

Air Core Reactors: Magnetic Clearances, Electrical Connection, and Grounding of their Supports

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Abstract:

Dry type air core reactors are devices which are used at both distribution and transmission voltages for a variety of applications such as fault current limiting, power flow control, reactive compensation (shunt reactors), and as the inductive part of tuned harmonic filters. They may be relatively small devices weighing tens or hundreds of pounds with power ratings less than 100 kvar, up to very large coils weighing as much as 100,000 lbs. or more, and having power ratings in the range of 600 Mvar (60 Hz equivalent.)

Although they are well established and proven devices which have been widely used for many years by electric utilities around the world, much confusion and misunderstanding still exists in terms of how to properly make reliable electrical connections to air core reactors, how to properly ground their supports and how to deal with the effects of their stray magnetic fields. These issues arise as a consequence of the fact that air core reactors do not have a magnetic core to constrain the magnetic field and as a result the magnetic field is “broadcast” in and around the reactor. This broadcasted field or so called “stray field” induces eddy currents in any metallic objects on which it impinges, hysteresis losses in ferromagnetic material, and potentially large currents in closed loops such as can be formed by concrete reinforcements, fencing, or improperly arranged support grounding connections. These eddy currents and closed loop currents can give rise to severe heating problems on terminal connections, concrete reinforcements and fencing under steady state conditions, and also to damaging forces during short circuit.

This practical paper illustrates the basic nature of the magnetic field of air core reactors and the theory behind the formation of eddy currents, closed loop currents and hysteresis losses. Guidance is given on how to arrange the electrical connection, and the characteristics of connectors to use, to minimize terminal heating and avoid damaging forces during short circuit. The concepts of magnetic clearances are explained and alternative methods of handling concrete reinforcement and fencing are illustrated along with the “Do’s and Don’ts” of reactor support grounding.

Introduction:

Dry type air core reactors are devices which are used at both distribution and transmission voltages in both AC and DC systems for a variety of applications such as fault current limiting, power flow control, reactive compensation (shunt reactors), DC Smoothing and Coupling reactors, and as the inductive part of tuned harmonic filters, among others. They may be relatively small devices weighing tens or hundreds of pounds with power ratings less than 100 kvar, up to very large coils weighing as much as 100,000 lbs. or more, and having power ratings in the range of 600 Mvar (60 Hz equivalent.) Despite the wide range of applications and sizes, dry type air core reactors share a basic common structure (with numerous variations in construction details depending on ratings and application).

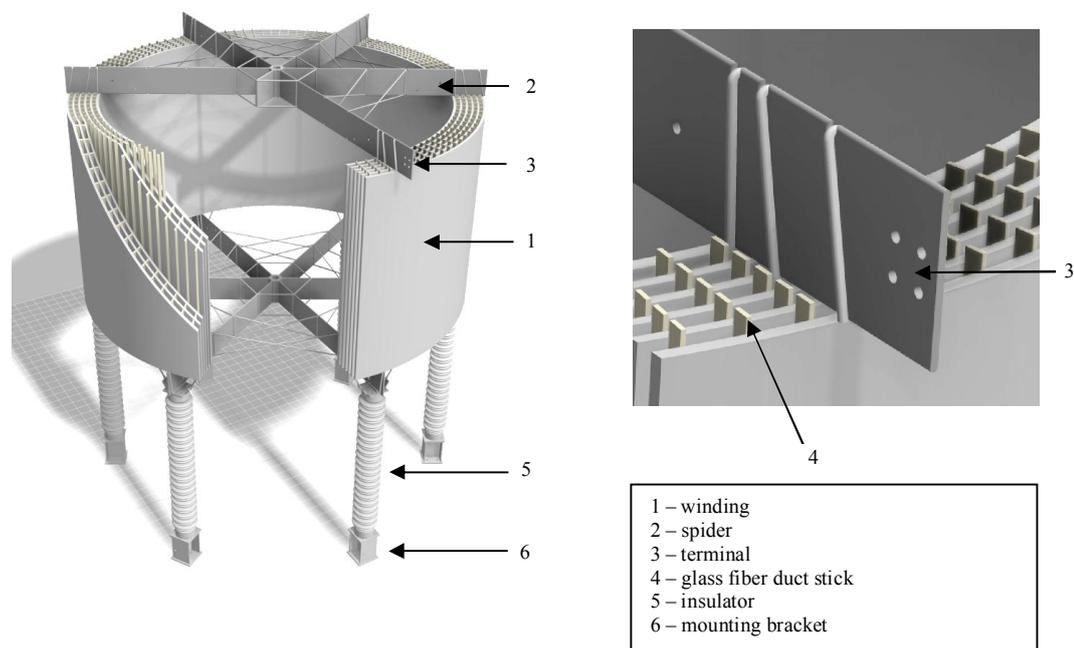


Figure 1 - Dry Type Air Core Reactor - Basic Construction

A dry-type air-core reactor (refer to figure 1) consists of one or more concentric cylindrical windings (1) which are electrically connected in parallel by welded connections to aluminum cross arms, commonly referred to as spiders (2), which are located at the top and bottom of the coil. The individual windings are wound with one or another type of a variety of specialty cables or individual aluminum wires which are insulated with insulating tapes or films and encapsulated in a fiberglass epoxy composite. Each spider carries a terminal (3) for electrical connection of the reactor. The individual concentric cylindrical windings are radially separated from each other by glass fiber polyester resin composite duct sticks (4) which form the air ducts which are necessary for the cooling of the winding. Cooling is provided by natural convection of ambient air, which enters at the bottom end of the winding and exits at its top end. A protective paint or coating is applied to the surface of the fiberglass epoxy encapsulated winding to protect the epoxy from ultraviolet radiation and to improve tracking withstand and weather resistance. In case of adverse pollution conditions at the site of installation, reactors for some applications may be equipped with a protective roof or so called “top hat” (not shown). The reactor is mounted on several base insulators (5) and mounting brackets (6). The rating of the insulators depends on the specific system requirements at the site of installation.

I) Magnetic Fields of Air Core Reactors

Since air core reactors do not have a magnetic core to constrain the magnetic field, the magnetic field is “broadcast” in and around the reactor. The strength of this “broadcasted field” or more commonly referred to as “stray field” depends on the power rating of the reactor. In general, the higher the kvar rating of the reactor, the higher the strength of the stray field. This stray field impinges on both the reactor components themselves such as windings, spiders, corona electrodes and supports, but also adjacent parts such as terminals, connectors, connecting bus or cable, bus supports, and in general any adjacent electrically conductive material.

Figure 2 illustrates the magnetic field distribution of a typical air core reactor, its magnitude is in milli Tesla [mT]. Note that the stray field of an air core reactor has rotational symmetry.

As can be seen from the magnetic field lines (Plot d.)), in the mid-plane as well as on the rotational axis (Plot a.) and c.)), the field is directed in axial direction, whereas in all other locations the field has components in both the axial and radial direction. In vicinity of the winding ends of the reactor the magnetic field is predominantly directed in radial direction (Plot b.)).

