

Approximate design of cyclic electromagnetic drive with respect to permissible heating condition

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Abstract—Impulse technologies application in cyclic electromagnetic machines demands improvement of thermal design procedures for the short-time mode. When such machines are developed, the thermal design procedures allow optimizing their operation with respect to the given working procedure. New design relations describing electromagnetic drive heating in the short-time mode have been derived from the finite-difference Newton equation solution. It is assumed that the electric drive is a homogeneous body with ideal heat conductivity. The approximate expressions of permissible heating with respect to impact energy depending on the number of operating cycles or impacts and initial temperature exceed over ambient temperature have been obtained. The derived dependences for the cyclic electromagnetic machine short-time mode can be widely used in practice. They will help to optimize electric drive operation with respect to the permissible heating condition when there is no need to use complicated mathematical formulas. A two-coil cyclic electromagnetic machine is considered as an example of using the design procedure for output parameters in the short-time mode.

Keywords – cyclic electromagnetic drive, initial temperature exceed, cyclic heating process, short-time mode

I. INTRODUCTION

Impulse technologies in industry are implemented by machines and units based on impact electromagnetic machines [1, 2].

Currently the impact electromagnetic machines are extremely improved and some of them are introduced into serial production [3].

Electromagnetic design methods are well-known and their improvement is going on [4-8].

New impulse technologies need improved engineering design procedures permitting to optimize an electric drive operation with respect to a given working procedure [9-12].

The electric drive cyclic mode with input power significantly more than power in the continuous running duty is considered in the paper.

When electric drive temperature achieves certain maximum permissible level, it is necessary to switch off and cool the drive.

When the electric drive is switched on again, initial temperature of it can exceed environment temperature.

Such control method with technological process interrupting permits to increase impact energy and electric drive power. This method is main one for a number of units.

The heating and cooling process in the electric drive cyclic mode for any n th cycle ($n = 0, 1, 2 \dots$) is described by the Newton equations:

$$\begin{cases} C \frac{d\tau}{dt} + k_h S_{cs} \tau = P_L, & nt_c \leq t \leq nt_c + t_{cf}; \\ C \frac{d\tau}{dt} + k_h S_{cs} \tau = 0, & nt_c + t_{cf} \leq t \leq (n+1)t_c, \end{cases} \quad (1)$$

where τ is the electric drive temperature excess over the ambient temperature; C is the electric drive heat capacity; k_h is the heat-transfer factor; S_{cs} is the cooling surface area; P_L is the heat loss; $t_c = t_{cf} + t_{cp}$ is duty cycle time; t_{cf} is the coil current flow time; t_{cp} is the current pause time; n is the number of cycles.

The electric drive load plot is stated in Fig. 1.

II. CYCLIC ELECTRIC DRIVE APPROXIMATE DESIGN

The equations system (1) solution in finite differences has the form:

$$\tau(n)_{\min} = \tau(0)\gamma^n + \frac{\tau_s(1-a)(1-\gamma^n)\frac{\gamma}{a}}{1-\gamma}, \quad (2)$$

$$\tau(n)_{\max} = \tau(0)\gamma^n + \frac{\tau_y(1-a)(1-\gamma^n)}{1-\gamma}, \quad (3)$$

where $\gamma = e^{-\frac{t_c}{T_0}}$, $a = e^{-\frac{t_{cf}}{T_0}}$, T_0 is the electric drive heating time constant; τ_s is the overheating stationary value for long-standing power output; $\tau(0)$ is the initial temperature exceeding over the ambient temperature; $\tau(n)_{\min}$, $\tau(n)_{\max}$ are correspondingly the minimal and maximal overheating values in n th heating working cycle.

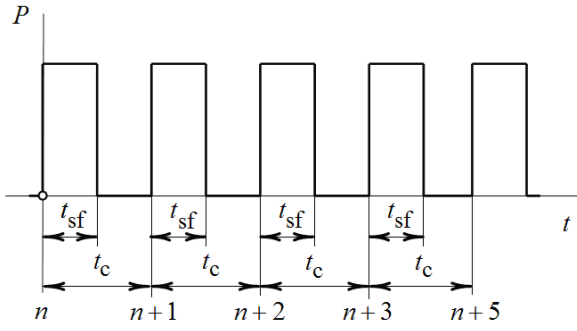


Fig. 1. Electric drive load plot.

