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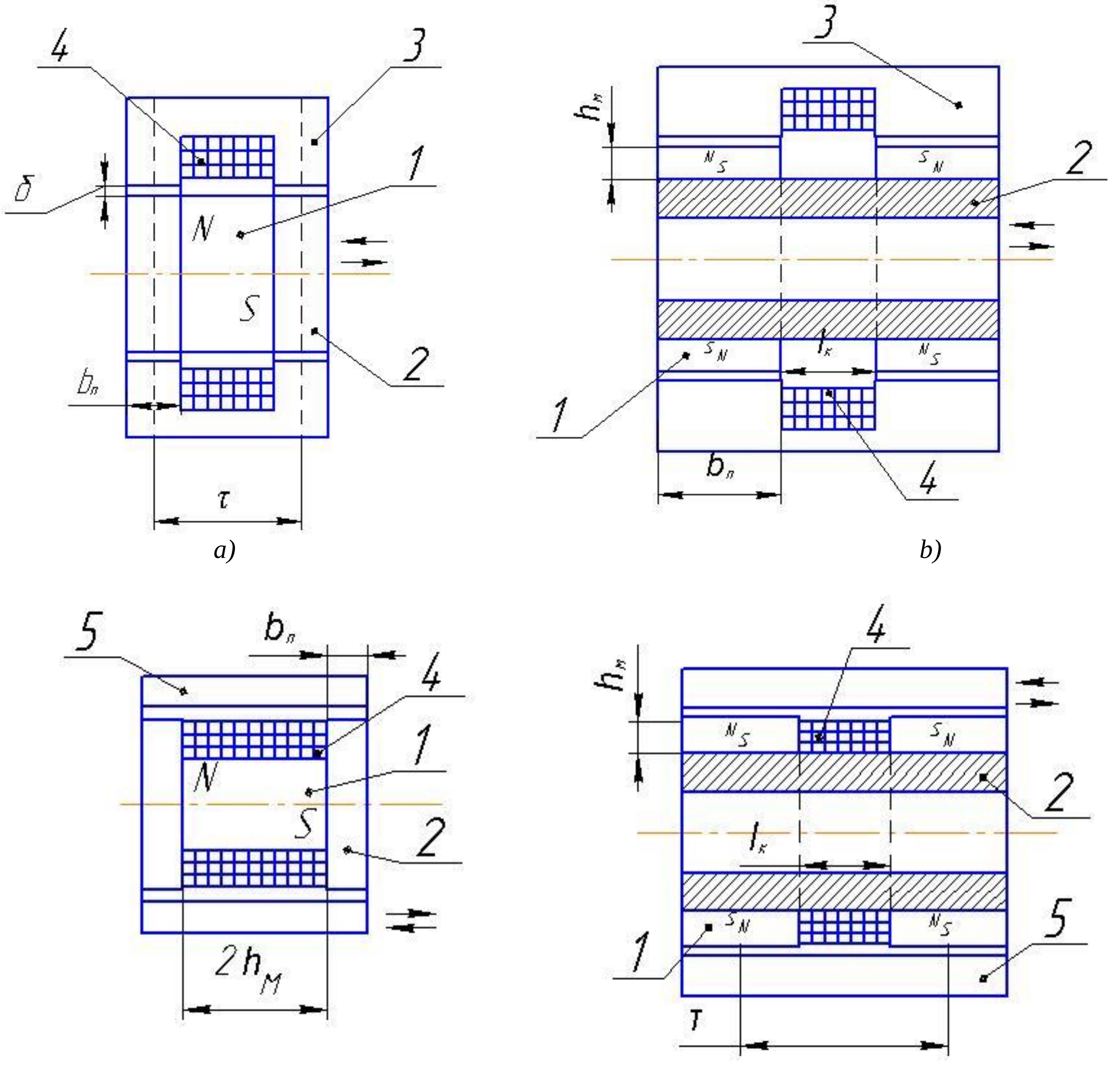
ANALYSIS OF LINEAR ELECTRIC GENERATORS' STRUCTURES

It is known that one of the largest renewable energy resources is a global resource of sea wave power. Possible way to use such energy resource is transformation of wave power into electrical energy by means of linear generators with permanent magnets. Many different designs of linear generators are known [1], but there is no information about comparative analysis of their structures as well as selection of dimensional specifications and size of the permanent magnets guideline. In this work such analysis was made. Generators with permanent-magnet excitation with fixed single-phase windings. The basic constructions of such generators are shown in Fig. 1, *a-d.*



a) *b)*

c) *d)*

Fig. 1. Basic construction of linear generators (cross-sections of cylinder generators are shown).

