COMPARISON OF AIR-CORE AND IRON-CORE REACTORS FOR MEDIUM-VOLTAGE POWER-QUALITY APPLICATIONS

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INTRODUCTION

Reactors or Inductors are being used in various power quality applications like damping reactors for capacitor protection, within detuned or tuned filters to prohibit current fluctuation between load and filter and filter overload, as shunt reactors to compensate capacitive power or within multi-level inverters like SVC applications for current smoothing.

The choice of the core medium defines basic properties of the reactor like e.g. linearity, size and stray field. These properties influence the use in the above mentioned applications.

Dry-type reactors give the benefit of being essentially service-free. Fluid-cooled designs allow for a better cooling and therefore reduced size with the setback of usually higher energy loss and service expense. This paper will focus only on dry-type reactors.

For low-voltage applications, air-core reactors are very seldom utilized. They are more commonly used for medium-voltage applications due to their easier isolation system. Iron-core reactors, which are designed with laminated iron-cores due to size and linearity issues, are utilized in very much the same applications. The preference for one design over the other may be from experience, familiarity, misconception or some good technical reason. (Controllix Corporation, 2014)

In this paper a general comparison between air-core and laminated iron-core reactors is carried out focusing on the major differences and benefits relevant to medium-voltage application of the two inductor types.

BACKGROUND

Air-Core Reactors

Air-core reactors consist of a winding typically wound with wire, stranded wire or thin foils of Copper or Aluminum. They are supported by mechanical structures and placed on stand-off insulators that define the isolation systems' strength against ground potential (Figure 1).

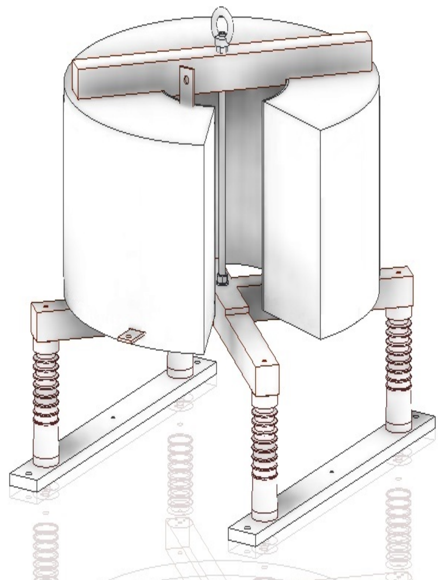

Figure 1: Air-Core Reactor on Post Insulators

The inductance of air-core reactors is to the largest extent defined by the winding itself with some small influence of the coupling between the phases of a winding system. Thus the winding geometry and the number of turns define the inductance value (HAK, 1938). For identical inductance values the number of turns of an air-core reactor is generally larger when compared to an iron-core reactor.

The absence of the iron-core results in a simple and lightweight construction. Consequently, the magnetic field of an air-core reactor is not guided within a material with a higher magnetic permeability. Instead, the magnetic field establishes within air and causes a large stray-field outside the mechanical dimension of the reactor itself.

Iron-Core Reactors

Iron-core reactors are made up of a core material with a high magnetic permeability compared to air. Due to price, size and linearity issues larger iron-core reactors are mostly made up of laminated steel.

The high permeability of the utilized laminated steel allows for a defined path of the magnetic field within the core of the reactor. Thus the iron-core design guides the magnetic field within the reactor's mechanical boundaries nearly eliminating the magnetic stray field.

Laminated steel is a soft-magnetic material with a non-linear behavior. Consequently, iron-core reactors saturate for large current values.

Introducing air-gaps in the core design linearizes the behavior of the inductor. Theoretically one air gap would suffice. But large air gaps cause large stray fields around this air gap. Especially for larger frequencies these stray fields tend to penetrate the winding. This penetration will eventually cause hot spots due to additional losses and mechanical forces and will therefore reduce the lifetime of the reactor. Multiple small air gaps like PolyGap® design annihilate the stray field and lead to a robust frequency behavior of the inductor.