The values $\tau(n)_{\max}$ and $\tau(n)_{\min}$ have not to exceed the given allowable value τ_a :

$$\tau(n)_{\max} \leq \tau_a, \quad \tau(n)_{\min} \leq \tau_a.$$

With respect to non-zero initial condition $\tau(0) \neq 0$ the expressions (2) and (3) are simply reduced to the form:

$$\frac{\tau_s}{\tau_a} = \left[1 - \frac{\tau(0)}{\tau_a} \gamma^n \right] \frac{1-\gamma}{(1-a)(1-\gamma^n)} \cdot \frac{a}{\gamma}, \quad (4)$$

$$\frac{\tau_s}{\tau_a} = \left[1 - \frac{\tau(0)}{\tau_a} \gamma^n \right] \frac{1-\gamma}{(1-a)(1-\gamma^n)}. \quad (5)$$

The substitutions of the heat power overloading factor $\frac{\tau_s}{\tau_a}$ by k_{po} and the relative initial temperature excess over the ambient temperature $\frac{\tau(0)}{\tau_a}$ by ε give:

$$k_{po} = \frac{(1-\varepsilon\gamma^n)(1-\gamma)}{(1-a)(1-\gamma^n)} \cdot \frac{a}{\gamma}; \quad (6)$$

$$k_{po} = \frac{(1-\varepsilon\gamma^n)(1-\gamma)}{(1-a)(1-\gamma^n)}. \quad (7)$$

The expression (6) is suitable for minimal overheating value in the working cycle. The expression (7) is suitable for the maximal overheating.

The power overloading factor is:

$$k_{po} = \frac{P_L}{P_a},$$

where P_a is the loss with respect to allowable heating from the condition of the long-time mode; P_L is the power loss in the time interval t_{cf} .

The power loss is:

$$P_L = \frac{1}{t_{cf}} \int_0^{t_{cf}} i_c^2 R dt,$$

where i_c is the coil current, R is the coil active resistance.

Power overloading can be expressed by:

$$k_{po} = \frac{A_{im}(1-\eta)}{t_{cf} \eta k_h (\vartheta_a - \vartheta_0) S_{cs}}, \quad (8)$$

where A_{im} is the head impact energy; η is the electric drive emission; ϑ_a is the allowable electric drive overheating temperature; ϑ_0 is the ambient temperature.

With respect to (8) impact energy is:

$$A_{im} = \frac{t_{cf} \eta k_h (\vartheta_a - \vartheta_0) S_{cs}}{(1-\eta)} \cdot k_{po}. \quad (9)$$

With respect to replacement in (9) by (6) and (7):

$$A_{im}|_{\min} = \frac{t_{cf} \eta k_h (\vartheta_a - \vartheta_0) S_{cs}}{(1-\eta)} \cdot \frac{(1-\varepsilon\gamma^n)(1-\gamma)}{(1-a)(1-\gamma^n)} \cdot \frac{a}{\gamma}; \quad (10)$$

$$A_{im}|_{\max} = \frac{t_{cf} \eta k_h (\vartheta_a - \vartheta_0) S_{cs}}{(1-\eta)} \cdot \frac{(1-\varepsilon\gamma^n)(1-\gamma)}{(1-a)(1-\gamma^n)}. \quad (11)$$

If the heating mode is quasisteady and $n_{\max} \rightarrow \infty$, then (10) and (11) for allowable impact energy are reduced to:

$$A_{im \max} = \frac{t_{cf} \eta k_h (\vartheta_a - \vartheta_0) S_{cs}}{(1-\eta)} \cdot \frac{(1-\gamma)}{(1-a)} \cdot \frac{a}{\gamma};$$

$$A_{im \min} = \frac{t_{cf} \eta k_h (\vartheta_a - \vartheta_0) S_{cs}}{(1-\eta)} \cdot \frac{(1-\gamma)}{(1-a)}.$$

According to (10) and (11), the equations with dimensionless parameters are derived:

$$A_{im \min}^* = \frac{(1 - \varepsilon \gamma^{n_{\max}})(1 - \gamma)}{(1 - a)(1 - \gamma^{n_{\max}})} \cdot \frac{a}{\gamma}, \quad (12)$$

$$A_{im \max}^* = \frac{(1 - \varepsilon \gamma^{n_{\max}})(1 - \gamma)}{(1 - a)(1 - \gamma^{n_{\max}})}. \quad (13)$$

Fig. 2 shows functions $A_{im}^* = f(n_{\max})$, found from (13).

