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Magnetic Field of Power Plant Air Core Reactor

J. Morozionkov, J. A. Virbalis

Departement of Theoretical Electrical Engineering, Kaunas University of Technology,
Studentų str. 48, LT-51367 Kaunas, Lithuania, phone: +370 37 300267; e-mail: arvydas.virbalis@ktu.lt

Introduction

Electrical reactors are the electromagnetic devices the primary purpose of which is to introduce inductive reactance into a high voltage circuit. They are used in electrical power transformation and distribution systems as well as in the control and communication systems.

Taking into account needed electromagnetic parameters and linearity of veber–ampere characteristics the reactors are divided into four groups: air-core reactors, reactors with broken magnetic systems, with closed magnetic systems (saturable reactors) and having magnetic systems with gap (bus reactors) [1, 2].

The air core reactor is used to limit the short circuit current. It can be the consumer of reactive power when it is necessary to increase transmission line capability. The air core reactors are serial-connected to power line [2].

The main technical parameters of reactor are: nominal voltage U_n, nominal current I_n and relative inductive resistance (ratio of reactor voltage, when $I=I_n$, and nominal phase voltage of electrical network) [2].

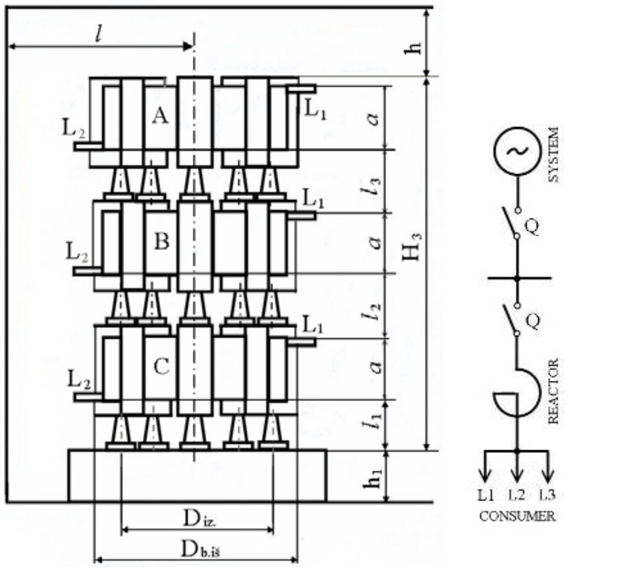
Magnetic field of reactor can sometimes reach the values dangerous to human [3]. Therefore it is important to know the distribution of magnetic field and its extreme values.

The detailed construction of air core reactor

The coils of reactor are manufacturing separate for every phase. The three phase coils are distributed one over other (see. Fig. 1, *a*). The coils are separated by support insulators this way, that mutual inductivity among windings could be significantly less then coil inductivity. Depending on nominal current the coils can have one or some parallel turns.

We investigate reactor RB-101600-0,35. Its nominal parameters are f=50 Hz, U_N = 10 kV, I_N = 1600 A, the inductive reactance x = 0,35 Ω.

There are five wires connected parallel. The total area of wire cross-section is d=5×320 mm^2. In vertical direction the number of turns is equal to 16. The middle phase of reactor has the reverse direction of turns in comparison with lower and upper phases.



a) b)

Fig. 1. Distribution of reactor phase coils (a) and reactor representation in network diagram (b)

Electromagnetic processes inside reactor

Let reactor have only one turn. The voltage u and instantaneous power p can be expressed

$$u = ir + \frac{d\Psi}{dt}; \quad p = i^2 r + i\frac{d\Psi}{dt}. \tag{1}$$

In these expressions the signs correspond to increase of current and interlinked magnetic flux, when voltage is positive.

Magnetic field energy of reactor W_M is:

$$W_M = W_{M0} + \int_{t_{pr.}}^{t} \left(p - i^2 r\right) dt = \int_0^{\Psi} i \mathrm{d}\Psi = i\Psi = iN\Phi. \tag{2}$$

where W_{M0} is initial magnetic field energy.

Evaluating equations:

$$H = \frac{I \cdot N}{h}; \ B = \mu_0 H; \ \Phi = BS_{\Phi}; \tag{3}$$

we can express the average energy value $\overline{W}_M$ in one period of current alternation this way

$$\overline{W}_M = \frac{I \cdot N \cdot \Phi}{2} = \frac{(I \cdot N)^2 \mu_a S_\Phi}{2h}; \qquad (4)$$

where h – turn height; S_Φ – the area of space inside windings.