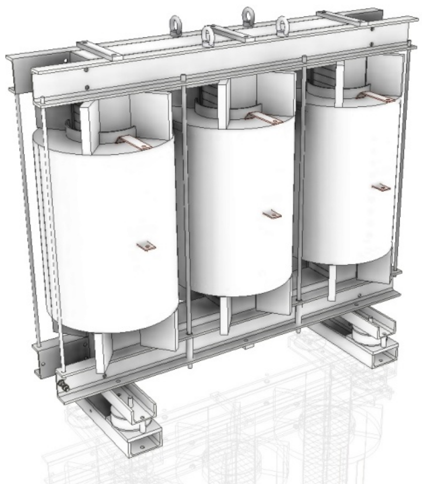

Figure 2: Iron-Core Reactor

The inductance value of the iron-core reactor (Figure 2) is defined by its winding geometry as well as number of turns and its core design. The winding is again made up of Copper or Aluminum wire or foils. The number of turns will generally be smaller when compared to the air-core reactor.

The winding will be on high potential while the core will be either grounded or floating on a different potential than the one of the winding. Since the winding is placed around the core or physically within the core, the winding-to-core isolation system must withstand the medium-voltage potential differences within the small physical distances between winding and core.

GENERAL COMPARISON

The question often arises which reactor design is more convenient for a specific application. Besides price and preference the two designs show characteristic differences that benefit or prohibit their use in some applications.

Air-Core Reactor	**Iron-Core Reactor**
Easier Isolation System	Sophisticated Isolation System
Mostly RMS Current Rating	Harmonic Current Rating
Cannot Saturate	Limit of Linearity
Large Magnetic Stray Field	Stray Field within the electrical spacing required by the system voltage
Open air mounting on concrete basement	Cubicle mounting with little space requirements.

Table 1

Table 1 shows in the view of the author the most prominent differences between air-core and iron-core reactors. The following sections will discuss these differences in detail.

Isolation system

The core of an iron-core reactor is either on ground potential or it might float on a different potential than the winding potential. When considering medium voltage reactors the potential difference might be quite large compared to the physical distance between the core and the winding.

Hence the most critical aspect of the lifetime design of medium-voltage iron-core reactors is its winding-to-core isolation system which in most cases is equivalent to the winding-to-ground isolation system. A failure of the isolation system will in almost all cases lead to an immediate destruction of the product.

As discussed above, the number of turns in the iron-core reactor is smaller than in the air-core reactor. Due to the lower number of turns the potential difference from turn to turn is bigger. This must be considered during the design of the winding.

While the iron-core reactor is made up of core and winding, the isolation system of the air-core reactor must only consider the winding. The potential difference to ground is generally carried by post insulators. These have to be utilized according to the required isolation strength. But they are readily available on the market either made of porcelain, organic material, or comparable isolation materials.

That leaves the inter-turn isolation to be considered. Due to the higher number of turns when compared to the iron-core reactor, the potential difference from one turn to the next is smaller than for the iron-core reactor. Thus by comparison the stress on the inter-turn isolation is smaller as well.

For the dimensioning of the inter-turn isolation strength the highest stress conforms to the highest voltage gradients appearing at switching of the equipment.

Especially if the propagation speed is small compared to the length of the winding, the propagation of the impulse within the winding must be considered. The full impulse might distribute within a smaller number than the complete number of turns of the winding leading to a non-linear distribution of the voltage within the winding (Hamid, 2012).

Since the length of the winding is considerably smaller for iron-core reactors, this effect is more critical for air-core reactors and must be considered when designing their insulation system.

For isolation testing, various methods are available on the market. IEC60076-6 states routine and type tests for isolation testing with induced overvoltage, turn-to-turn voltage and lightening impulse testing (IEC70076: Power Transformers - Part 6: Reactors, 2007). These tests help to build the customer's trust in the product.

In the author's view lightening-impulse testing gives good detection of insulation-system failures. Pulsing along the coil proves the safety of the inter-turn insulation and is relevant for air-core and iron-core reactors. Pulsing against ground only tests the stand-off insulators of air-core reactors, whereas for iron-core reactors, pulsing against ground assures that the isolation system against ground is properly dimensioned and functioning.

Essentially for both reactor types the isolation system must be designed for the lifetime of the reactor. Its design is somewhat easier for air-core reactors. For iron-core reactors the isolation system must be more sophisticated due to the close distance of core and winding and the lower number of turns. The strength of the isolation system can be proven by actual testing according to the standard.

