Distribution Losses In Industrial Facilities

There is a dramatic difference in an AC power distribution system between the simple DC resistance values of the various conducting elements, and the actual apparent AC resistance, under heavy current load, of these same elements. Motors, lighting systems, wiring, mechanical terminations, distribution panels, protective devices, transformers, switchgear, and all end of circuit equipment experience a variety of resistance increasing inefficiencies that combine to create an average wattage loss in a typical industrial facility of from 10% to 25% of total demanded power. Identifying and calculating the sum of the individual contributing loss components is a challenging engineering specialty, requiring extensive experience and knowledge of all the factors impacting the operating efficiencies of each of these components.

The following list is a simplified overview of several of the more important loss factors in an industrial facility, including a broad range estimate of reasonable loss values attributable to each stated effect. Note that all of these are current dependent, and can be readily mitigated by any technique that reduces facility current load.

Hysteresis Losses

Hysteresis loss is a heat loss caused by the magnetic properties of the armature in an AC motor. When an armature core is in a magnetic field, the magnetic particles of the core tend to line up with the magnetic field. When the armature core is rotating, its magnetic field keeps changing direction. The continuous movement of the magnetic particles, as they try to align themselves with the magnetic field, produces molecular friction. This, in turn, produces heat. This heat is transmitted to the armature windings. The heat causes armature resistances to increase.

• ***Typical hysteresis losses as a percentage of building demand: 2% to 5%***

Skin Effect Losses

The apparent resistance of a conductor is always higher for AC than for DC The alternating magnetic flux created by an alternating current interacts with the conductor, generating a back EMF which tends to reduce the current in the conductor. The center portions of the conductor are affected by the greatest number of lines of force, the number of line linkages decreasing as the edges are approached. The electromotive force produced in this way by self-inductance varies both in magnitude and phase through the cross-section of the conductor, being larger in the center and smaller towards the outside. The current therefore tends to crowd into those parts of the conductor in which the opposing EMF is a minimum; that is, into the skin of a circular conductor or the edges of a flat strip, producing what is known as 'skin' or 'edge' effect. The resulting non-uniform current density has the effect of increasing the apparent resistance of the conductor and gives rise to increased losses.

Harmonic loading increases skin effect losses by the square of the increase in frequency above nominal line frequency, and so is responsible for a substantial lost wattage in any facility with large populations of nonlinear equipment loads, such as VFDs, DC drives, rectifiers, induction heating or other arcing or switching power supply devices.

• ***Typical skin effect losses as a percentage of building demand: 2% to 8%***

Proximity Effect Losses

Proximity effect is a property existing when conductors are close together, particularly in low voltage equipment, where a further distortion of current density results from the interaction of the magnetic fields of other conductors.

In the same way as an EMF may be induced in a conductor by its own magnetic flux, so may the magnetic flux of one conductor produce an EMF in any other conductor sufficiently near for the effect to be significant.

If two such conductors carry currents in opposite directions, their electromagnetic fields are opposed to one another and tend to force one another apart. This results in a decrease of flux linkages around the adjacent parts of the conductors and an increase in the more remote parts, which leads to a concentration of current in the adjacent parts where the opposing EMF is a minimum. If the currents in the conductors are in the same direction the action is reversed and they tend to crowd into the more remote parts of the conductors.

This effect, known as the 'proximity effect' (or 'shape effect'), increases the apparent AC resistance. If the conductors are arranged edgewise to one another the proximity effect increases. In most cases the proximity effect also tends to increase the stresses set up under short-circuit conditions and this may therefore have to be taken into account.

• ***Typical proximity effect losses as a percentage of building demand: 1.5% to 3%***

Transformer Losses

The two primary types of transformer losses are core losses and load losses. The core loss of a transformer arises because the core must be taken through its alternating cycles of magnetization. Core losses occur because there must exist a magnetizing current in the primary winding of a transformer which is additional to that current which flows to balance the current in the secondary winding. The magnetizing current is required to take the core through the alternating cycles of flux at the rate determined by system frequency. In doing so, energy is absorbed. This is known as the core-loss. The core-loss is present whenever the transformer is energized.

Transformer load losses occur because the flow of a current in any electrical system also generates loss dependent upon the magnitude of that current. Transformer windings are no exception and these give rise to the load loss of the transformer. Load loss is, of course, present only when the transformer is loaded and its magnitude is proportional to the load squared.

There are three categories of load loss which occur in transformers :

- Resistive losses, often referred to as I^2R losses.
- Eddy-current winding losses due to the alternating leakage-fluxes
- So-called stray losses in leads, core-framework and tank due to the action of load-dependent stray alternating fluxes.

Resistive losses, as the term implies, are due to the fact that the windings cannot be manufactured without electrical resistance (at least, until commercial superconductors are successfully developed) and are therefore a "fact of life" which cannot be eliminated for the transformer designer.

The leakage-flux occurring in transformer windings is greatest at the winding ends, but is present throughout the entire winding body. Consequential eddy currents are set up that oppose the natural direction of current flow and greatly increase the transformer’s apparent AC resistance.

Stray losses exist in all transformers, but present more of a problem on larger transformers, because the physical size of the leads and the currents they carry are greater.