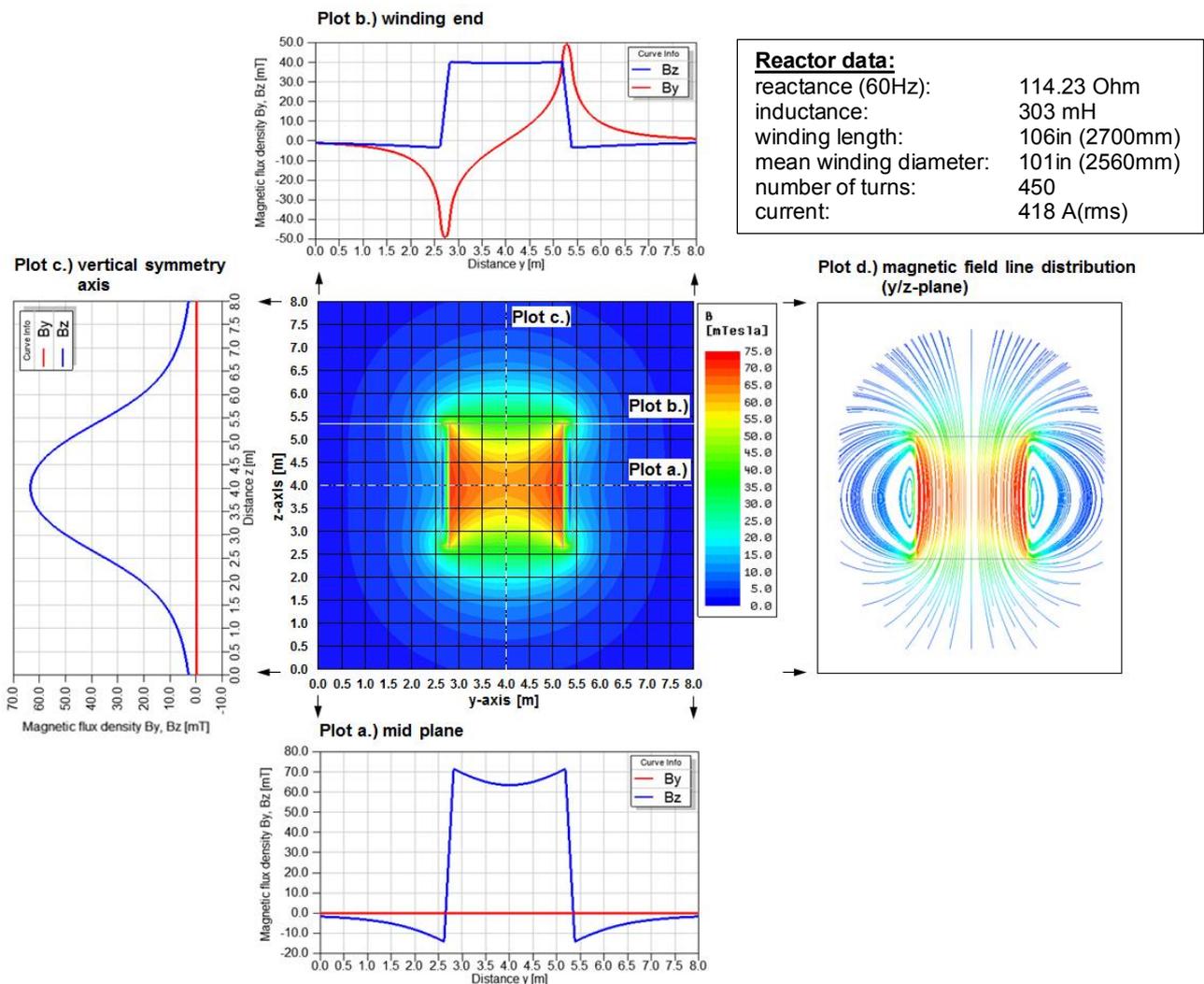
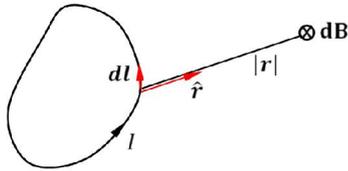


Figure 2 – Magnetic Field Plot

Biot-Savart's law (1) may be applied to calculate the magnetic field of a cylindrical winding [9].

$$d\mathbf{B} = \frac{\mu_0}{4\pi} \frac{I d\mathbf{l} \times \hat{\mathbf{r}}}{r^2} \quad (1)$$



- $d\mathbf{B}$** magnetic flux density of a short current filament
- μ_0 physical constant ($4\pi \cdot 10^{-7} \text{ H/m}$)
- I electric current
- $d\mathbf{l}$** infinitesimal length of current carrying wire filament
- $\hat{\mathbf{r}}$ unit vector of vector \mathbf{r}
- $|\mathbf{r}|$ distance between current filament and field point

The external magnetic field of a dry-type air-core reactor winding at a significant distance from the winding may be approximated by the field of a current loop as shown in Figure 3. This approximation holds for coils having a winding length shorter than about three times the winding diameter. The field produced by a current carrying winding loop in a distance r of more than around three times the loop diameter may be approximated according to [5] by the equations (2) and (3). (For locations much closer to the reactor, numerical techniques are required.)

$$|B| = \frac{\mu_0 \cdot n \cdot I \cdot D^2}{8 \cdot r^3} f(\Theta) \quad (2)$$

$$f(\Theta) = \sqrt{\sin^2(\Theta) + \frac{\cos^2(\Theta)}{4}} \quad (3)$$

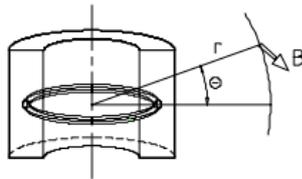


Figure 3 - loop, equivalent to a reactor winding

- $|B|$ magnitude of the magnetic field
- μ_0 permeability in air ($\mu_0 = 4\pi \cdot 10^{-7} \text{ H/m}$)
- n no. of turns
- I current
- D loop diameter (mean winding diameter)
- r, Θ coordinates
- $f(\Theta)$ directivity function as per (3)

Using (2) and (3) in the lateral direction $\Theta = 0$, $f(\Theta) = 0.5$) the magnitude of the magnetic flux density at moderate distances away from the reactor may be estimated by

$$|B| = \frac{\pi \cdot n \cdot I \cdot D^2}{4 \cdot r^3} \cdot 10^{-7} \text{ Tesla} \quad (4)$$

As it can be seen from equation (4), the field strength quickly drops off with increasing distance from the reactor; being inversely proportional to the cube of the distance.

In the case of air core reactors carrying alternating current, the stray magnetic field will induce eddy currents and associated eddy current losses in any electrically conductive parts which reside in the stray field, whether they be made of either ferromagnetic or nonmagnetic material. Where the stray field links closed conducting loops; very large closed loop currents may be induced, with associated steady state heating and potentially large forces under short circuit conditions. Finally, where the stray field interacts with current carrying conductors, such as buswork or cables; oscillatory vibration forces will be induced under steady state conditions and correspondingly larger forces under short circuit conditions.

I.1) Eddy Current Losses

In order to reach an estimation of the eddy losses in the structural elements of an air core reactor such as spiders and the terminals as well as the connection bus work an approach as described in [10] chapter 2 can be chosen.

The terminals and spiders are considered as a plate with thickness d (profile thickness) with the assumption that the thickness is less than the so called “skin depth” or “penetration depth” δ and the field direction is parallel with the plane of the plate.

The penetration depth is calculated as follows:

$$\delta = \sqrt{\frac{2}{\omega \kappa \mu}} \quad (5)$$

where:

- δ penetration depth [m]
- ω $2\pi f$, f in [Hz]
- κ specific conductance [S/m]
- μ permeability, [H / m]

The skin depth in aluminum at 100°C ($\kappa = 23.1$ MS/m) is 14.8mm at 50Hz and 13.5mm at 60Hz

The eddy losses can be calculated with some approximation as follows:

$$p = \frac{B^2 \gamma^3 h}{6 \mu_0^2 \kappa \delta} \quad \text{where} \quad \gamma = \frac{d}{\delta} \quad (6)$$

where:

- p specific eddy losses [Watt / m]
- B magnetic flux density [T_{peak}] at the spider or terminal location
- d thickness of profile [m]
- h height of profile [m]
- μ_0 $4\pi \cdot 10^{-7}$ H/m
- κ specific conductance, [S/m]
- δ penetration depth [m]

Example: A magnetic field of 100 mT_{peak 50 Hz} in a 100mm x10mm profile results in specific losses of 95 W/m at 100°C ($\kappa = 23.1$ MS/m)

The foregoing approximation is acceptably accurate for non-magnetic material geometries with $d < \delta$ at fundamental frequency. At high frequencies, or in the case of ferromagnetic material, the reduced skin depth due to the higher frequency and/or high magnetic permeability results in significant errors if this approach is used. Hysteresis losses are also not accounted for in the above formulae.

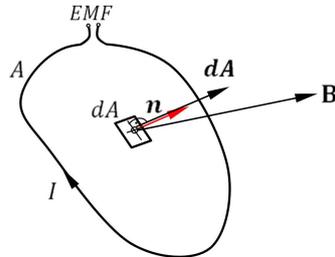
In practical cases, connector and terminal losses are today normally calculated using FEM methods.

I.2) Induced Currents and Losses in Closed Loops

Faradays law of induction states that the EMF (electromotive force) induced in a closed loop is proportional to the negative of the time rate of change of the magnetic flux linked by the loop.

$$EMF = -\frac{d\phi}{dt} \quad (7)$$

Figure 4 - EMF and flux linkage



In the case of a magnetic field \mathbf{B} the flux linking the loop is:

$$\phi = \int_A \mathbf{B} \cdot d\mathbf{A} \quad (8)$$

where $d\mathbf{A} = dA \cdot \mathbf{n}$ is a vector normal to the small surface dA and \mathbf{n} is a unit vector normal to this surface.

