# 1 Introduction

Air core reactors are commonly used as shunt reactors, fault current limiting reactors, tuning reactors in capacitor banks, or as thyristor controlled reactors in static compensators. They don't saturate, are virtually maintenance free and are light and easy to install.

The magnetic field established as a result of the current flowing through the reactor is not constrained to a core as is the case with iron core reactors — instead air core reactors are surrounded by a magnetic field that requires some care in design and application.

Taking reasonable precautions will ensure that detrimental mechanical and thermal effects caused by the interaction of the magnetic field and surrounding conductive material are managed safely and adequately.

Calculation of the magnetic field around an air core reactor is a non-trivial task involving solving volume integrals of the Biot-Savart law at various locations around the reactor [2]. Our analysis software does this calculation and presents the resulting magnetic field as a function of distance from the reactor and height above ground level. The magnetic field plot for an 11 kV, 1600 A, 0.16 mH current limiting reactor is shown in the figure.
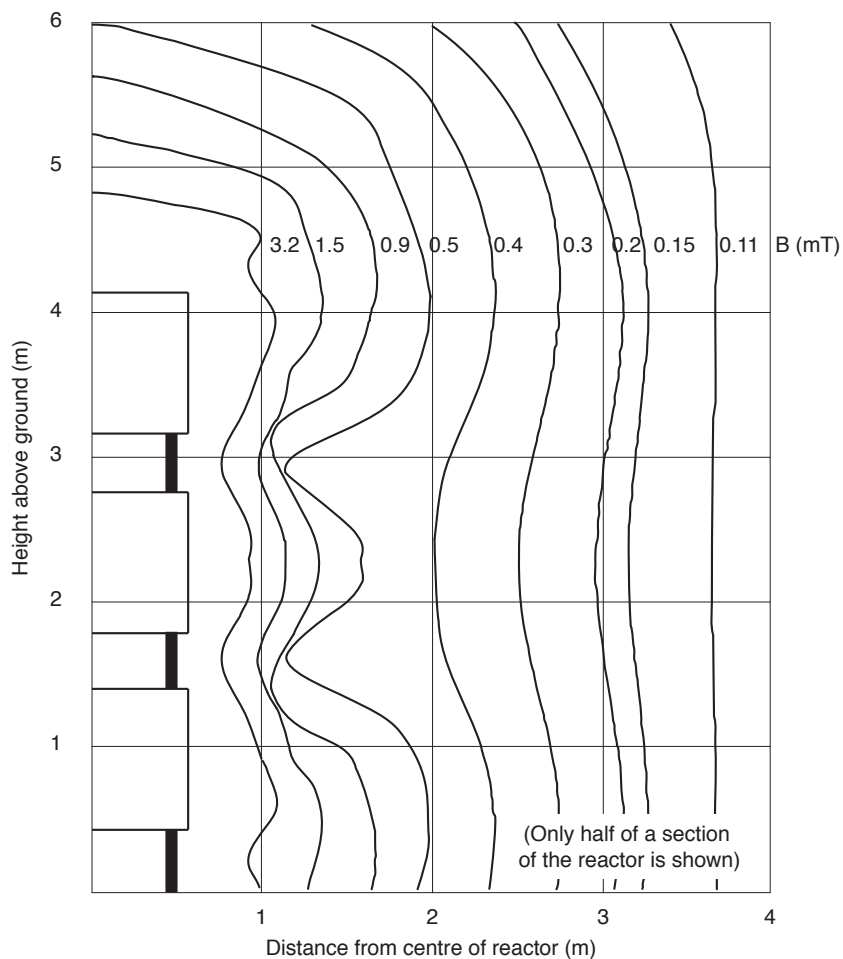
The analysis software takes into account the geometrical arrangement of the reactors and winding details. As an example it considers the impact of the vertical arrangement and the fact that in the

case of three-phase stacked reactors the middle coil of the stacked assembly is generally wound in the opposite direction to the top and bottom coils. This is done to ensure that in the event of a fault, the mechanical force experienced by the coils is attractive rather than repulsive.

2 Exposure to magnetic fields

The effects of human exposure to magnetic fields has been extensively reported on by the International Commission on Non-Ionizing Radiation (ICNIRP). An earlier report posted in 1998 [3] made recommendations for safe limits of occupational and general public exposure. These limits were adjusted with the benefit of substantial additional field research in the 2010 report [4] which recommends occupational exposure limits as follows:

Frequency range (f)	Magnetic flux density B (T)
1 Hz – 8 Hz	$0.2/f^2$
8 Hz – 25 Hz	$2.5 \times 10^{-2}/f$
25 Hz – 300 Hz	1×10^{-3}
3 kHz – 10 MHz	1×10^{-4}

For most applications this results in recommended exposure limits in the vicinity of an air core reactor to 1 mT. This is a significant relaxation of the limits originally recommended in the 1998 report mentioned above.