Typical transformer losses as a percentage of building demand: 1% to 2%

Line Losses

In addition to I^2R losses and dielectric losses, cables have other losses such as skin-affect and proximity-effect developed by magnetic induction. For single conductor cables, however, where conductors are not operating close to each other, proximity effect is negligible. Skin-effect loss is caused by the reversing magnetic field, about the cable, which tends to concentrate the current toward the periphery of the conductor. This affect then reduces the effective carrying capacity of a conductor in its central portions. Proximity-effect loss is caused by the opposing force of magnetic fields set up by neighboring conductors. This displaces the points of maximum reactance to a maximum distance from each other, resulting in maximum current density at the nearest surfaces of the two conductors. Operating together in a typical industrial conduit enclosed distribution system, these various loss factors can sufficiently increase the building wiring's apparent AC resistance to more than an order of magnitude above nominal DC resistance values. Thus, typical I^2R wiring losses are often far greater than simple chart-based values.

With the above, recall that I^2R losses occur in *ALL* distribution system conducting components, not only the wire.

• ***Typical line losses as a percentage of building demand: 1% to 3%***

Eddy-Current Losses

With any electrical system component comprising an iron or steel frame and an electrical coil, flux will flow in the steel as a result of the alternating current in the coil. The flux in the steel will itself induce an EMF in the material following the basic laws of induction. Since the material is essentially an electrical circuit closed on itself, the induced EMF will cause a circulating electrical current called an eddy-current. Its value is dependent on the value of EMF and on the resistivity of the path of current. As in any other electrical circuit the power loss is the product of the square of the current times the resistance. In a similar manner to hysteresis losses, the eddy-current loss manifests itself as heat, contributing to the maximum operating temperature limit of the device.

Eddy current losses occur in protective circuit breakers, lighting ballasts, power supply transformers, magnetic motor starters, voltage reducing or isolation transformers, current overload relays, control contactors and relays, all motor windings, and even building wiring, when the wiring is in circular proximity to steel or iron structures, such as electrical enclosures, distribution panels, or terminal or distribution blocks.

• ***Typical eddy current losses as a percentage of building demand: 1.5% to 4%***

Tel: 615-822-7250 Fax: 615-822-7252 Web: http://www.energyautomation.com

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.

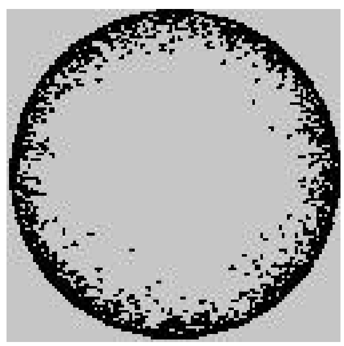

Figure 1 - Current distributions for skin effect

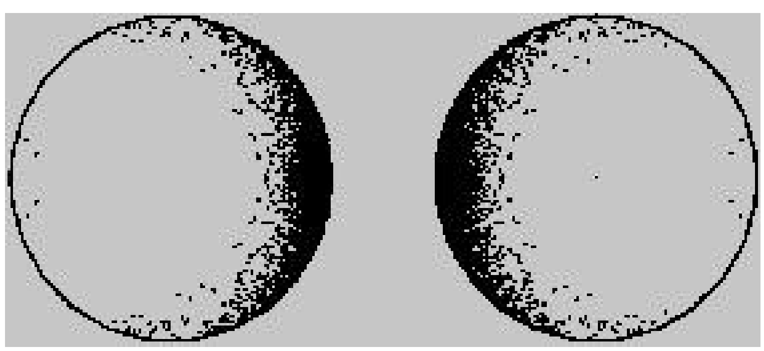

Figure 2 - Current distributions for proximity effect with current flow both in the same direction

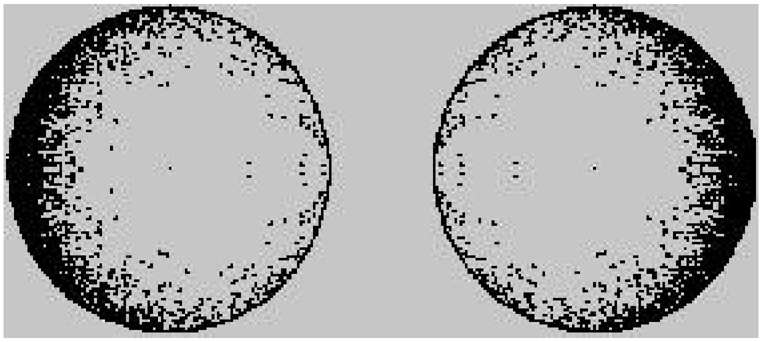

Figure 3 - Current distributions for proximity effect with current flow both in opposite directions

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 (Rdc) is the base resistance ignoring high frequency effects. The AC resistance (Rac) 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 Rac to Rdc 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 Rac/Rdc is the resistance loss increase (all waveform frequencies are at 100 KHz):

Rac/Rdc at One Skin Depth Increases with Layers

Waveshape	Layers	Rac/Rdc	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:

Rac/Rdc Increases with Conductor Thickness or Height

Conductor Height	Rac/Rdc @ 1 Layer	Rac/Rdc @ 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:

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

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

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

Hr 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:

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

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

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:

m_o is the material's permeability

s 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 Rac/Rdc 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

1.) P. L. Dowell, "Effects of Eddy Currents in Transformer Windings," Proc. IEE, Vol 113 No. 8, August 1966

2.) Bruce Carsten, "High Frequency Conductor Losses in Switchmode Magnetics", High Frequency Power Conversion Conference Proceedings, CA, May 1986

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