Selection of parameters of geometrically similar impact electromagnetic machines

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Abstract. The interrelation between machine volume, cooling surface area and linear dimensions of geometrically similar volumes is established for impact electromagnetic machines. Magnetic field finite-element simulation results show the electromagnetic machines volumes influence on economic indicators.

1. Introduction
Impact electromagnetic machines and devices are widely used in industry for mechanization of many technological processes [1-4]. Electromagnetic machines design methods improvement goes on [5, 6].

The present paper states the results of investigations of geometrically similar cores volumes influence on design factor with respect to core linear dimensions.

2. Linear dimensions criterion
A new thermal criterion

\[ K_T = \frac{P}{k_T \tau V^2} \]

is introduced to be a measure of linear dimensions for geometrically similar electromagnets cores in operating conditions [7], where \( P \) is the consumed power, \( k_T \) is the heat-transfer factor, \( \tau \) is the temperature excess, \( V \) is the electromagnet volume.

The equation (1) is chosen to be the main criterion as electromagnetic unit reliability depends on winding temperature excess stability in recursive short-term and long-term modes. The temperature value should be less than allowable one. Evidently, there is no explicit linear dimension – volume function (1) for geometrically similar systems.

Decrease of dimensions changes the windings temperature excess. Hence, stability of the numerical relation of volume, heat dissipation areas and linear dimensions is important for geometrically similar electromagnets.

If iron loss can be neglected in a dc system, power dissipated in a winding is:

\[ P = I^2 R, \]

where \( I \) is the current in the winding, \( R \) is the winding wire resistance:
where $\rho$ is the wire specific resistance, $l_{av}$ is the turn average length, $d_{av}$ is the turn average diameter, $d_1$ is the winding internal diameter, $d_2$ is the winding internal diameter, $w$ is the number of turns, $q$ is the wire cross-section:

$$q = \frac{S_{ap} k_{or}}{w} = \frac{h_{ap} l_w k_{or}}{w},$$

where $S_{ap}$ is the winding aperture cross-section area, $h_{ap}$ is the aperture height, $l_w$ is the winding length, $k_{or}$ is the aperture occupation ratio.

Then, from (1)–(4) the expression for magnetic force is:

$$I_w = \sqrt{\frac{K_T 2k_T \pi S_{ap} k_{or}}{\rho}} \frac{\sqrt{V^2}}{\pi(d_1 + d_2)l_w}.$$  (5)

The magnetic force equation for the prolonged heating mode can be derived directly from the Newton heat-balance equation:

$$P = k_T S_c \tau,$$  (6)

where $S_c$ is the winding cooling surface area.

Assume that heat is sunk only from winding external and internal surfaces:

$$S_c = \pi(d_1 + d_2)l_w,$$  (7)

while end surface cooling is neglected.

Then magnetic force is obtained from (6) with respect to (2)–(4), (7):

$$I_w = \sqrt{\frac{2k_T \pi S_{ap} k_{or} l_w}{\rho}}.$$  (8)

Let us note that (5) and (8) are equivalent for all systems where heating is caused only by losses in the winding. These expressions of magnetic force describe the heating mode when winding overheating temperature value is no more than allowable one.

Equation (5) can be represented as:

$$I_w = \sqrt{\frac{K_T \sqrt{V^2}}{\pi(d_1 + d_2)l_w}} \frac{2k_T \pi S_{ap} k_{or} l_w}{\rho}.$$  (9)

Equivalence of (8) and (9) gives:

$$\frac{K_T \sqrt{V^2}}{\pi(d_1 + d_2)l_w} = 1.$$  (10)

With respect to (7) equation (10) gives the expression involving only geometrical parameters:

$$K_T = \frac{S_c}{V^2} = \text{const}.$$  (11)

Thus, the identical relation (11) establishes the system heat exchanging surface area – volume ratio.

3. Comparison of dc electromagnets with geometrically similar cores

To estimate thermal criterion, it is necessary to compare dc electromagnets geometrically similar magnetic cores.