From equations (7) and (8) it is clear that the EMF will depend on the size of the loop and its orientation relative to the \mathbf{B} field direction; being thus proportional to the component of \mathbf{B} which is normal to the plane of the loop and to the loop area.

The loop current, I , which results from the induced EMF, will be in accordance with ohms law where the inductance and resistance of the loop are considered.

$$|I| = \left| \left(\frac{EMF}{Z_{loop}} \right) \right| \quad (9)$$

$$Z_{loop} = \sqrt{(R_{loop}^2 + X_{loop}^2)} \quad (10)$$

In order to analyze specific cases, the loop inductances and resistances must be calculated along with the linking flux and resulting EMF.

Calculation of the flux linking a loop by formulas may be done only for simple geometries. More complex geometries typically require either purpose built software or finite element modelling.

I.3) Short Circuit Forces

The Lorentz force law states that the force on a current carrying conductor in a time varying magnetic field is:

$$\vec{F} = I \vec{l} \times \vec{B} \quad (11)$$

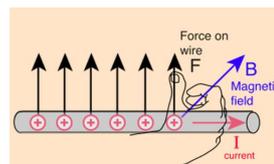


Figure 5 – right hand rule

The direction of the force, in accordance with the well-known right hand rule, is such that it is directed normal to the plane formed by the B-field vector and the current direction vector.

Another method for calculating the magnetic field forces is to determine the change in the magnetic energy which is produced by an imaginary change in the configuration of the current circuit [11]. If any dimension x of a current-carrying circuit is changed by a small distance dx , magnetic field forces must be overcome (in addition to the elastic stresses). If we denote the magnetic field force in the direction of x with F_x , a displacement of dx becomes a mechanical work done.

$$dW_1 = F_x dx \quad (12)$$

Assuming the current I is held constant in this change, e.g. by providing a sufficiently high resistance in the circuit, the total flux of the current circuit,

$$\Phi = L I \quad (13)$$

increases with such a change in the amount

$$d\Phi = I dL = I \frac{\partial L}{\partial x} dx \quad (14)$$

If the change takes place in time dt , then a self-induction voltage is obtained

$$u_L = \frac{d\Phi}{dt} = I \frac{\partial L}{\partial x} \frac{dx}{dt} \quad (15)$$

This requires an electrical work for the current I during the time dt of

$$dW_2 = u_L I dt = I^2 \frac{\partial L}{\partial x} dx \quad (16)$$

Finally, the energy accumulated in the magnetic field is increased

$$W_m = \frac{1}{2} L I^2 \quad \text{by} \quad dW_m = \frac{1}{2} I^2 \frac{\partial L}{\partial x} dx \quad (17)$$

Since the energy expended must equal the energy obtained, it follows

$$dW_2 = dW_m + dW_1 \quad (18)$$

Or, after inserting the expressions (12), (14) and (15)

$$F_x = \frac{1}{2} I^2 \frac{\partial L}{\partial x} \quad (19)$$

The force is therefore always directed to increase the inductance. It can be calculated if the dependence of the inductance of the current circuit of x is known.

In the case of two different circuits 1 and 2, the forces occurring between the circuits can be found by a similar consideration. The displacement dx of the two current circuits relative to one another results in a change in the mutual inductance, by which, on the one hand, the voltages induced in the two current circuits and on the other hand, the change in the field energy. This follows the force acting in the direction

of the displacement and to bring the current loops into such a position that the mutual inductance becomes as high as possible

$$F_x = I_1 I_2 \frac{\partial M}{\partial x} \quad (20)$$

Additional to the effects of the force to the current carrying structures it should also be noted that this force has a vibrational nature (in the case of AC systems). Whereby the mechanical frequency of this force is twice the excitation frequency ($f_{\text{mech}}=120\text{Hz}$ in case of a 60Hz AC system). Thus also considerable noise emissions may be triggered due to the vibration of the affected structures.

II) Clearance Guidelines for Air Core Reactors

The following points serve to summarize the basic installation clearance requirements associated with air core reactors.

The clearance requirements are of three types:

- Electrical
- Ventilation
- Magnetic

Electrical Clearance:

As the normal air core reactor has exposed live parts at essentially all points on its outer surface, provision must be made for electrical clearance from the reactor surface to nearby grounded surfaces and to the surface of other reactors or other live parts in adjacent phases or circuits. Standard electrical substation clearances to live parts are perfectly adequate. No special precautions over and above normal substation practices are required.

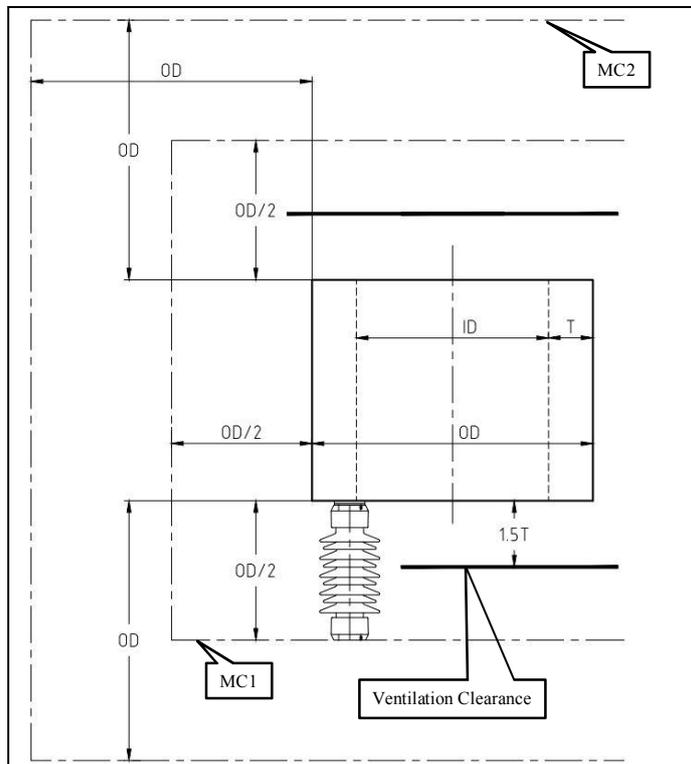
Ventilation Clearance:

For a typical air core reactor which is mounted such that the cooling ducts are oriented in the vertical direction, adequate provision must be made for the unimpeded entrance and exit of cooling air at the bottom and the top of the cooling ducts respectively. In most cases, the ventilation clearance will be less than the magnetic clearance requirements and as such it is typically not a decisive factor in the installation arrangement (Refer to Figure 6).

Magnetic Clearances:

The magnetic clearance requirements for air core reactors arise as a consequence of the interaction of their stray magnetic fields with conductive parts in the vicinity of the reactor and the resulting currents which may be induced in those parts. The induced currents are of two types and as such they give rise to two types of clearance requirements:

- Eddy Currents; which are induced in nearby conductive parts give rise to a minimum clearance required to metallic parts which do not form closed loops. These clearances are typically referred to as MC1 clearance (Refer to Figure 6).
- Circulating Currents; caused by the coil flux linking a closed electrically conducting loop. Examples of such loops are those formed by concrete reinforcement rebar, nearby fencing, nearby structural members in a building, inappropriately arranged grounding connections, or a combination of the above. These clearances are typically referred to as MC2 Clearance (Refer to Figure 6).



MC1 Clearance to Metallic Parts Not Forming Closed Loops

MC2 Clearance to Metallic Parts Forming Closed Loops

Note: the designation of MC1 and MC2 distances as OD/2 and OD from the reactor surface, as shown here, are a rough approximation to the values on manufacturers drawings which are based on calculated field strengths rather than fixed distances.

Figure 6 - Ventilation and Magnetic Clearances

A very common, though understandable, misconception is that these "magnetic clearances" are applicable only to ferromagnetic materials. This is simply not the case. The clearances apply to all electrically conductive materials; nonmagnetic or ferromagnetic. It is true that ferromagnetic materials will typically present even more severe problems, particularly in respect of eddy currents, than non-magnetic materials such as aluminum or copper, however non-magnetic materials may also have very substantial induced eddy currents and, owing to their generally lower resistivity, even more serious closed loop currents and short circuit forces when arranged in an inappropriate orientation and/or location in the reactor's magnetic field. In difficult situations, low resistivity non-magnetic stainless steel provides the best solution.