Magnetic field strength H and magnetic flux density B have only axial components.

When reactor has round turns, we can evaluate the reactor heat losses W_h this way:

$$W_h = i^2 r = i^2 \rho \frac{l_{ap.} N}{S_{ap.}} = \rho \frac{(iN)^2}{V_{ap.}} l_{ap.}^2 = \frac{8\pi}{\mu_0} \rho \frac{(h + R_0)}{V_{ap.}} W_M, \qquad (5)$$

where R_0 – inner radius of windings.

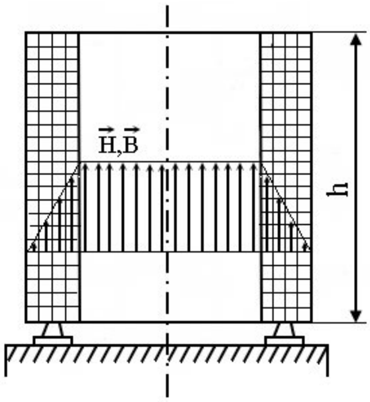


Fig. 2. Magnetic field inside reactor coil

The reactive power can be expressed by magnetic field energy:

$$Q = \omega W_M = 2\pi f W_M. \qquad (6)$$

Magnetic field outside reactor

Magnetic field strength in any space point can be calculated using Biot-Savart-Laplace law (see Fig. 3):

$$H = \oint_{l_i} \mathrm{d}\boldsymbol{H}_i; \quad \mathrm{d}\boldsymbol{H}_i = \frac{[\boldsymbol{r} \times \mathrm{d}\boldsymbol{l}] \cdot i}{4\pi r^3} = \frac{i \cdot \mathrm{d}\boldsymbol{l}}{4\pi r^2} \sin \angle r, \mathrm{d}l; \qquad (7)$$

where d$\boldsymbol{l}$ is length element of current, r- radius-vector of point, in which field is calculated. The integration must be done for all elements of reactor coil. Let us have solenoid with free shape plane windings (Fig. 4, a).

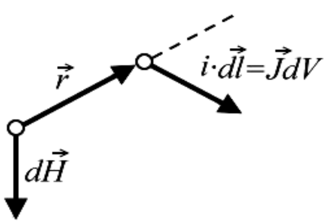
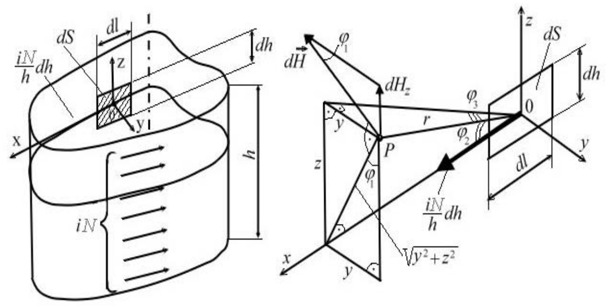


Fig. 3. Magnetic field source



a) b)

Fig. 4. The solenoid (a) and magnetic field of elementary area (b)

If magnetomotive force iN is distributed uniformly by solenoid axis, we express the axial component of magnetic field strength by solid angle (see Fig. 4, b). The centre of Cartesian coordinate system is in the centre of elementary area dS. The area dS is situated in xz plane; the current i is directed along axis x. The side dl is directed along axis x, and the side dh – along axis z. The winding axis is parallel to axis z.

Assume that the coordinates of measurement point P in which an axial component of magnetic field strength dH_z is computed are x, y and z. The distance at point P to coordinate system origin is $r = \sqrt{x^2 + y^2 + z^2}$ and to axis x is: $\sqrt{y^2 + z^2}$. Evaluating the geometrical structure (Fig. 4) and using Biot-Savart-Laplace law, we obtain:

$$\begin{cases} \mathrm{d}H_z = \mathrm{d}H \sin\varphi_1; \ \mathrm{d}H = \dfrac{1}{4\pi} \dfrac{i \cdot N}{h} \mathrm{d}h \mathrm{d}l \sin\varphi_2; \ \mathrm{d}S = \mathrm{d}h \mathrm{d}l; \\ \sin\varphi_1 = \dfrac{y}{\sqrt{y^2 + z^2}}; \quad \sin\varphi_2 = \dfrac{\sqrt{y^2 + z^2}}{r}; \\ \mathrm{d}\Omega = \dfrac{\mathrm{d}S}{r^2} \sin\varphi_3 = \dfrac{\mathrm{d}h \mathrm{d}l}{r^2} \dfrac{y}{r}. \end{cases} \qquad (9)$$

Therefore

$$\mathrm{d}H_z = \frac{1}{4\pi} \frac{iN}{h} \frac{\mathrm{d}h \mathrm{d}l}{r^2} \frac{y}{\sqrt{y^2 + z^2}} \frac{\sqrt{y^2 + z^2}}{r} = \frac{iN}{h} \frac{\mathrm{d}\Omega}{4\pi}, \qquad (10)$$

where dΩ is the solid angle, subtended by the area dS at a point P.