The basic constructions are named so, because they are used as a basis in the majority of known linear generators. On fig. 1, *a, c* the construction with a permanent magnets are presented. Magnets were magnetically charged in axial direction coinciding with the direction of moveable element - rotor. Numbers on figures correspond to: 1 - the permanent magnet; 2 - the poles of the low-coercitivity material; 3 – stator magnetic circuit; 4 - winding. In the construction of the generator (Fig. 1, *a)* the permanent magnet 1 with poles 2 is moveable element, and in the construction (Fig. 1,c) – a permanent magnet 1 is fixed and the rotor is a cylinder 5 made from low-coercitivity material. Fig. 1, *b, d* presents the design of generators with permanent magnets magnetically charged in the radial direction, i.e. perpendicular to the direction of the rotor motion. Numbers on figures correspond to those from Fig. 1, *a, c*. Permanent magnets in the construction of Fig. 1, *b, d* are in the form of hollow mutually shifted along axial axis cylinders, magnetically charged in opposite directions and located on cylinder (yoke) 5 of the low-coercitivity material. In the construction (Fig. *1, b)* the movable element is the cylinders 2 with permanent magnets 1 on its outer surface. In construction 1,d, the winding 4 is located on the yoke 2 in the gap between the magnets 1; the movable element is an outer cylinder 5 of the low-coercitivity material. Cylindrical construction of generators causes difficulties with usage of the plate magnetic materials. In this case, the usage of the composite of the low-coercitivity materials is necessary. Such materials have lower magnetic properties than electrical steels, but almost eliminate eddy-current losses. Usage of plate magnetic circuit is possible in planar constructions of generators.

On fig. 1 generators' rotors are shown in the initial position, i.e. without any external mechanical impact. The magnetic flux F penetrating winding turns will be the maximum $(F = F_{m})$. Moving the rotor from its initial position causes reduction of the air gap area between the stator and rotor poles, resulting in a change of magnetic flux *F* and production of the electromotive force (EMF) in the windings. The minimum value of the flux F_0 in constructions in Fig. *1, a, b* will be observed if the displacement of rotor (x) is greater than the width of the pole b_n,, but not more than half of the polar pitch τ, *i.e.* $b_n < x \leq \frac{\tau}{2}$. Instant value of EMF produced in the windings, $e = -w\frac{dF}{dt}$, where *w* - the number of winding's turns. At the periodic vibration of the rotor an average value of the EMF is:

$$E_{av} = \frac{\int_0^{T/2} edt}{\frac{T}{2}} = \frac{-\int_{F_M}^{F_0} wdF}{\frac{T}{2}} = \frac{-w(F_0 - F_M)}{\frac{T}{2}} = 2wf_E F_M\left(1 - \frac{F_0}{F_M}\right) = 2wf_E k_f F_M, \quad (1)$$

where $f_E = \frac{1}{T_E}$ - frequency of EMF; T_E - period of EMF; $k_f = 1 - \frac{F_0}{F_M}$ - coefficient for taking into account changes of the magnetic flux at displacement of the rotor to the limit positions.

Fig. 2 shows a possible variation of the initial position of the rotor in time and corresponding changes in the magnetic flux in the magnetic circuit of the generator and EMF of winding.