The above MC1 and MC2 clearance guidelines are normally provided on manufacturer's outline drawings. The manufacturer will typically arrive at these clearances based upon the distance at which the field strength has decayed to internal manufacturer specified values. In approximate terms, the MC2 clearances are generally about double the MC1 clearances and correspond roughly to a distance of a full diameter from the reactor surface, above and below and to the side of the reactor. MC1 clearances typically then, are in the range of one half of a diameter from the reactor surface (refer to Figure 6).

A second common misconception is the belief that these magnetic clearance guidelines are "absolutes"; scientifically calculated values that if respected will lead 100% of the time to a problem free installation, and if not respected, will always result in problems. This is not so, in either respect. As hopefully has and will become clear in this paper, the issue of magnetic clearances is about both the coil magnetic field (magnitude and direction in the area of interest) as well as about the size, orientation, conductivity and magnetic permeability of the part or loop which may interact with the

magnetic field. To perfectly summarize all of this in a very simple and generic “two number practical clearance distance” (MC1, MC2) on a drawing is impossible, as although the magnetic field of the reactor can be very accurately calculated by the manufacturer, the other half of the equation - the very important details of the nearby metallic parts and/or loops; usually are not known by the reactor designer. This leads to two important conclusions:

- First, the magnetic clearance guidelines (MC1 and MC2) shown on manufacturer’s drawings are to a significant extent based on manufacturer’s experience, extensive testing, and on “what historically works”. They are intended to provide conservative figures that will lead to problem free installations in most, if not all, circumstances. That said, for very good reasons, there is guidance in the standards that also recommends, particularly in new installations, to simply avoid closed loop formation wherever possible (see Annex E, Section E.4 of reference [1]).
- The converse of the above is also true, also as outlined in the same standard. In many instances magnetic clearance distances which are significantly less than the standard MC1 and MC2 figures will still result in a satisfactory installation; however such cases should be referred to the manufacturer for analysis and advice based on the specific circumstances. Such analyses very often result in being able to fit air core reactors into existing installation locations where the initial MC1 and/or MC2 clearances on proposal drawings would suggest that they simply do not fit into the available space. Further examples are shown in reference [7].

III) Practical Implications of the Theory

III.1) Terminal Losses and Terminal Heating

The admissible limits for the terminal temperature rise of reactors are given in Table 5 of IEEE C57.16-2011 “ IEEE Standard Requirements, Terminology, and Test Code for Dry-Type Air Core Series- Connected Reactors” Section 8.2.4. (The shunt reactor standard, IEEE C57.21-2008, also references this clause.) A similar table is included in the IEC reactor standard; IEC Std. 60076-6: 2007 "Power transformers – part 6: Reactors" Table 1. [1][2][3]

Table 5 of IEEE C57.16-2011:

| Terminal description Connection, bolted or the equivalent | Maximum Value | |
|--------------------------------------------------------------------|------------------|---------------------------------------------------------------------|
| | Temperature [°C] | Temperature rise at ambient air temperature not exceeding 40°C [°C] |
| Bare-copper, bare-copper alloy ore bare-aluminum alloy - in air | 90 | 50 |
| Silver-coated or nickel-coated - in air | 115 | 75 |
| Tin-coated - in air | 105 | 65 |

Generally, the temperature rise of terminals of electrical equipment is a function of losses due to the terminal resistance (including the contact resistance) and the throughput current. Recommendations for adequate dimensioning of terminals depending on current may be found in national standards, for example in NEMA CC1-2009. [4] In the case of air-core reactors however, the eddy losses of the terminals and the accompanying connectors due to the stray field of the reactor, have to be considered

as well. An intended mitigation of the temperature rise by utilization of higher-ampere-capacity connectors may actually be counterproductive and may rather increase the heating of the terminals.

To mitigate eddy current heating of the terminal and the connector it is important to have geometries that are “streamlined” to the magnetic field, or in other words, which do not provide a large frontal area to the magnetic field. This is achieved by providing terminals with rectangular cross section of limited thickness (e.g. 3/8 in (10 mm)) normal to the radial and axial field direction; like an extension of the spider arm. The required cross sectional area of the terminal is provided by increasing its width in vertical direction. The reasons for this are evident when the theory presented in section I.1 is considered (eddy losses are strongly proportional to the dimension normal to the field direction) and noting the strongly radial nature of the field in the terminal vicinity, as can be seen in Figure 2 and Figure 7 .

The same concept is applicable to the connector bolted to the terminal. The connector should have large contact surface area, but should not present a large frontal area to the radial or axial magnetic field and where multiple cables are involved, should not create a flux linking loop between the parallel cables.

The factors influencing the eddy current heating of the terminal by the connector attached to the terminal are demonstrated by a practical example of a high current / high Mvar power, two coil stacked thyristor controlled shunt reactor (TCR):

Reactor data (single coil):

- winding length 47 inches (1200 mm)
- mean winding diameter 110 inches (2790mm)
- outside diameter 128 inches (3275 mm)
- current (50 Hz) 3160 A rms
- Number of Turns 58.5 (x2)
- Inductance 19.01mH
- MVAR/coil (50 Hz) 59.6
- shape of terminal rectangular, 4 inches x 6 1/4 inch (100 x 160 mm), radial x vertical)
- cross section of terminal 2.48 inch² (1600 mm²)
- material aluminum alloy conductivity ~ 28Sm/mm²

The direction and magnitude of the field to which the terminal and the connector are exposed is shown by the field plot in Figure 7. The flux density lines indicate the direction of the magnetic field, and the colors, its magnitude in Tesla (rms value) for a current of 3160 A rms.

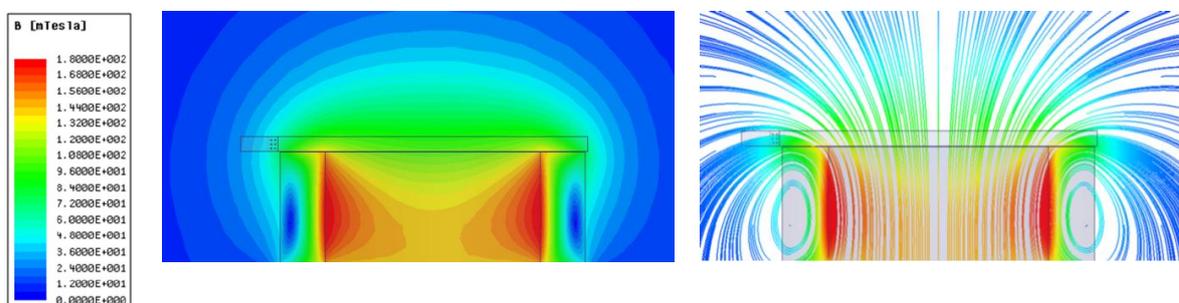


Figure 7 - Magnetic field plot (contour plot and field line plot) of terminal plus connector arrangement

As the figure shows, the field drops significantly with distance from the winding so that the field strength at a distance of about 8 inches (200 mm) from the winding is reduced to less than 50 % of the field in the immediate vicinity of the winding.

Referring to Figure 8, the connector flag is represented by a plate of 11.8 x 6.3 inches (300 x 160 mm) (radial x vertical) which is firmly attached to the terminal. The contact area between flag and terminal is 3.9 x 6.3 inch (100 x 160 mm) (radial x vertical). The density of eddy currents induced in the connector flag are illustrated by the color scale. (Note: through current is not considered). As can be seen in the figure, the eddy current density is concentrated at the end of the flag which is closest to the winding.