The magnetic field of all coils is proportional to sum of elementary solid angles, subtended by elementary areas dS at the point P (evaluating sign) [2]:

$$H_z = \frac{iN}{h} \frac{1}{4\pi} \int_S \mathrm{d}\Omega, \quad \int_S \mathrm{d}\Omega = \frac{S}{r^2} \sin\varphi_3 = \frac{hl}{r^2} \frac{y}{r}. \qquad (11)$$

The magnetic field strength on axis created by any reactor coil can be computed as field of massive turn with current I (Fig. 5) situated in middle coil plane. In Fig. 5 d$\boldsymbol{l_1}$ and d$\boldsymbol{l_2}$ are the winding elements. They are perpendicular to figure plane; d$\boldsymbol{l_1}$ is directed towards us, and d$\boldsymbol{l_2}$ - from us, d$\boldsymbol{H}_1$ is magnetic field strength created in point P by current element Id$\boldsymbol{l}_1$; d$\boldsymbol{H}_2$ - magnetic field strength created in point P by current element Id$\boldsymbol{l}_2$. Total value of radial component H_r is equal to zero. In any axis point magnetic field is directed along axis: d$\boldsymbol{H}$=$\boldsymbol{e}_z$dH_x=$\boldsymbol{e}_z$dHcosφ.

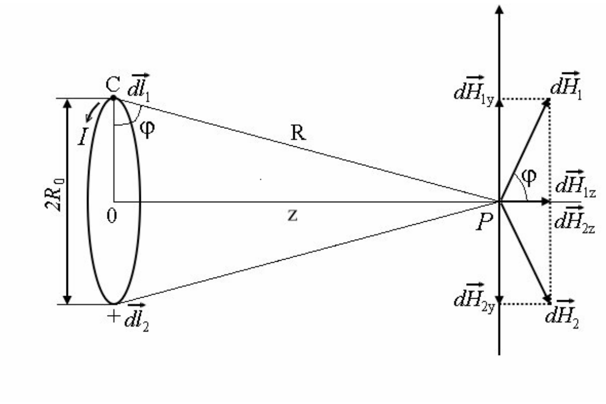


Fig. 5. Magnetic field strength on coil axis

By Bio-Savar-Laplace law

$$\mathrm{d}H = \frac{IN\mathrm{d}l\sin\alpha}{4\pi R^2} = \frac{IN\mathrm{d}l}{4\pi R^2}, \tag{12}$$

where α is angle between d$\boldsymbol{l}_1$ and $\boldsymbol{R}$ (since d$\boldsymbol{l}_1 \perp \boldsymbol{R}$, sin$\alpha$=1); I – reactor current, N – number of coil turns.

$$H = \int_0^{2\pi R_0} \frac{IN\mathrm{d}l}{4\pi R^2} = \frac{INR_0}{2R}\cos\varphi, \tag{13}$$

where R_0 – the inner radius of coil.

We can find R of triangle OCP:

$$R = \sqrt{R_0^2 + z^2}, \tag{14}$$

z – the distance from reactor axis centre to measurement point P. Evaluating (14) we obtain:

$$H = \frac{INR_0^2}{2\left(R_0^2 + z^2\right)^{\frac{3}{2}}}. \tag{15}$$

Computation of reactor magnetic field

The axial components of magnetic field strength created by any phase coil can be calculated using (15):

$$H_A = \frac{I_A \cdot N}{2} \cdot \frac{R^2}{\left(R^2 + z_A{}^2\right)^{1.5}}, \tag{16}$$

$$H_B = \frac{I_B \cdot N}{2} \cdot \frac{R^2}{\left(R^2 + z_B{}^2\right)^{1.5}}, \tag{17}$$

$$H_C = \frac{I_C \cdot N}{2} \cdot \frac{R^2}{\left(R^2 + z_C{}^2\right)^{1.5}}, \tag{18}$$

where z_A, z_B and z_C are the reactor coils geometrical centres heights of phases A, B and C, correspondingly.