3 Induced voltages and currents

The magnetic field will induce an electromotive force (EMF) in conductive materials. This results in potential difference between components that are not bonded to the same ground potential, potential difference across conductive material that do not form a closed loop, and current in components that do form closed loops.

Potential difference across and between components is addressed by means of bonding each component to a common earth potential.

The magnitude of the current in a closed loop in the presence of a magnetic field is given by the following expression of Faraday's law [1]:

$$I = \frac{\omega B A}{Z}$$

$$Z = \frac{\rho l}{A_e}$$

Where
I = current in the closed loop (A)
ω = Rate of change of the magnetic field, (rad s^{-1})
B = Magnetic field component perpendicular to the loop, flux density (T)
A = Area of the loop (m^2)
Z = Impedance of the loop (Ω)
ρ = resistivity of the loop material (Ωm)
l = total length of the loop, (m)
A_e = loop conductor surface area (m^2)

It is clear that without detailed knowledge of the magnetic field surrounding the reactor (which can be obtained from the manufacturer as mentioned above) *and* the geometry of the site layout and the material used on site, it is not possible to make any prediction on the extent of current that may flow in a closed loop in the final installation.

As an example, the current that can be expected in a rectangular loop of two meters by six meters formed by 70 mm^2 earth conductor, at a distance of two meters from the above current limiting reactor coil surface can be estimated as follows:

The current (in amperes) flowing in the loop can be estimated as:

$$
\begin{aligned}
I &= \frac{\omega B A A_e}{\rho l} \\
&= \frac{(2 \times \pi \times 50) \times (0.5 \times 10^{-3}) \times (2 \times 6) \times (70 \times 10^{-6})}{(1.7 \times 10^{-8}) \times (2 \times (2 + 6))} \\
&= 485
\end{aligned}
$$

Should this loop be opened, there will be less than 2 V across the open loop. The same loop, directly beneath the reactor, can be expected to conduct approximately 3.1 kA.

It is clear that loop area and the magnetic field at a distance from the reactor are both very important factors to consider. Hence we make the general recommendation that closed loops should be avoided in the vicinity of an air core reactor.

4   Fencing

Outdoor open type reactors placed in high voltage switchyards are either placed inside HV cage fences or on top of base supports to allow access underneath the reactors (normally at least 2.4 m to the bottom of the support insulators of live equipment) as shown in the left in the figure below.

Concerns about magnetic radiation commonly require that working near air core reactors is restricted to locations where the magnetic field is less than 0.5 mT (depending on local regulations) and this is generally enforced by means of an HV cage fence or similar barrier.

Where reactors are placed indoors (for example as required by space constraints or environmental factors such as extremely high pollution levels or extreme climatic conditions) access is generally restricted by means of wire mesh panels.

All portions of the fence must be grounded. Even if there is no magnetic coupling between a reactor and a portion of the fence, there can still be capacitive coupling between the reactor which is at one potential, and the fence, which is in another.

An alternative solution is to use a barrier of nonmetallic fencing, such as wood, plastic or fibreglass.

The photo in the centre illustrates the use of wooden fencing material around large shunt reactors in a transmission substation. The fence serves the dual purpose of access restriction for electrical clearances as well as ensuring personnel do not work for extended periods in the presence of high magnetic fields.

Whatever the reason for placing a conductive fence around an air core reactor, provision must be made to assure that the reactor's magnetic field does not induce high currents in metallic fencing components. All metallic fencing must be broken up into electrically isolated sections if it is located very near the reactor.

The photo on the right illustrates a break in the fence around an 11 kV shunt reactor. The gate mechanism is placed across a single grounded section in the fence to ensure that current does not flow through the latch and that no potential difference arises when the gate is opened. As usual with all fencing application, the gate and gate posts are grounded.

5 Grounding

Special care should be taken in the installation of the station earth grid in the vicinity of air core reactors. The grid should be designed not to have closed loops. Current will be induced in such loops resulting in heating of such loops with the possible degradation of either the grounding system or the concrete, or both.
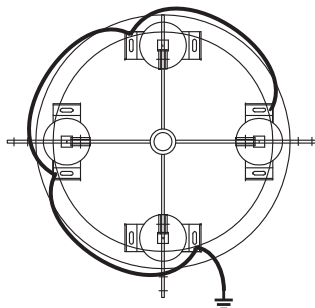
The diagram explains the manner in which earthing of equipment in the vicinity of air core reactors should be done. The overall principal is to avoid closed loops.

6 Use of air core reactors in enclosures

End users occasionally request air core reactors to be installed inside enclosures or inside buildings. The end user should understand the implications of installing an air core reactor inside such an enclosure:

1. Where the enclosure is made of a non-conductive material there is no impact on the magnetic field and a reactor that is quite capable of being used outdoors is placed indoors but without any changes to the surrounding magnetic field,

2. Where the enclosure is made of a conductive material there will be heating of the enclosure due to induced eddy currents at least, and in the worst case if a closed loop is formed by any part of the enclosure the induced current may result in extremely high temperatures.