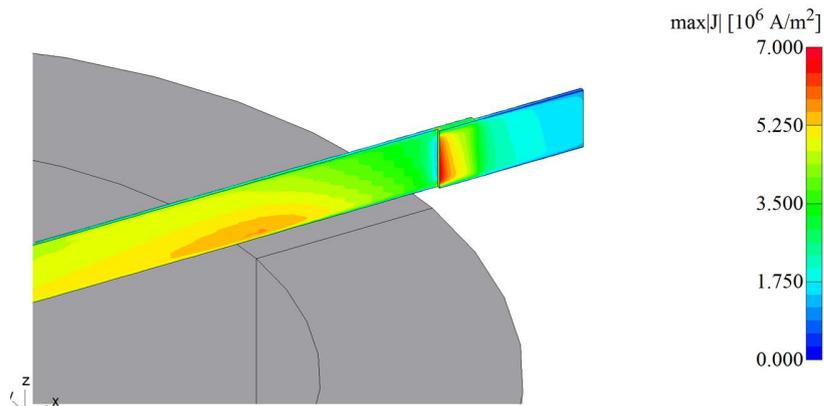


Figure 8 - Eddy current density of a connector flag attached to the reactor terminal

Figure 9 shows both the through current I^2R losses and the eddy losses of the connector flag, depending on its thickness. The losses arising from contact resistance are disregarded. Calculation of eddy losses is done by 3D FE methods.

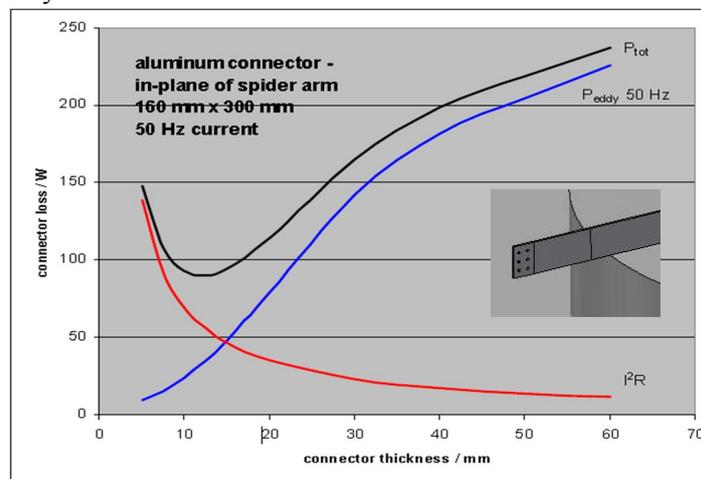


Figure 9 - Connector losses vs. thickness

The connector losses have a minimum at about 1/2 inch (12 mm) thickness. A similar loss vs. thickness characteristic is found at 60 Hz with the losses about 20 % higher than those at 50 Hz.

The losses in the connector plate (and in the terminal) will increase when the terminal and the attached connector are orientated in horizontal position, due to the increase in losses contributed by the axial component of the field, while retaining similar losses resulting from the radial field component.

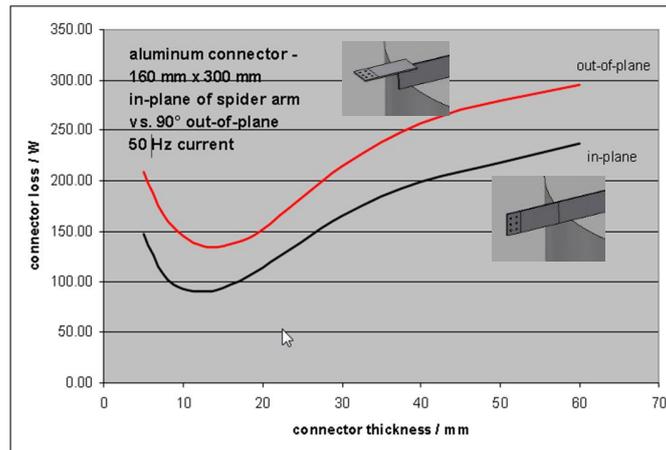


Figure 10 - Connector losses at in-plane vs. out-of-plane arrangement

Besides the general question of the type, size, and physical construction of connectors to be used with air core reactors, another question which often arises relates to their various possible physical arrangements. The following example, illustrated with actual measurements of terminal temperature, shows again the same principle at work; minimizing the frontal area of the connection arrangement presented normally to the predominant direction of the magnetic field of the reactor and avoiding the creation of flux linking loops.

The results in Table 1 are showing the measured terminal temperatures resulting from arranging the connectors axially, one above the other on one side of the terminal, as compared to arranging the same connectors on opposite sides of the terminal. Clearly the axial arrangement on one side of the terminal is the better arrangement, with the “opposite sides configuration” resulting in a 25% higher temperature rise. These results are completely as one would expect when considering the frontal area the two different arrangements present to the magnetic field of the reactor, as well as the formation of a small flux linking loop by the “opposite sides configuration”; all as outlined in earlier sections of this paper.

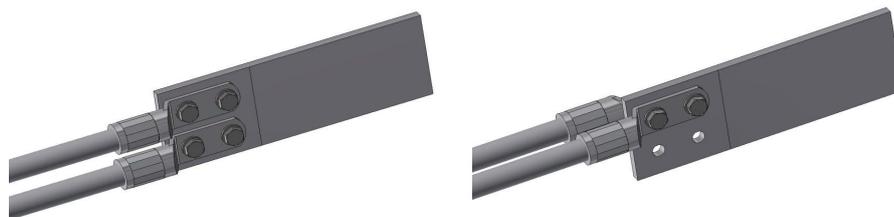


Figure 11 - Axial (left) vs “Opposite Sides” (right) configuration of connection leads

Table 1- Measured Temperature Rise on Axially vs. “Opposite Sides” Arranged Cables

| Connection Arrangement | Cable Temperature Rise | Barrel Temperature Rise | Terminal Temperature Rise |
|-------------------------|------------------------|-------------------------|---------------------------|
| Axial Cables | 98 °C | 98 °C | 98 °C |
| “Opposite Sides” Cables | 123 °C | 123 °C | 123 °C |

Notes: Test Current: 4000 Amp, Cables: 2x1600 MCM each 6 feet in length, 4 hole terminal palm compression connectors, Terminal: 3/8” x 12”.

The above example illustrates the issues resulting from a large frontal area to the field and the formation of closed loops where cable connections are not arranged in an appropriate manner. The same comments apply in the event of attempting to use bus tube to make connection to air core reactors of significant power rating. Owing to the large frontal area which bus tube presents to the field, it is generally problematic to bring bus tube right up to the reactor terminal, and especially so if it is oriented tangentially rather than radially to the reactor (refer also to the case study at the end of this paper).

Recommended Connection Arrangement for Air Core Reactors

Based on all of the foregoing, a connection arrangement as shown in Figure 12 and Figure 13 is recommended for sizeable Mvar ratings and/or reactors with significant short circuit current ratings. For small kvar ratings and low short circuit currents, the principles outlined here become less critical, but still represent good practice.

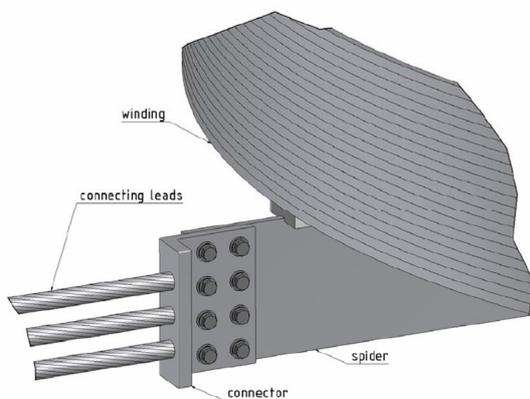


Figure 12 - Connector Design

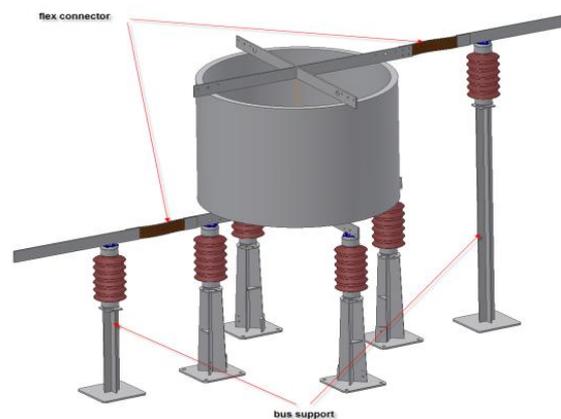


Figure 13 - Connection Arrangement

- The connector flag (as well as the terminal) should be arranged vertically.
- The height of the connector flag should preferably be the same as the height of the terminal and all holes of terminal should be used for bolting; use stainless steel bolts with Belleville spring washers on both sides.
- The thickness of the connector flag should not exceed approximately 1/2 inch or 12mm.
- The material of the connector may be either aluminum alloy or copper (in case of copper to aluminum, a bi-metal plate should be inserted). Nickel plating of the contact surface area may be considered, in order to allow higher terminal temperature (115°C instead of 90°C).
- The end of the customer connector flag may be configured as a crimped connection (Figure 14) or prepared for a welded connection as shown in Figure 15 or a clamped connector arrangement as shown in Figure 16. A minimum distance of this connection point of approximately 8 inches (or 200 mm) from the winding surface is recommended in order that it be located in a reduced field area.



