to accurately find the total loss. It's no wonder most designers don't apply these formulas!

EASI has invested heavily into the field testing, product applications, computer modeling, and software development systems required to align our predictive methods against the accepted mathematics of distribution loss modeling, and to include the above mathematics concepts into each predictive modeling exercise we undertake in a power system efficiency design.

## How do I Minimize Proximity Effect?

### Transformers

In transformer design, layer quantity and organization are the key. Initially, select a core and a number of turns that minimizes the total number of layers needed. The best cores will have a long winding width to height ratio, allowing the conductor to be more spread out. Raising the operating frequency to reduce the number of layers may be beneficial.

Paradoxically, once the core and number of turns have been selected, an increased number of layers may reduce loss. Although increased layers are detrimental to the AC to DC resistance ratio, the optimum total height increases even as each individual layer becomes thinner. This adds additional copper area, decreasing the DC resistance. This only applies if the bobbin can tolerate the extra height required.

Maximizing the number of layers is most easily accomplished by using foil windings wherever possible. Ten layers of foil will have a lower loss than ten round wires on a single layer, assuming optimum thickness for each. The foil winding has a higher  $R_{ac}/R_{dc}$  ratio due to the multiple layers but, with the higher total optimum height, a net overall lower AC resistance.

Interleaving the winding will reduce proximity effect by reducing the effective number of layers. Using this technique, some of the primary's layers are wound, then some of the secondary's, then some more of the primary's, etc.. This reduces the effective number of layers in each winding section, and the resulting field build up.

Additionally, keep conducting materials (terminations, shields, etc.) away from the magnetic field. If a shield is necessary keep it less than a skin depth thick.

In the absence of correctable transformer design within an existing facility, reduction of net current yields marked reductions in proximity effect and eddy current losses within transformers and other magnetic devices, such as motors, ballasts, and power supplies.

### Distribution Systems

Building power distribution systems composed of round wire conductors inside pipe conduit demonstrate substantial proximity effect losses. Where the system provides power to a substantial population of PWM or other nonlinear AC loads, and is conducting substantial current at higher than line frequency, skin effect losses combine with proximity effect losses to yield working AC resistance substantially greater than DC resistance.

As with transformers, a calculative approach to loss determination can provide a working platform from which decisions can be made as to eliminating or reducing either line frequency current, harmonic current, or both, in a program of skin effect, proximity effect, and eddy current loss reduction.

### Summary

Even very experienced power system engineers have little direct knowledge of calculating or correcting proximity effect losses in magnetics and distribution wiring. While some knowledge of simple eddy current losses in windings is well disseminated, the combined effects of full load current values for proximity effect, skin effect, and eddy current losses in an operating facility power distribution system requires tedious and often proprietary knowledge to calculate and correct. Many utility and plant personnel persist in ignoring these substantial electrical system losses as systems planning and maintenance issues.

Worsening the problem is the persistent use of misleading test methodologies in estimating facility electrical system losses, the most widely used such method being simple point to point DC resistance measurements of unloaded wiring, which frequently yields resulting values an order of magnitude less than actual full load AC resistance.

EASI specializes in the evaluation and systematic correction of full load electrical system losses. Since 1978, we have collected data from thousands of operating facility electrical systems in our ongoing analysis of all forms of electrical losses. And, we have coordinated our work with the growing body of world industry study and publications, to erect the systems design program we now use to determine the actual proximity effect, skin effect, eddy current, and simple AC line losses occurring within each of the client facilities we evaluate for corrective measures.

Sometimes, there are dramatic savings in facility electrical losses to be gained from relatively simple measures for eliminating or reducing real current, reactive current, and/or harmonic current, sufficient to provide a sensible economic gain, and a rapid financial payback from such a corrective project.

#### References

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- 3.) J. P. Vandelac, "A Novel Approach for Minimizing High Frequency Transformer Copper Loss," 0275-9306/87/0000 1987 IEEE
- 4.) KO Systems, "Proxy, A Proximity and Skin Effect Analysis Program," 10437 Laramie Ave, Chatsworth, CA, 818 341 3864