The effective value of total axial magnetic field strength is:

$$H_\Sigma = \sqrt{H_A^2 + H_B^2 + H_C^2}. \tag{19}$$

In horizontal plane magnetic field is calculated by (11). The measurement point P (Fig. 6) is in h_{mat}=1,8 m height (the human head level). The measurement path is perpendicular to x axis ($\varphi_3 = 90^0$, sinφ_3 = 1). Therefore

$$H_z = \frac{I \cdot N}{h}\frac{\Omega}{4\pi} = \frac{I \cdot N \cdot S}{h \cdot 4\pi \cdot r^2}, \tag{20}$$

The computation results of magnetic field instantaneous values on the axis are presented in Fig. 7. These results are obtained for initial phases of phase coil currents, correspondingly, φ_A=30º, φ_B=150º and φ_C=270º. In Fig.8 the results of effective values magnetic field strength and magnetic flux density are presented. They are computed in horizontal plane h_{mat}=1,8 m.

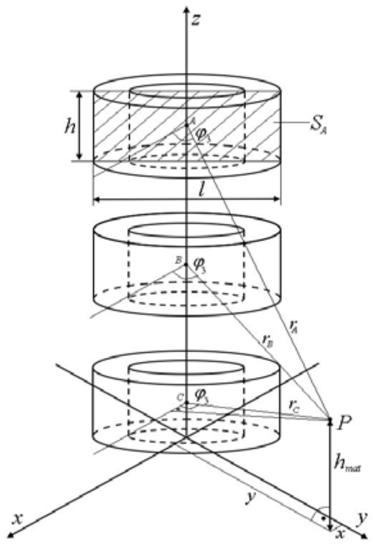


Fig. 6. Formation of magnetic field near the reactor: S_r- area of reactor lateral surface; h_{mat}- height of measurement point P; *A, B, C* – points of reactor coils geometrical centres

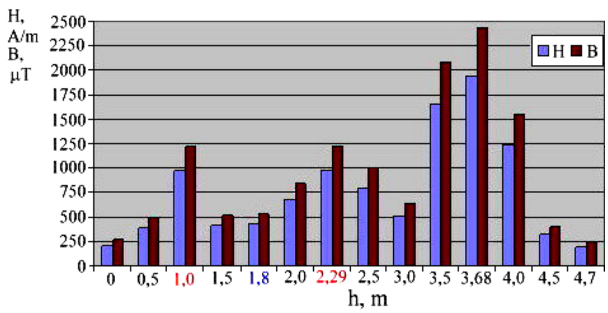


Fig. 7. Distribution of magnetic field strength H and magnetic flux density instantaneous values on reactor axis, when i_A=I_m

In the surroundings of reactor the magnetic field decreases about in inverse ratio to distance at reactor axis. The relations $H(x)$ and $B(x)$ obtained in the horizontal plane

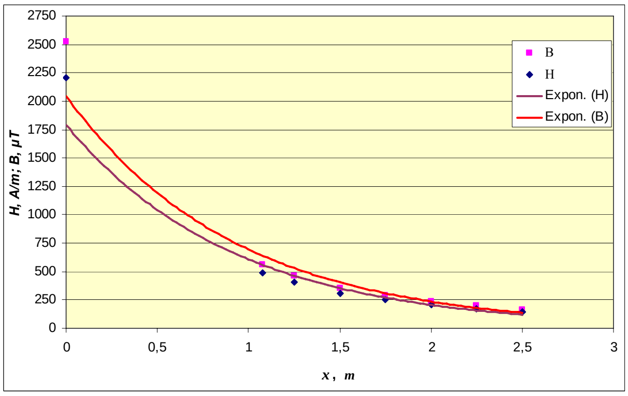


Fig. 8. Diagram of magnetic field strength H and magnetic flux density B in horizontal plane (h_{mat}=1,8 m) of reactor surroundings