Figure 14 - crimped

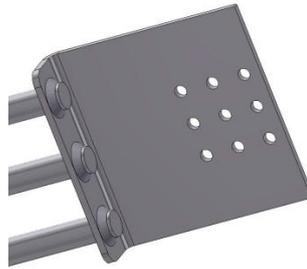


Figure 15 - welded

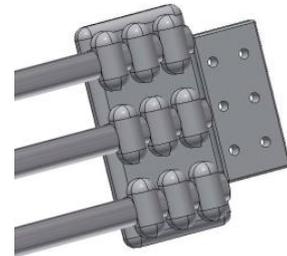


Figure 16 - clamped

- The connecting leads in the vicinity of the reactor shall be placed in a radial direction and perpendicular to coil vertical axis, to minimize the heating effect and the magnetic force.
- In cases where parallel cables are utilized they should be axially aligned in order to avoid the induction of closed loop currents between the cables by the axial magnetic field of the reactor. Refer to Figure 12.
- Connection leads should be provided with sufficient sag so as to provide adequate mechanical decoupling of the reactor terminals from connecting bus-work.
- For non-plated terminals and connectors, the contact areas must be abraded lightly by using 3M Scotch-Brite pads which have been saturated with contact grease (e.g. Penetrox-A). Guidance in this regard is also given in the Trench instruction manual.

Ampacity Selection for Connecting Cables and Bus-bars:

The purpose of this section is not to describe the guidelines for choosing cable ampacities in the substation. Rather, the focus here is on the last 10 feet or so of cable or bus-bar that makes the connection to the coil terminals. The desire is not only to have sufficient conductor cross section to handle the current, but also to have sufficient heat sink capacity from the connecting cable or bus-bar to aid in maintaining a cool terminal temperature.

The connector geometry and configurations were addressed earlier. Here, we address strictly the ampacity selection of the cable or bus-bar connected to the reactor. For cable connections, in order to ensure adequate heat sinking of the terminal connection, the total cable ampacity (in MCM) connected to a coil terminal should be a minimum of twice the rated current in amperes. For a bus-bar connection, a current density of not greater than 500 Amps/in² (0.775 amps/mm²) should be used.

Example: (based on 2000 Amps rated current)

For a cable connection: Total Cable MCM = 2000A x 2 = 4000 MCM (2027 mm²)

For a bus-bar connection: Total bus-bar cross sectional area = 2000 A / 500 A/in² = 4 in² (2580 mm²)

III. 2) Circulating Currents in Horizontal Plane Closed loops Such as Foundation Reinforcement

By necessity, concrete foundations and floors very often use steel rebar reinforcement to satisfy the mechanical loading demands of the foundation or floor. The rebar is typically tied together with steel wire when assembling the rectangular rebar grid. This creates many small rectangular short circuited loops which will experience circulating currents, losses and short circuit current forces. The

expansion and contraction of the rebar during load cycling of the reactor current can also cause cracks and degradation of the concrete.

Solutions:

- (a) When the foundation or floor already exists, the coil must be installed at MC2 height above the foundation or floor to minimize the magnetic field effects.
- (b) If sufficient height is not available to allow satisfying the MC2 clearance, and also providing the power rating of the reactor is not too high, aluminum magnetic shields can be placed on the foundation or floor to keep the magnetic field from penetrating to the rebar. This shield will still have losses and forces on it but will save the foundation or floor integrity. Note: Such shielding measures should only be done in consultation with the reactor manufacturer.
- (c) If the foundation or floor is not yet constructed, applying short tubes of rubber hose at the rebar crossover points to isolate them (and also avoiding making electrical connection of the bars via the steel wires) will eliminate the closed loops. Alternatively, fiber glass reinforcing mesh can be used in lieu of steel rebar.



Figure 17 - reinforcement using rubber hose insulation

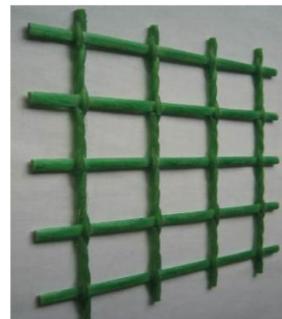


Figure 18 – fiber glass mesh

III. 3) Circulating Currents in Vertical Plane Closed loops Such as Fencing, Large Beams and Columns

In view of the fact that the external surfaces of air core reactors are live parts, common practices to ensure personnel safety are to either fence the area around the reactors or to raise the reactors on support structures such that the height of the base of the insulators is a minimum of 8'6" (2600mm) above grade level. With either of these approaches, care must be taken in respect of both grounding and, for reactors of sizeable power rating, the formation of closed flux linking loops near to the coil.

Issues with Fencing:

When traditional metallic fencing is arranged around air core reactors, there are multiple opportunities to create problematic loops:

- horizontal plane loops formed by the posts and the horizontal crossbars of the fence encircling the complete reactor arrangement.
- vertical plane loops in individual or multiple fence sections formed by the fence posts and connecting crossbar(s) or stringer mesh support wires at the top and bottom of the fence
- loops formed by a combination of the vertical plane of a fence section and closing of the loop by multiple connections to the ground grid.
- Loops created when adjacent sections of fence which are separately grounded become electrically connected and form a loop through the latch and lock of a closed gate

In most cases the main problems which arise from the presence of such flux linking loops are:

- The existence of points of high resistance or intermittent contact in the path of the loop current; giving rise to extreme local heating or arcing at the high resistance contact point (eg. latch and lock of a gate)
- inducing large currents, sometimes hundreds of amps, in the ground grid

The challenge in addressing these issues is to simultaneously avoid creating loops which are problematic while at the same time satisfying the utility, NESC and IEEE guidelines in terms of fence grounding, and step and touch potentials. [Refer to references 12 and 13].

Solutions:

First and foremost, whatever solution is employed, it must be ensured to be a safe one and meet the intent and requirements of the NESC and IEEE 80.

Given the wide variation in situations and fence design specifics, only some general pointers from the perspective of managing the reactor magnetic field are possible in this paper. The user/station design engineer must ensure that the result is satisfactory from the grounding perspective:

- involve the reactor manufacturer in the project at the earliest possible stage. The extent to which fence loops may be problematic is dependent on the specific reactor ratings and planned physical arrangement. (Note that reactors of moderate size may present little or no problem.) The manufacturer should be able to provide helpful guidance in specific cases.
- use double posts at one corner of the fence, thereby avoiding a large horizontal plane loop
- to ensure a safe installation in respect of step and touch potentials, fences are typically connected to ground at intervals ranging from 5 to 15m along the length of the fence. This can result in large vertical plane loops involving the ground grid. A possible solution to the involvement of the ground grid in such loops is to break the fence into multiple sections of suitable length using multiple posts, and then ground each section at only one location. In cases where it is also necessary to eliminate loops in the individual fence sections, these can be avoided by isolating the stringer wire or crossbar at a single point to break the loop. (Refer to Figure 19)
- the problem of the latch and lock of a gate being involved in a high current loop can be avoided in a few different ways; one of these is to provide a low resistance alternate path for the loop current through a suitably arranged electrically parallel copper conductor of significant ampacity

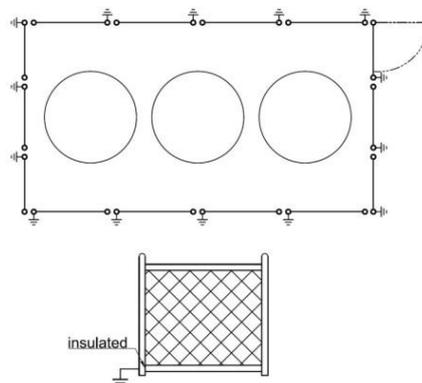


Figure 19 - Sectionalizing fencing to allow multiple ground connections

It should also be mentioned that there are very often cases where air core reactors are raised on support structures to provide, for example, a minimum 8'6" (2600mm) clearance to live parts, and the reactors are sometimes still fenced as well. In such instances, especially where there are also long insulators, closed loops in fences which are located well within MC2 in the lateral direction may not link significant flux due to the coil elevation above grade level. In such situations, a brief consultation with the reactor manufacturer may simplify the installation and reduce the necessary size of the fenced area and/or the need to avoid vertical plane loops in the fence. In addition, in the case of transmission voltage class air core reactors, the electrical strike distance requirements from the live reactor surface to an adjacent fence will most often exceed the MC2 distance; thereby making the electrical clearance the decisive clearance distance parameter.