Current Rating

The isolation system defines the allowed temperature rise of the reactor. When comparing air-core and iron-core designs, the air core reactor's loss is only generated in the winding.

Additional losses in the mechanical structure must be considered when designing the lifetime of the structure. In case of cage mounting or shielding, care must be taken to avoid eddy current floating in the cage or shield because of higher system losses and detuning of the reactors. But they are generally small compared to the main loss components within the winding.

The loss in the winding is mainly made up of ohmic loss which is dependent on the RMS current in the winding and some additional frequency dependent loss (skin effect et. al.). But for most applications the knowledge of the RMS current will give a plausible design value for the dimensioning of the air-core reactor's winding system.

Within the iron-core reactor, the loss is made up of the winding loss and the core loss. The winding loss is principally defined like above for air-core reactors. But in contrast to the winding loss, the core loss is strongly dependent on the frequency of the current since it is mainly caused by eddy-current loss and hysteresis loss (both effects being exponentially dependent on frequency). Therefore the harmonic spectrum of the load current must be considered and will define the loss within the core of the iron-core reactor.

Thus the RMS current or an equivalent fundamental current is not the only current governing the design of the core and therefore of the complete iron-core reactor. Instead, the frequency dependence of the load current and thus the worst case harmonic current spectrum must be considered and therefore also specified.

An equivalent current at fundamental frequency will give a plausible value for the winding loss. Testing with this current will lead to good knowledge of the temperature rise within the winding and is therefore a good way to check if the winding will overstep the end temperature of the isolation system. But it cannot represent the core loss generated by harmonic currents especially if their frequencies are large.

To protect against overheating of the core of iron-core reactors temperature sensors can be applied in all cases where the core is on ground potential.

Interestingly, due to the lower number of turns of the winding of iron-core reactors, the additional loss in the core does not automatically lead to a higher overall loss when compared to air-core reactors. Instead when considering the quality factor $Q = \omega L / R$ with ω the angular frequency, L as inductance and R as equivalent resistance, Q is typically larger for iron-core reactors in the frequency range up to a few kHz (U.Reggiani, 2000).

The actual specification, application and design of the two reactor types will show which type will give higher loss in which specific project.

Saturation

Air-core reactors use air which is magnetically linear to carry the magnetic field. Hence an air-core reactor is linear, i.e. its inductance value does not depend on its current load. Even when overloaded, the air-core reactor it will not saturate.

Therefore air-core reactors are utilized for fault-current limiting applications.

Due to the magnetically non-linear material of the core, iron-core reactors inherently saturate if the current oversteps the so-called linearity current I_{LIN}. If the current stays below I_{LIN}, the iron-core reactor shows linear behavior.

The amount of magnetic flux density depends on the cross section of the core material carrying the flux density and on the flux generated by the winding. Thus the design of the winding and the design of the core define the limit of linearity of the iron-core reactor.

Consequently during the design phase this value has to be considered. Especially if the reactor is utilized in filter applications with harmonic current content, the linearity current I_{LIN} must not only consider the RMS current of the reactor. Instead, the worst case scenario is the addition of all harmonic currents I_v.

$$I_{LIN} = s \cdot \sum_{v} I_v$$

Further considerations of voltage fluctuation and material and manufacturing tolerances lead to more or less conservative safety factors s for the linearity current. In practice a safety of 20 % has proven sufficient for almost all applications (i.e. s = 1.2).

Please note that the above definition of I_{LIN} is not a direct function of the RMS current. Instead it is based on the actual application of the reactor and dependent on its current load spectrum.

Figure 3 depicts the saturation of an iron-core reactor computed by FEM. The normalized differential inductance Ld/LN and absolute inductance La/LN of the reactor are plotted over the normalized current I/IN. Basis for the normalization are the nominal values for inductance LN and current IN. For comparison, the linear inductance of an air-core reactor is depicted as small-dotted line.