If $T_0 \gg t$, then $1 - e^{-\frac{t}{T_0}} \approx \frac{t}{T_0}$.

The expressions (10) and (11) for impact energy are simplified:

$$A_{im}(n_{\max})_{\min} = \frac{\eta k_h (\vartheta_a - \vartheta_0) S_{sc}}{(1 - \eta)} \times \frac{\left[1 - \varepsilon \left(1 - \frac{t_c}{T_0} n_{\max} \right) \right] (T_0 - t_{cp})}{n_{\max}}; \quad (14)$$

$$A_{im}(n_{\max})_{\max} = \frac{\eta k_T (\vartheta_a - \vartheta_0) S_{cs}}{(1 - \eta)} \times \frac{\left[1 - \varepsilon \left(1 - \frac{t_c}{T_0} n_{\max} \right) \right] T_0}{n_{\max}}. \quad (15)$$

If $\frac{t_c}{T_0} n_{\max} \leq 0.1$, the computation error is less than 5%.

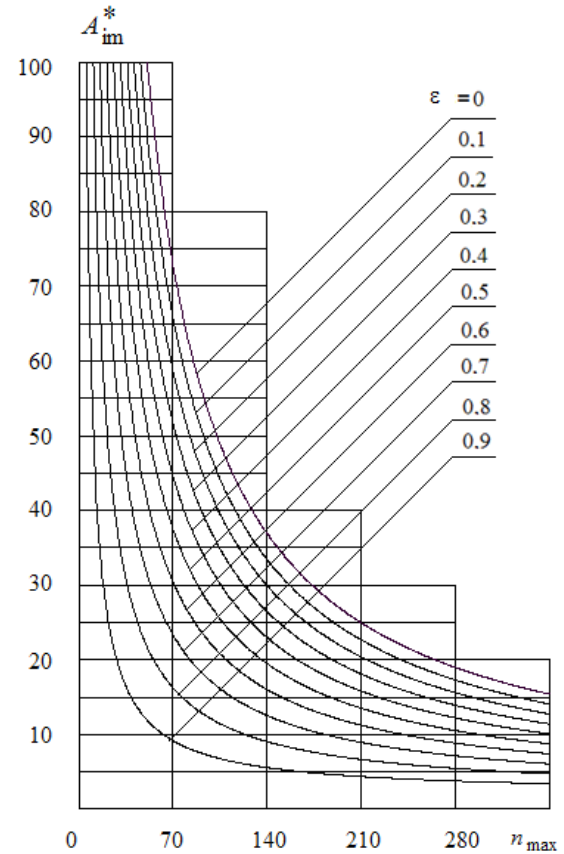


Fig. 2. Functions $A_{im}^*(n)_{\max} = f(n)$ at $\frac{T_0}{t_c} = 2500$ and $\frac{t_{sf}}{t_c} = 0.5$.

III. ELECTRIC DRIVE DESIGN EXAMPLE

For instance, it is necessary to build the regulation curve for the allowable impact energy A_{im} in the given range of executed working cycles (impacts) $n_{\max} = 2300 \dots 4800$.

When an electric drive is switched on, its overheating is $\vartheta_{ini} = 95^\circ \text{C}$.

The electric drive in Fig. 3 is powered by a half-wave rectifier from an AC source 50 Hz, providing current pulses width $t_{cf} = 0,012 \text{ s}$.

The electric drive parameters are $\eta = 0.32$, $\vartheta_0 = 30^\circ \text{C}$, $\vartheta_a = 125^\circ \text{C}$, $\vartheta_{ini} = 95^\circ \text{C}$, $k_h = 12 \text{ W}/(\text{m}^2 \cdot \text{K})$, $d_1 = 30 \text{ mm}$, $d_2 = 75 \text{ mm}$, $L_c = 42 \text{ mm}$, $D = 84 \text{ mm}$, $L = 100 \text{ mm}$, $m_{EM} = 3.76 \text{ kg}$, $T_0 = 2.94 \cdot 10^3 \text{ s}$.