Of course, an alternative solution is to use non-metallic fencing.

Issues with Large Beams and Columns:

In cases where air core reactors are located in the vicinity of interconnected columns and beams, similar closed loop and eddy current issues arise as to those with fencing. In this case however, the beams and columns are often made of structural steel. This exacerbates the problem as the ferromagnetic nature of the material results in a tendency for portions of the structure to concentrate the coil flux, leading to even more severe eddy current heating problems at certain locations. Also as a result of the ferromagnetic material, the closed loop currents and eddy currents will flow in a thin layer on the surface of the material resulting in relatively higher resistance values and more severe heating under most circumstances. Even greater problems may arise when sizeable reactors are placed in the vicinity of building walls and ceilings which are constructed of metal cladding which is bolted or riveted to the structural members. In these circumstances it is not unusual to find that some of the bolted or riveted connections create high resistance contact points in the path of closed loop currents; resulting in very severe local heating at the high resistance contact points. The severity of such local heating can be sufficient to cause bolted or riveted connections to glow red hot and even potentially lead to building fires if there is combustible material in contact with the hot parts.

Solutions:

The situations described above are some of the most difficult magnetic clearance problems to deal with, particularly with existing structures. The following techniques can often provide solutions:

- involve the reactor manufacturer in the project at the earliest possible stage; a full or partial magnetic clearance analysis will usually provide valuable guidance (over and above the simple MC1 and MC2 distances) as to the specific issues with a planned installation, along with steps to take to avoid problems
- wherever possible, avoid the formation of flux linking loops
- as with fencing, take care to avoid the formation of loops involving the ground grid; which can be created by multiple point grounding of the structure
- avoid connecting metallic fences directly to metallic structures such as buildings by terminating the fence at a post which is located a few inches from the building
- observe the magnetic clearance guidelines
- with the support of the reactor manufacturer, in some circumstances problems can be solved through a magnetic clearance analysis and the judicious use of shielding techniques

III. 4) Circulating Currents in Elevating Support Stands

Personnel protection can be achieved by using elevating support stands to keep live parts out of reach of substation personnel. This commonly is done instead of fencing within the station. Such elevating pedestals may be provided by the reactor supplier in the form of fiberglass pedestals or individual aluminum, steel, or stainless steel columns under each insulator. Often however, utilities construct lattice type structures, usually made of steel, which form closed loops under the coil. For small reactors, such loops may not present difficulties, but for larger Mvar coils they may well lead to problems.

Solutions:

- Steel parts can be isolated from each other to avoid closed loops by using isolated bolting techniques, however this is not simple, and always presents concerns about whether the isolated bolting will be correctly installed in the field
- Maintain at least MC2 distance to the support structure parts if they form closed loops
- For moderate size reactors; utilize a single post mounting pole with mounting arms extending radially outwards from the center to support the insulators, instead of a square frame structure.(Refer to Figure 20)
- Ground the bases of the structure at a single point only; using star point or daisy-chain connections.(Refer to Figure 21)



Figure 20 - Single Post Mounting of Reactors

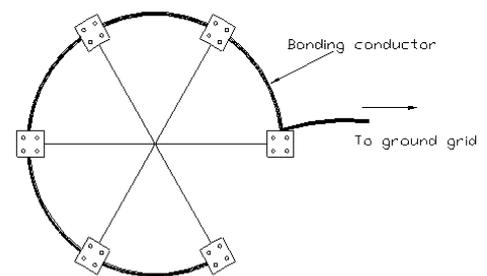


Figure 21 - Daisy Chain and Star-Point single point grounding

IV) Case Study: Thyristor Controlled Shunt Reactors (TCR's) with an Inappropriate Connection Arrangement:

The following case study illustrates an actual case of an inappropriate connection arrangement for TCR's in a Static VAR Compensator (SVC). The connection issue was identified during the installation phase and tests were subsequently done on a mockup arrangement at the factory to demonstrate the expected excessive in-service terminal temperatures which would result if the installation arrangement was not modified.

The subject SVC is comprised of three TC reactor banks: TCR1, TCR2 and TCR3. Each phase of the TCRs consists of two stacked coils (bottom and top coil) with porcelain insulators between the coils. Three such stacks form a 3-phase reactor bank.

The reactances per phase (at 60 Hz) and the rated currents and Mvar ratings of the reactors are:

TCR1: 7.955Ω / 3283 A ... 85.7 Mvar/phase

TCR2 and TCR3: 15.91Ω / 1928 A ... 59.1 Mvar/phase

The arrangement of the TC reactors of each bank, TCR1, TCR2 and TCR3 is illustrated in Figure 22 and Figure 23. All reactors are mounted as 2 coils stacked per phase, phases side-by-side with a clearance of approx. 2.5 m (8.2 feet) between phases.

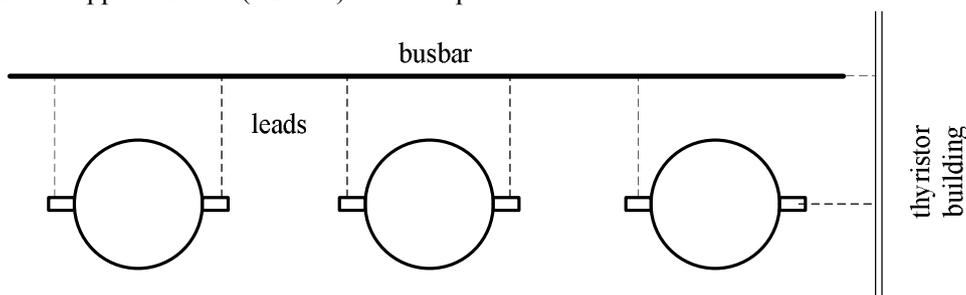


Figure 22 - Simplified sketch of the TC reactor arrangement (top view)



Figure 23 - Reactor bank TCR2

The electrical connection of the TC reactors from their terminals to the bus-bars is made by aluminum cables. Each cable consists of about 91 aluminum strands of 3.74 mm diameter resulting in a cable diameter of 41.1 mm. The total cross section is 1000 mm², the DC resistance is 28.9m Ω /km and the

ampacity is 1305 A. The leads of TCR1 consist of 3 parallel cables and those for TCR2/TCR3 consist of 2 parallel cables (Figure 24, Figure 25)

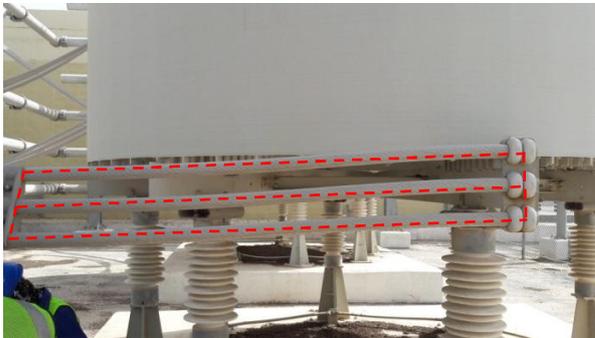


Figure 24 - TCR1, cable connection arrangement (loop shown in red)

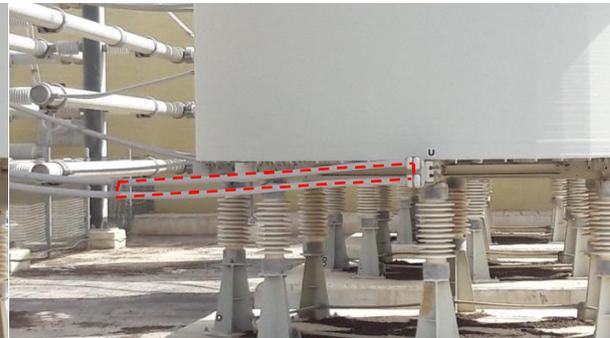


Figure 25 - TCR2 / TCR3, cable connection arrangement (loops shown in red)

The cables are fixed by angled connectors to the reactor terminals so that the cables are orientated tangentially to the coil (refer to Figure 24 and Figure 26).