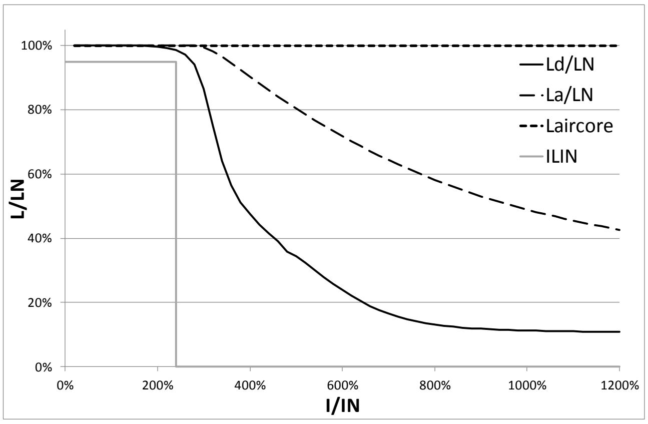

Figure 3: Computed Linearity of Iron-Core Reactor

To demonstrate the concept of the linearity current I_{LIN}, a light-grey line is added to Figure 3. If the inductance is above this normally guaranteed value of e.g. 95% of LN, the iron-core reactor is in its linear operating range.

Essentially the concern of saturation of iron-core reactors can be eliminated by specifying the limit of linearity based on the application and by a reactor design taking this limit properly into account. Hence even though fault-current limiting nearly prohibits the use of iron-core reactors, the saturation does not prohibit proper iron-core designs for applications like detuned or tuned filters even though these applications load the reactor with large harmonic current content.

Note: Iron-core reactors will always have an air inductance whose value is equivalent to the air-core inductance of the winding itself (compare Ld/LN @ 1200% in Figure 3). This air-inductance is guaranteed and limits the fault level even though the iron-core reactor might fully saturate.

Magnetic Stray Field

While the iron-core reactor has the setback of saturation, at the same time it has the huge benefit of a minimized stray field.

The effects of human exposure to magnetic fields has been investigated by the International Commission on Non-Ionizing Radiation and reported in 2010 (Radiation, 2010). Here a limit of 0.1 mT to 1 mT is defined within the frequency range relevant for power quality applications of reactors.

When properly designed using a multiple air-gap design the relevant stray field of an iron-core reactor is limited to its mechanical dimension. Typically the value of 1 mT will not occur outside of the electrical spacing of the iron-core reactor itself (Figure 4). This allows for small installation space frames when compared to air-core reactors. At the same time electrical installations in the close vicinity of the iron-core reactor are not influenced by any stray field.

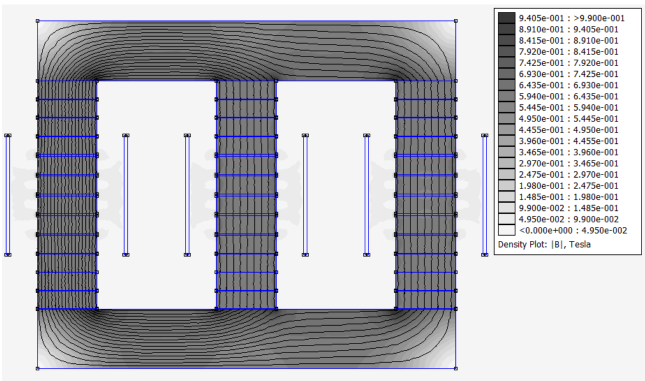

Figure 4: Magnetic Field of an Iron-Core Reactor

This again allows for the installation of iron-core reactors within the limited space of buildings, containers or even cabinets. Taking the cost for real estate or the limited room within existing facilities into account the small space required for an iron-core reactor might make its utilization more cost effective when compared to an air-core reactor.

Hence for standardized pre-assembled systems within containers or cabinets, iron-core reactors have the benefit of their negligible stray field when compared to air-core reactors. Within limits the actual design of iron-core reactors can even be adjusted to limited space requirements.

The large stray field of an air-core reactor (Figure 5) may interfere with other electrical equipment. It may heat up steel or aluminum structures and it can even damage concrete buildings due to the steel skeleton within the concrete. Especially closed conducting loops within the stray field must be prohibited.

The contour of field lines depends on the *h/D* ratio. Usually, a *h/D* ratio between 0.5 to 1.5 is maintained with *h* the winding height and *D* the winding diameter. In these cases the magnetic field at a distance of half the diameter (0.5 *D*) from the reactor surface will typically be less than 10% of the magnetic field at the centre of the reactor (where it is maximum).