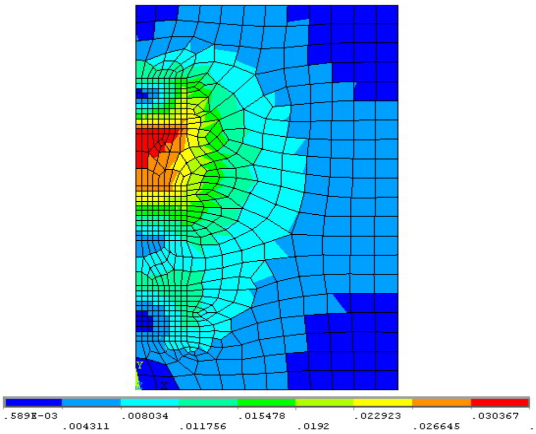


Fig. 9. Distribution of magnetic flux density B in the radial plane obtained by modelling

h_{mat}=1,8 m was approximated using regression analysis by equations:

$$H_{1,8} = H_{1,8}(0) \cdot x^{-1,1983} \text{ A/m}, \quad (21)$$

$$B_{1,8} = B_{1,8}(0) \cdot x^{-1,1982} \text{ μT}. \quad (22)$$

The field in the plane h_{mat}=1,8 m is calculated in two stages. At first, the magnetic field is calculated on axis. Then the distribution of magnetic field is calculated by (21) and (22) in surroundings of reactor.

The distribution of magnetic field in the meridional plane obtained by modelling is presented in the Fig. 9. The program ANSYS was used. The modelling results correspond with the computation results.

Conclusions

1. The air core reactor is used to limit the short circuit current. Magnetic field of reactor can sometimes to reach the values dangerous for human. It is important to know the distribution magnetic field and its extreme values.
2. The magnetic field in surroundings of reactor can be calculated when the distribution of magnetic field on reactor axis is known. The magnetic field on reactor axis can be calculated by Biot-Savart-Laplace law.

References

1.**Буль О. Б.** Методы расчета магнитных систем электрических аппаратов: магнитные цепи, поля и программа FEMM. – М.: Academia. – 2005. – 336 с.

2. **Ящура А. И.** Система технического обслуживания и ремонта энергетического оборудования. Справочник. – М.: НЦ ЭНАС. – 2005. – 504 с.

3. **Morozionkov J., Stašelis A.** Pramoninio dažnio elektromagnetinio lauko magnetinės dedamosios tyrimas // Agroinžinerija ir energetika. –Akademija, 2006. – Nr. 11 – P. 117–122.

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The air core reactor is used to limit the electrical network short circuit current. Magnetic field of reactor can reach the values dangerous to human. It is important to know the distribution of magnetic field in reactor surroundings and especially in perpendicular to reactor axis plane which height is 1,8 m (level of the human head). The magnetic field in surroundings of reactor can be calculated when the distribution of magnetic field on reactor axis is known. The field strength on reactor axis can be calculated by Biot-Savart-Laplace law. Ill. 9, bibl. 3 (in English; summaries in English, Russian and Lithuanian).

Е. Морозенков, Ю. А. Вирбалис. Магнитное поле реактора без стали электрической силовой установки // Электроника и электротехника. – Каунас: Технология, 2007. – № 8(80). – С. 67–70.

Реактор без стали необходим для ограничения подаваемого в электрическую цепь тока в режиме короткого замыкания. Магнитное поле реактора в определенных режимах может достичь опасных для человека значений. Поэтому важно знать распределение магнитного поля реактора, особенно в перпендикулярной оси реактора плоскости на уровне 1,8 м (уровень головы человека). Значения магнитного поля вблизи реактора можно получить зная распределение магнитного поля на оси реактора. Распределение магнитного поля на оси реактора можно рассчитать пользуясь законом Био-Савара-Лапласа. Ил. 9, библ. 3 (на английком языке; рефераты на английском, русском и литовском яз.).

J. Morozionkov, J. A. Virbalis. Elektros jėgainės bešerdžio reaktoriaus magnetinis laukas // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2007. – Nr. 7(79). – P. 67–70.

Bešerdis reaktorius naudojamas riboti į elektros tinklą tiekiamai srovei riboti trumpojo jungimo atveju. Tam tikrais režimais veikiančio reaktoriaus magnetinis laukas gali pasiekti žmogui pavojingas vertes. Todėl svarbu žinoti magnetinio lauko pasiskirstymą šalia reaktoriaus, o ypač reaktoriaus ašiai statmenoje plokštumoje, esančioje 1,8 m aukštyje (žmogaus galvos lygmenyje). Magnetinį lauką šalia reaktoriaus galima apskaičiuoti žinant magnetinio lauko pasiskirstymą reaktoriaus ašyje. Jį galima apskaičiuoti naudojant Biot, Savart‘o ir Laplace‘o dėsnį. Il. 9, bibl. 3 (anglų kalba; santraukos anglų, rusų ir lietuvių k.)