This tangential alignment is in contrast to the recommendations outlined in this paper and also as stated in the Trench reactor installation and operation manual [8], which requires that the connection leads to be aligned in the radial direction to minimize heating effects in the leads due to eddy currents.



Figure 26 - electrical connection showing tangential cable arrangement

The remote ends of the leads are fixed to the bus-bars resulting in about 5 m (16.4 feet) length of the leads from the coil terminal to the bus-bars. The parallel cables of the leads are held together by an aluminum fastener placed at a distance of about 1.5 m (4.9 feet) from the reactor terminal.

As has been outlined in earlier parts of this paper, air core reactors produce a magnetic field which fringes out from the winding ends. For reactors of significant MVAR rating, such as those shown in this case study, the fringing fields are of substantial magnitude. The radial component of this magnetic field which is directed perpendicular to the plane of the tangential loop created by the cables of the connection leads between the reactor terminal and the fastener (see Figs. 2, 3, 4, 4a) will, in this case, induce a current in the loop which is significantly larger than the normal rated current flowing through the leads; and thereby create an unacceptable terminal heating situation.

These results can be calculated, however for this specific case, it was decided to construct a mock-up of the in-field situation to demonstrate the expected outcomes experimentally and arrive at actual measured currents and temperatures.

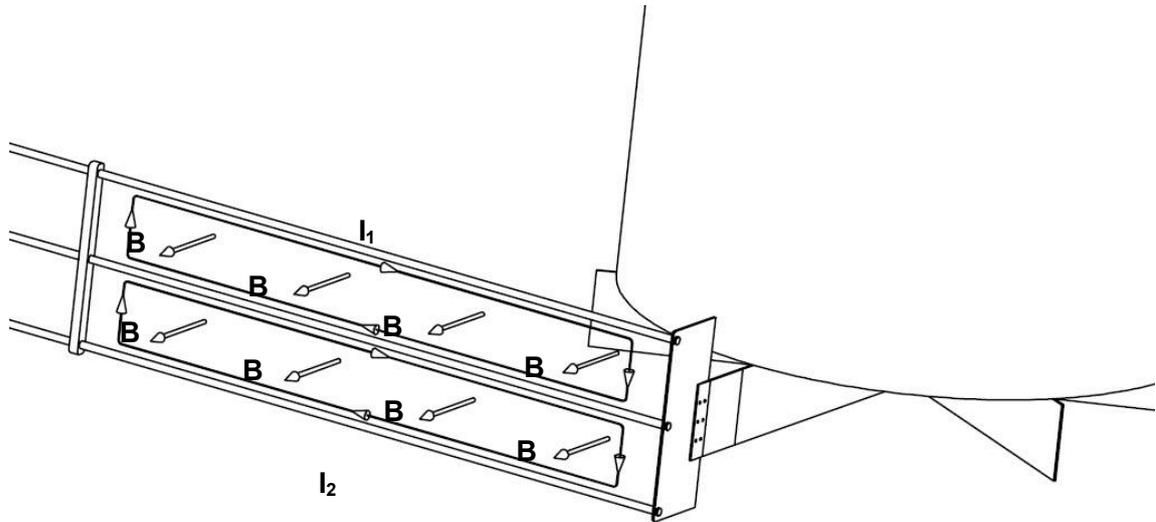


Figure 27 - radial field linking tangentially arranged conductor loops and inducing a circulating current (loop enlarged for illustration purposes)

Mock-up test Arrangement:

A mock-up test arrangement was prepared. It consisted of very similar aluminum cables, connector and fastener and a test coil which created a very similar magnetic field to the on-site reactor. During the heat run test, the cable and terminal temperature-rise as well as the induced closed loop current in the cables were measured.

The overall test arrangement was as shown in Figure 28 and Figure 29. The cable mock-up was placed in the magnetic field of the test reactor in such a way that the magnetic flux density in the reactor's radial direction was equivalent to the original setup at the SVC site, having a value of 30.5 mT rms (the same as the on-site TCR1 at rated current). The length of the mock-up loop was 1.5 m (4.9 feet), the center-center distance between adjacent cables was 100 mm (3.9 inches). These critical parameters are virtually identical to the on-site figures.



Figure 28 - test setup with connector cables arranged tangentially to reactor surface

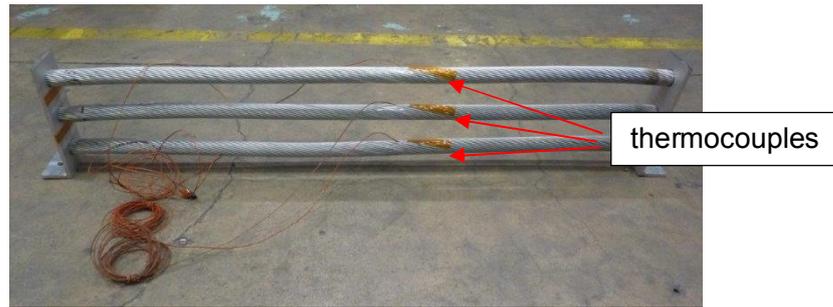


Figure 29 - model representing the on-site cable arrangement

Measurement Results:

- measured induced loop current in cables at radial magnetic flux density $30.5 \text{ mT}_{\text{RMS}}$ (note that this is the induced closed loop current only, and does not include through current)
 - top cable: $4523 \text{ A}_{\text{RMS}}$
 - middle cable: $94 \text{ A}_{\text{RMS}}$
 - bottom cable: $4406 \text{ A}_{\text{RMS}}$
- temperature rise in cables after 30min heat run
 - top cable: 209 K
 - middle cable: 25 K
 - bottom cable: 225 K

As can be seen from the results above, the induced current in the cable loops was on the order of 4500 Amps. As expected, the middle cable carried very little net induced current due to the cancelling effect of the upper loop current and lower loop currents flowing in opposing directions in the center cable. The temperatures in the upper and lower cables were approximately 250 degrees C after allowing for a 25 degree C ambient. Clearly a modified arrangement was necessary.

For comparison purposes, an alternative arrangement utilizing the typically recommended radial connection to the coil was also tested using the same test coil and field strengths.

Mock-up test with a radial cable arrangement:

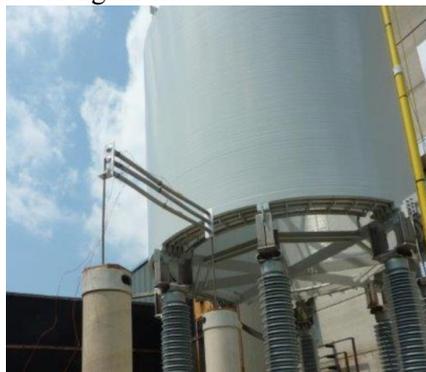


Figure 30 - connector cables arranged radially to reactor surface

Measurement Results:

- measured current in cables at radial magnetic flux density $30.5 \text{ mT}_{\text{RMS}}$
 - top cable: $23.5 \text{ A}_{\text{RMS}}$
 - middle cable: $5.8 \text{ A}_{\text{RMS}}$
 - bottom cable: $35.3 \text{ A}_{\text{RMS}}$

- temperature rise in cables after 90min heat run
 - top cable: 19 K
 - middle cable: 16 K
 - bottom cable: 19 K

With the radial arrangement, the induced currents and temperatures were, as expected, reduced to negligible values. (The small induced currents which were observed were due to the cables not being arranged exactly one above the other throughout their length, and therefore the resulting small loop linked some of the axial coil field in the region.)

VI) Conclusion:

For those who are unfamiliar with the peculiarities of air core reactors; applying them, and installing them can initially seem to be a confusing and difficult task. However, to a significant extent this is more a matter of familiarity than fundamental difficulty. With a basic understanding that results from applying simple electromagnetic concepts as are outlined in this paper, the principles become clear. With this understanding, it can be seen that applying reactors, making reliable connections, implementing appropriate grounding, and dealing with their stray magnetic fields are all relatively straight forward issues that can most often be easily solved. In the more complex cases, the reactor supplier should be able to provide support in finding a clear way forward.

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