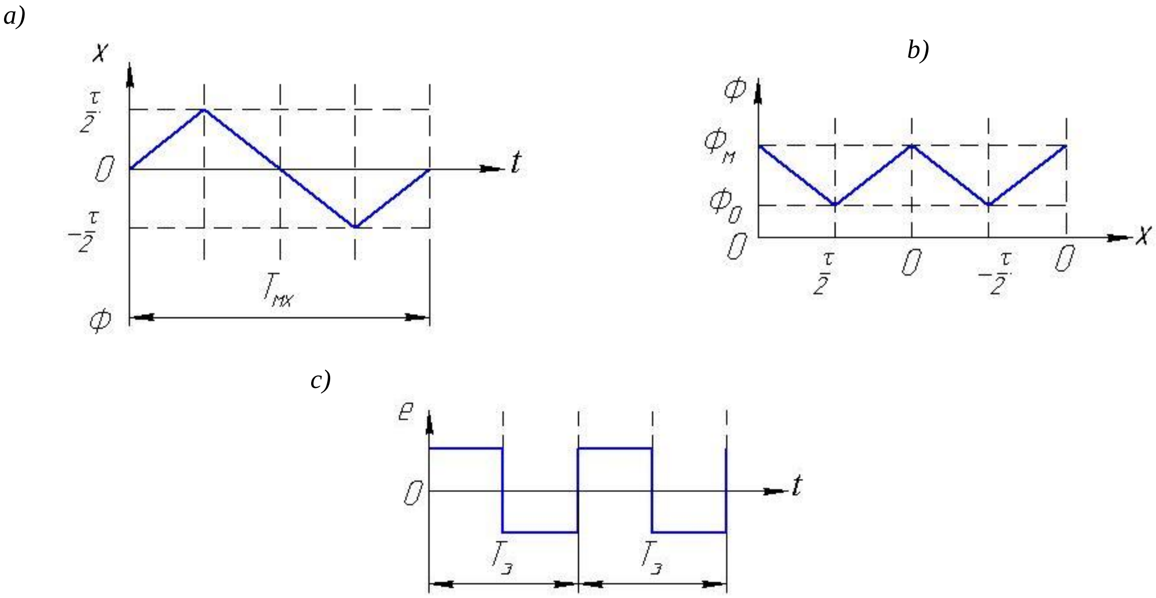


Fig. 2. Change of the rotor position *x*, the magnetic flux *F* and the EMF e
(T_{MX} - the period of vibration)

From the analysis of the graphs (Fig. 2) it is evident that $T_{MX} = 2T_E$ it follows that $f_E = 2f_{MX}$, where $f_{MX} = \frac{1}{T_{MX}}$ - the frequency of rotor vibrations. Against this background, we can write down an equation (1) in view of:

$$E_{av} = 4wf_{MX}k_fF_M. \tag{2}$$

From the analysis of the graph in Fig. 2,a an equation for average speed of rotor $\vartheta_{av} = \frac{4x_{\text{м}}}{T_{MX}} = 4f_{MX}x_{\text{м}}$ is evident, where $x_{\text{м}}$ - the maximum displacement of the rotor in one direction (vibration amplitude). Then $4f_{MX} = \frac{\vartheta_{av}}{x_{\text{м}}}$. Substituting this relation into the formula (2) we get:

$$E_{av} = \frac{wk_fF_M\vartheta_{av}}{x_{\text{м}}}. \tag{3}$$

Effective range of EMF $E = k_aE_{av}$, where k_a - coefficient of EMF curve shape.

Full power of generator:

$$S = E \cdot I = 4wf_{MX}k_ak_fF_MI, \tag{4}$$

where I - effective current.

From the formula for electric loading $A = \frac{Iw}{l_k}$, where l_k - the length of the winding, we can find

$$A = \frac{I \cdot l_k}{w}. \tag{5}$$

The maximum value of the magnetic flux

$$F_M = S_\delta \cdot B_\delta = \pi D b_n B_\delta, \tag{6}$$

where D - bore diameter; B_δ - magnetic induction in the air gap; S_δ - the area of air gap.

Substituting into (5) and (6) into (4), we obtain

$$S = 4f_{MX}B_\delta A k_a k_f \pi D b_n l_k. \tag{7}$$

From this we obtain

$$Db_nl_k = \frac{S}{4\pi k_a k_f f_{MX} B_\delta A}, \tag{8}$$

or considering equation (3)

$$Dl_k = \frac{S}{\pi k_a k_f B_\delta A \vartheta_{av}\left(\frac{b_n}{x_{\text{м}}}\right)}. \tag{9}$$

Equations (8) and (9) allow to calculate the basic dimensions of the generator to provide them with a given power. Value of the ratio $\frac{b_n}{x_{\text{м}}}$ is selected in the range from 0.8 to 1.0.