Validity of the equation (11) for all geometrically similar systems is tested for the typical cylinder electromagnet design. Figure 1 shows a V volume electromagnet outline. The electromagnet
dimensions are $d_1 = 120$ mm, $d_2 = 218$ mm, $l_w = 273$ mm.

![Image](image_url)

**Figure 1.** Cylindrical $V$ volume electromagnet outline

Changing the electromagnet model scale and re-calculating geometrical dimensions $S_e$ is found in the given volume.

Basic design data including the thermal criterion (11) for electromagnets models are presented for several geometrically similar systems in Table 1.

| Model volume ($m^3$) | $V$  | $2V$ | $4V$ | $6V$ | $8V$ | $10V$ |
|----------------------|------|------|------|------|------|-------|
|                      | 0.0204 | 0.0409 | 0.0818 | 0.1226 | 0.1635 | 0.2044 |
| $S_e$ ($m^2$)        | 0.1484 | 0.469 | 0.746 | 0.977 | 1.184 | 1.374 |
| $K_T$                | 3.96   | 3.96  | 3.96  | 3.96  | 3.96  | 3.96  |

The linear dimension scale factor $M$ is calculated by the formula:

$$M = \sqrt[3]{m_V}$$

where $m_V$ is the volume zoom ratio.

As it follows from Table 1, the geometrically similar cylindrical electromagnets have the same thermal criterion magnitude $K_T = 3.96$. The proposed thermal criterion is valid for other magnetic cores of geometrically similar dc electromagnets. It has different absolute values for different types of geometrically similar electromagnets.

Therefore, (11) can be recommended as a valid geometrical criterion of “thermal similarity” to compare electromagnets of any type. Design factor – volume ratios are obtained at the same windings average overheating temperature $\tau = 100^\circ C$.

Magnetic forces in windings for the long-term mode were calculated by (8) with respect to electromagnet design in Figure 1, the volume $V$, the number of turns $w = 1800$ and the steel saturation curve in Figure 2.
Figure 2. Steel saturation curve

The electromagnet volume is varied keeping complete geometrical similarity. The linear dimensions dependence on volume change is expressed with the dimensionless scaling factor:

\[ M = \sqrt[3]{k_V} \]

where \( k_V \) is the volume zoom ratio \( (0 < k_V < \infty) \).

Simulation parameters are stated in Table 2.

Table 2. Simulation Parameters

| \( k_V \) | \( V_{cu} \) | \( V_{st} \) | \( I_W \) |
|---|---|---|---|
| | \( 10^{-4} \) (\( m^3 \)) | \( 10^{-4} \) (\( m^3 \)) | (A) |
| 0.125 | 8.4 | 17.2 | 5670 |
| 0.25 | 16.8 | 34.7 | 8321 |
| 0.5 | 33.5 | 69.3 | 11160 |
| 1.0 | 66.8 | 137.6 | 16650 |
| | | | |

Traction characteristics were built and analyzed according to the method proposed in [8]. Then investigation of geometrically similar electromagnets gave the efficiency factor \( E \) – design factor \( D \) ratio at the overheating temperature \( \tau = 100^\circ C \). As it was found, maximal design factor values are in the range from 380 to 455 \( \sqrt{N/m^2} \) (Figure 3) for the volume zoom ratios from 0.125 to 16.0 in Table 2.

Figure 3. Electromagnet design factor –volume ratio

As it is shown in Figure 4, geometrically similar systems volumes change at certain overheating
\[ \tau = 100^\circ C \] strongly influences the efficiency factor.

![Graph](image)

**Figure 4.** Electromagnet efficiency factor – volume ratio

Volume increase leads to a decrease of material consumption and, after all, reducing of electromagnetic forces work per volume unit. It follows from Figure 4 that the volume increase causes less efficiency factor growth and its stabilization at \( E = 0.5 \).

4. Conclusion
The design factor – volume function has been obtained for the typical construction of the cylindrical electromagnet to estimate geometrically similar magnetic cores volume values effect on design factor. Therefore, it is necessary to develop a method to analyze the design factor more precisely.

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