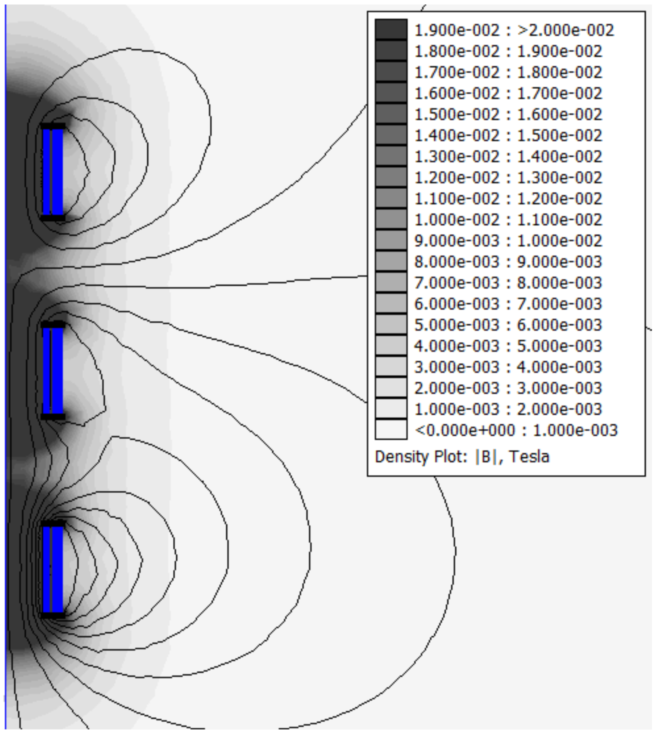

Figure 5: Magnetic Field of an Air-Core Reactor in Top-On-Top Design (only one half shown due to axis symmetry)

The critical value of 1 mT may even appear in a distance bigger than the actual diameter of the air-core reactor depending on its actual design. If this value is relevant for the application it must be determined with the reactor manufacturer during the design phase.

Providing enough magnetic spacing around the air-core reactor will take up physical space. Shielding for example with aluminum plates is possible but cost intensive. During the design phase the shielding must be discussed with the reactor manufacturer to prohibit against overheating of the shielding and against its influence on the air-core reactor's inductance.

Air-core reactors can be mounted inside panels provided the minimum magnetic clearances are maintained. When building enclosures for air-core reactors, the stray field must be known and considered while it can be neglected for the iron-core reactor. Consequently, the size of the panels for air-core reactors will be larger than for iron-core reactors.

Essentially a magnetic spacing has to be defined for air-core reactors. For iron-core reactors only the electrical spacing has to be considered.

CONCLUSION

This paper has given a general comparison of the critical parts of the isolation systems of both reactor types. For iron-core reactors, the knowledge of the harmonic content is important for the core design as well as the specification of the linearity limit. For air-core reactors, the knowledge of the stray field is critical which can normally be neglected for iron-core reactors.

Both air-core reactors and iron-core reactors have disadvantages and benefits. For many applications like detuned and tuned filter, shunts as well as SVC, their performance is nearly identical when properly specified, designed and applied.

This fact does not make it easier for the application engineer who should consider the type to utilize based on each project's specific requirements. A project in a large size outdoor installation might lead to air-core reactor application, while a project within a limited space frame for example on an offshore compressor station's tuned filter might lead to a choice of iron-core reactors.

Bibliography

Controllix Corporation. (2014). *Air Core vs. Iron Core Reactors*. Retrieved from http://www.controllix.com/display.cfm/p/45/pp/4

Hamid, H. A. (2012). *TRANSIENTS IN REACTORS FOR POWER SYSTEMS COMPENSATION.* Cardiff: School of Engineering, Cardiff University.

(2000). *IEC60076: Power transformers – Part 3: Insulation levels, dielectric tests and external clearances in air.* Geneva: IEC.

(2007). *IEC70076: Power Transformers - Part 6: Reactors.* Geneva: IEC.

Radiation, I. C.-I. (2010). *Guidelines for Limiting Exposure to Time-Varying Electric and Magnetic Fields.* Oberschleißheim: ICNIRP Secretariat, c/o Bundesamt für Strahlenschutz.

U.Reggiani, G. G. (2000). Comparison Between Air-Core and Laminated Iron-Core Inductors in Filtering Applications for Switching Converters. *CIEP 2000.* Acapulco.