Stable performance of generator is observed under conditions where the minimum amplitude of rotor vibration $x_{min} = b_n$. When $b_n < x \leq \frac{\tau}{2}$ - power S slightly increases due to the growth of coefficient k_f. In constructions Fig. 1, a,c the length of winding l_k cannot be less than 2hм, where hм - thickness at one pole of the magnet. In order to ensure a minimum value of F_0 in is necessary to calculate the displacement amplitude of the rotor like that: $x_{\text{м}} = b_n + \Delta b$, where segment Δb is determined from $F_0 = 0{,}05F_M$. Preliminary it can be calculated $\Delta b = 0{,}25b_n$. Allowable value b_n can be found with a help of magnetic circuit calculation in case when magnetic saturation of poles is impossible. In constructions of generators (Figure 1, *b, d)* $b_n = b_M$ where b_M - the width of the magnet and length of winding l_k, which is not directly related to the thickness of the magnet hм, and can be determined from the conditions of obtaining the required EMF. We can take: $l_k = b_n + 2\Delta b = b_n\left(1 + \frac{2\Delta b}{b_n}\right) = b_n \cdot k_l$, where k_l - coefficient, preliminary $k_l = 1{,}5$.

Dimensions of the generators' magnets are determined from the calculation of their magnetic circuits. So in open circuit operation the balance equation for magnetomotive force (MMF) of the magnet and magnetic voltage drop in external circuit is as follows:

$$2k_f H_\delta \delta = 2Hh\text{м}, \tag{10}$$

where $k_f > 1$ - coefficient corrects for the voltage drop in the magnetic and ferromagnetic areas; H_δ - the magnetic field intensity in the air gap; δ - the width of air gap; H - intensity of the field generated by the magnet on the surface of its poles; $h\text{м}$ - magnet thickness per one pole *(Figure 1a, c)* or thickness of the magnet *(Figure 1b, d).*

For the air gap $H_\delta = \frac{B_\delta}{\mu_0}$, where B_δ - magnetic induction of the gap; μ_0 - vacuum permiability. For permanent magnets with a straight deperming:

$$H = H_C\left(1 - \frac{B}{B_r}\right), \tag{11}$$

where H_C - the coercive force of the magnet by induction; B – density of field in the core cross-sect of the magnet; B_r - remanent induction.

Induction on the outer (end face) planes of the magnet's surface $B_{out} = \frac{B}{\sigma}$, where σ > 1 - coefficient corrects for the presence of stray flux. The magnet spreads the magnetic flux $F_M = B_{out} \cdot S_M$, where S_M - cross-sectional area. Some part of this stream F_s is scattered by elements of coil flux guide (poles, polepieces) without crossing the air gap. The residual part - F_δ enters the coil flux circuit 3 (Fig. *1,a,b)* of the stator penetrating turns of winging 4. It can be written:

$$F_b = F_\delta + F_s = F_\delta\left(1 + \frac{F_s}{F_\delta}\right) = F_\delta \cdot k_\sigma,$$

where $k_\sigma = 1 + \frac{F_s}{F_\sigma}$ - scatter coefficient of coil flux guide.

And so:

$$F_\delta = B_\delta \cdot S_\delta = \frac{F_b}{k_\sigma} = \frac{B_b \cdot S_M}{k_\sigma} = \frac{B \cdot S_M}{\sigma \cdot k_\sigma} = \frac{B \cdot S_M}{k_s}, \tag{12}$$

where $k_s = \sigma \cdot k_\sigma$ - overall scattering coefficient.

From (12) we obtain:

$$B_\sigma = \frac{S_M}{S_\delta \cdot k_s} \text{ and } B = \frac{S_\delta \cdot k_s}{S_M} \cdot B_\sigma. \tag{13}$$

Substituting (11) and (13) into equation (10), after transformations we obtain

$$B_\sigma = \frac{B_r}{k_F \cdot \mu_\text{м} \frac{\delta}{h\text{м}} + k_s \frac{S_\delta}{S_M}}, \tag{14}$$

where $\mu_\text{м} = \frac{B_r}{\mu_0 H_c}$ - relative magnetic permeability of the magnet's material.