Eddy current losses in conductive enclosures cannot be avoided unless a non-conductive material such as fibreglass is used for the construction. Losses in the enclosure material can be minimised by restricting the area of any one conductive area, for example by constructing panels from smaller sections that are insulated from each other.

Closed loops must be avoided on all four sides of metallic enclosures. This can be achieved by insulating the rear panel from the side and top panels, keeping in mind that all panel are to be grounded, as illustrated in the drawing. The sketch summarises the concepts of insulation of panels and grounding. The thicker lines indicate the location of insulated bolts. The drawing on the right indicates the reactor inside an enclosure with plinth and ventilation gaps in the side and front panels. Insulation material does not have to be very thick (3–5 mm) as there is no voltage increment across the various grounded panels, but care must be taken that the insulating material is able to withstand the mechanical and atmospheric environment for the duration of the life of the reactor.

The securing bolts between the rear and side panels, and between the top panel and the side/front panels must be insulated by means of insulating bushings and washers.

An inspection door can be inserted in any convenient panel to allow observation and routine maintenance-related thermal imaging of the reactor, terminals, conductors and the enclosure itself.

In the case of fully enclosed reactors, louvres can be inserted at the top and bottom of panels to assist in air flow by natural convection.
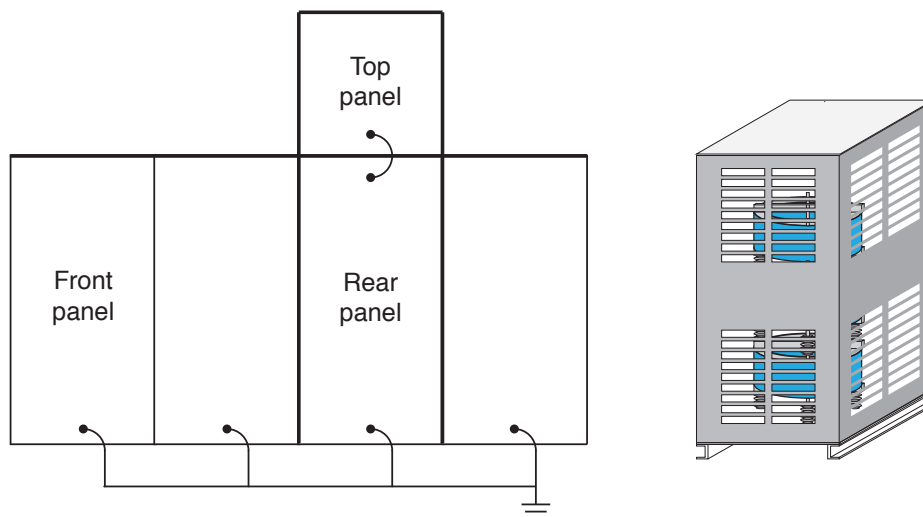
It is clear from the magnetic field plot presented at the start of this note that the highest magnetic flux density will exist directly above and beneath the reactor. In the case of enclosed reactors it may be beneficial to construct the top of the enclosure from a material such as fibreglass and to leave the bottom open.

Note that even though a reactor might be installed inside a metallic enclosure, the magnetic field may not be contained entirely inside the enclosure. More detailed, and more complex analysis will be required to determine the final magnetic field surrounding the enclosure.

7 Conclusion

Air core reactors have significant benefits compared to iron core, oil cooled equivalents but the magnetic field around the reactors needs to be considered when designing the application.

Positive cooperation between the supplier (who can provide the necessary field information) and the customer (who has detailed information on the site layouts) is required to ensure that the necessary precautions are taken when applying such reactors.

ONE has the necessary experience, analytical tools and engineering resources to assist you in all aspects of your air core reactor application.

Bibliography

[1] John D Kraus. *Electromagnetics*. McGraw-Hill International Book Company, third edition, 1984.

[2] J. Morozionkov and J. A. Virbalis. Magnetic field of power plant air core reactor. In *Journal of Electrical Engineering*, volume 7. Department of Electronics Engineering, Kaunas University of Technology, Lithuania, 2007.

[3] International Commission on Non-Ionizing Radiation. Guidelines for limiting exposure to time-varying electric, magnetic and electromagnetic fields (up to 300 GHz). In *HEALTH PHYSICS 74 (4) : 494-522*, ICNIRP Secretariat, c/o Gunde Ziegelberger, c/o Bundesamt für Strahlenschutz, Ingolstaedter Landstrasse 1, 85764 Oberschleissheim, Germany, 1998.

[4] International Commission on Non-Ionizing Radiation. Guidelines for limiting exposure to time-varying electric and magnetic fields (1 Hz – 100 kHz). In *HEALTH PHYSICS 99 (6) : 818-836*, ICNIRP Secretariat, c/o Gunde Ziegelberger, c/o Bundesamt für Strahlenschutz, Ingolstaedter Landstrasse 1, 85764 Oberschleissheim, Germany, 2010.