The allowable impact energy in the given range of executed cycles is determined as:

$$A_{im \max}(n_{\max}) = \frac{2\eta k_h \tau_a S_{cs}}{1-\eta} \cdot \frac{\left[1 - \varepsilon_{\tau} \left(1 - \frac{t_c}{T_0} n_{\max}\right)\right] T_0}{n_{\max}} =$$

$$= 1.42 \cdot \left[1 - 0.684 \cdot \left(1 - 5.08 \cdot 10^{-6} n_{\max}\right)\right] \cdot \frac{2.94 \cdot 10^3}{n_{\max}}.$$

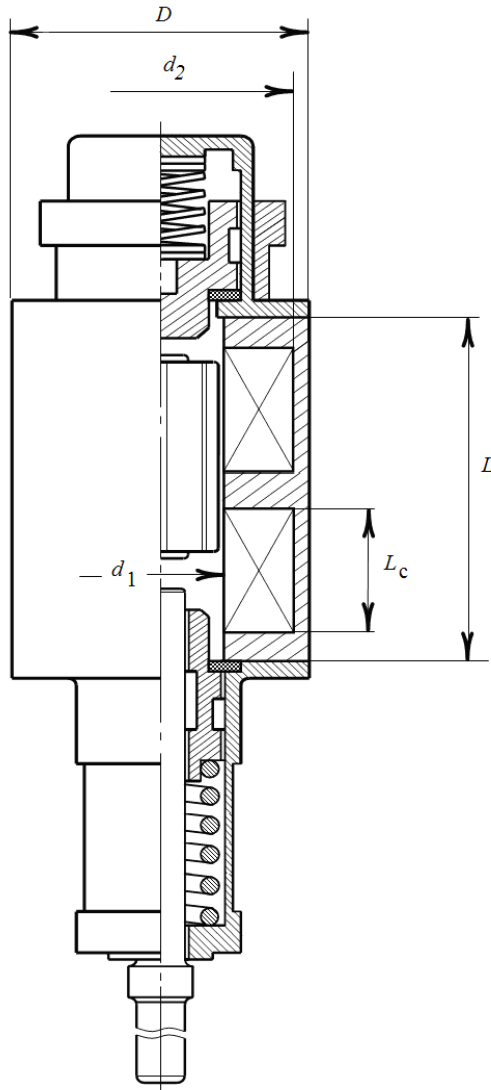


Fig. 3. Electromagnetic drive.

Cyclic electromagnetic drive and its design regulation curve are stated in Fig. 4.

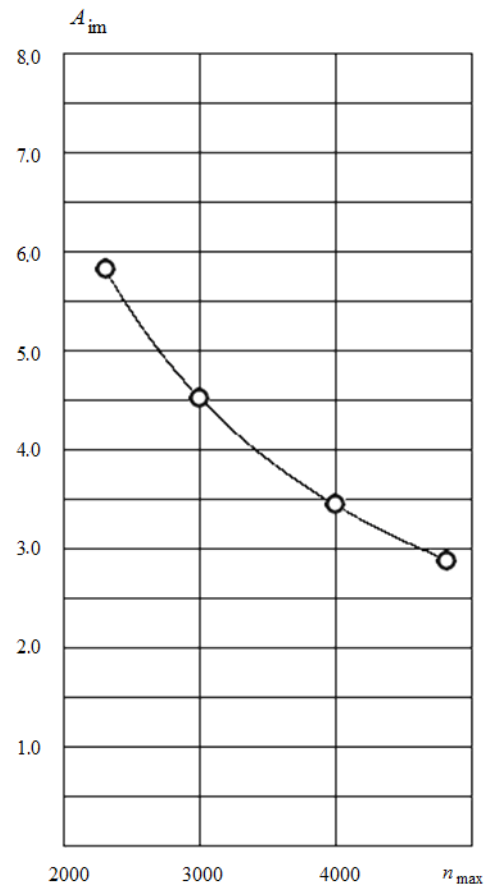


Fig. 4. Cyclic electromagnetic drive and its design regulation curve.

IV. CONCLUSION

The approximate design relations are derived to establish the allowable impact energy value depending on the executed working cycles number and initial temperature excess over the ambient temperature.

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