When calculating the size of the generator by equations (8) and (9) by the value B_σ and are given. To provide necessary value of B_σ - required thickness of the magnet is calculated according to the equation that we obtain from (14)

$$\frac{h\text{м}}{\delta} = \frac{k_F \cdot \mu_\text{м}}{\frac{B_r}{B_\delta} - \frac{k_s \cdot S_\delta}{S_M}}. \tag{15}$$

From (15) it follows that the generator can be implemented under the condition:

$$\frac{B_r}{B_\delta} > \frac{k_s \cdot S_\delta}{S_M}. \tag{16}$$

For construction presented on fig. 1, a,c the value $S_\delta = \pi D b_n$ (in the initial position of the rotor), $S_M = \frac{\pi D_m^2}{4}$, where D_m- the diameter of the magnet. After substituting S_δ and S_M (16) we obtain:

$$B_\delta < \frac{D_m}{4k_s\left(\frac{D}{D_m}\right)b_n} B_r \tag{17}$$

or, if the value B_δ is given:

$$b_n < \frac{D_m}{4k_s\left(\frac{D}{D_m}\right)} \cdot \frac{B_r}{B_\delta}. \tag{18}$$

In the construction given on figure 1, c the winding 4 in the initial position of the rotor is crossed not only by the flow of air gap F_δ but also by the stray flux of poles F_s. That is why the highest value of stray will be:

$$F_M = F_b = F_\delta \cdot k_\sigma.$$

But it does not lead to the increase in EMF as it is in generator on fig.1,a because the stray F_0 does not change after the displacement of the rotor by $\frac{\tau}{2}$ with respect to its initial position. In construction on the fig. 1,c the displacement of the rotor by $x > \frac{\tau}{2}$ is possible, but it can reduce the power of generator because it is hard to maintain the frequency of mechanical vibrations on the same level.

In the construction of generators on fig/ 1,*b*,*d* magnetic flux F_b coming from the outer surface of magnets enters an air gap in the stator yoke 3 (Fig. 1,b) and coil flux guideline of the rotor (Figure 1, *d)* almost completely, i.e. such relations are true: $F_b = F_\delta$; $B_b \cdot S_M = B_\delta \cdot S_\delta$. Since $S_M = S_\delta$ then $B_b = B_\delta$ and $k_\sigma = 1$. Then, in the case of magnets with straight deperming the value B_δ is calculated by the formula which follows from (14):

$$B_\delta = \frac{B_r}{k_F \mu_{\text{м}} \frac{\delta}{h\text{м}} - \sigma}.$$

If B_δ andδ are given it is necessary to provide the magnet's thickness:

$$\frac{h\text{м}}{\delta} = \frac{k_F \cdot \mu_{\text{м}}}{\frac{B_r}{B_\delta} - \sigma}.$$

Also it should be $B_\delta < \frac{B_r}{\sigma}$.

In the constructions on fig.1,*b*,*d* limit position of the rotor with respect to its initial position is $x_{\text{м}} = b_n + 0.5l_k$. This provides $F_0 \approx 0$.

Slightly modifying the constructions of generators on fig. 1, *a*, *c* by using the toothed rotor, one can increase the frequency multiplicity f_E in comparison withf_{MX}. A modified constructions are shown in Fig. 3 *a*, *b*.

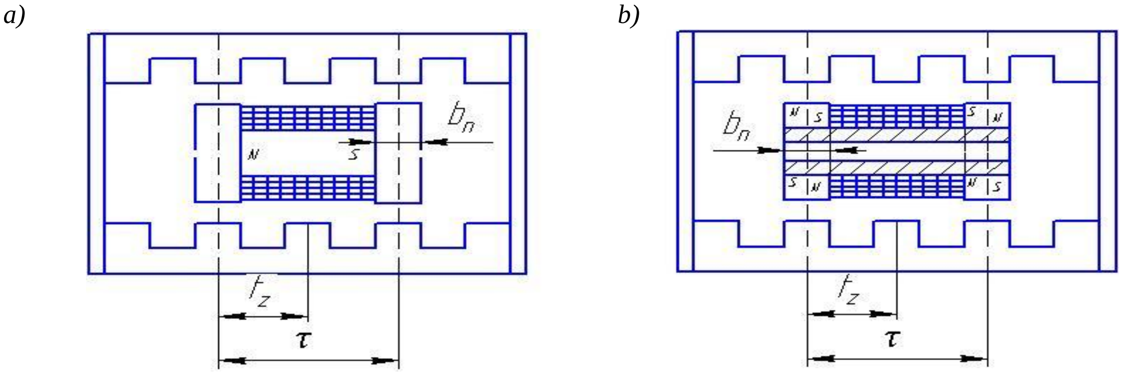


Fig. 3. Constructions of high-frequency linear generators

In generators on fig.1,a,c *the* slot pitch t_z is equal to the polar pitch τ. The displacement of the rotor by 0.5τ from initial position corresponds to the time 0.5T_E or 0.25T_MX. Then we obtain $f_E = 2f_{\text{MX}}$. If the length of the rotor is equal to τ and we make a few teeth, providing $\tau = kt_z$, where $k = 2{,}3, \dots$, then the displacement of the rotor by 0.5τ from initial position corresponds to the time $0.5\text{T}_E \cdot k$ or 0.25T_{MX}. Consequently, the frequency ratio will be: $f_E = 2kf_{MX}$. According to (1) this will lead to the increase of generator's EMF. In constructions on Fig. *3a, b* the magnetic flux F_0 will be a great in comparison with constructions on fig. 1 *a,d,* thereby reducing the coefficient k_f with the corresponding consequences.

Pole width b_n in constructions on fig. 3:

$$b_n = 0.5t_z = \frac{0.5\tau}{k}.$$

In constructions on Fig. 1c, d it can be taken $b_{n_0} = 0.5t$.

Ratio:

$$\frac{b_n}{b_{n_0}} = \frac{0.5\tau}{k\cdot 0.5\tau} = \frac{1}{k}.$$

Power ratio of generators, constructed in accordance with fig. 3 and fig. 1 with the same bore diameters and length of windings

$$\frac{S}{S_0} = \frac{kb_n}{b_{n_0}} = 1.$$

Consequently, the construction of the toothed rotor for generators, despite an increase in the frequency and EMF by k times does not lead to the increase its power output. On the contrary, it is a slightly reduced due to the reduction of k_f coefficient.

Conclusions.

1. Analysis of the basic structures of linear electric generators was carried out. Equations for calculating the power and EMF of generators, as well as for the calculation of their geometrical parameters were obtained.
2. A comparison of conventional and high capacity (toothed) generators was carried out. It was shown that usage of toothed rotor slightly reduces capacity of generator in comparison to the conventional one.

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ОЦІНКА ЕФЕКТИВНОСТІ РОБОТИ МАГНІТОРЕЙКОВОГО ДОВАНТАЖУВАЧА ПРИ ВИКОРИСТАННІ РІЗНИХ ТИПІВ МАГНІТНИХ БЛОКІВ

Вступ. Основним засобом транспортування вантажів і людей по горизонтальних виробках підземних підприємств є рейковий локомотивний транспорт. Одним з резервів підвищення продуктивності підземного транспорту є збільшення швидкості руху та вагової норми потяга, що обмежується можливостями традиційних гальмівних засобів локомотива. Згідно з діючими нормативними документами основним показником безпеки руху є гальмівний шлях поїзда – 40 м для вантажних і 20 м – для людських потягів, причому вказані значення повинні бути забезпечені в будь-яких умовах експлуатації. Колодково-колісні системи мають обмежену ефективність і не гарантують безпечну зупинку потяга на регламентованому гальмівному шляху. Це пояснюється тим, що при накладенні на колодку гальмівного притискання, величина якого більше деякого граничного для даних умов значення, відбувається зрив зчеплення і блокування колеса [1]. Величина граничного для даних умов гальмівного притискання визначається низкою чинників, серед яких найбільш значущими є вертикальне навантаження на колесо і стан рейкової колії. Розроблені у минулому способи покращення умов зчеплення колеса з рейкою, наприклад, підсипання піску або використання га-