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MACHINE-TRANSFORMER UNITS FOR WIND TURBINES

Background. Electric generators of wind turbines must meet the following requirements: they must be multi-pole; to have a minimum size and weight; to be non-contact, but controlled; to ensure the maximum possible output voltage when working on the power supply system. Multipole and contactless are relatively simply realized in the synchronous generator with permanent magnet excitation and synchronous inductor generator with electromagnetic excitation; moreover the first one has a disadvantage that there is no possibility to control the output voltage, and the second one has a low magnetic leakage coefficient with the appropriate consequences. Purpose. To compare machine dimensions and weight of the transformer unit with induction generators and is an opportunity to prove their application for systems with low RMS-growth rotation. Methodology. A new design of the electric inductor machine called in technical literature as machine-transformer unit (MTU) is presented. A ratio for estimated capacity determination of such units is obtained. Results. In a specific example it is shown that estimated power of MTU may exceed the same one for traditional synchronous machines at the same dimensions. The MTU design allows placement of stator coil at some distance from the rotating parts of the machine, namely, in a closed container filled with insulating liquid. This will increase capacity by means of more efficient cooling of coil, as well as to increase the output voltage of the MTU as a generator to a level of 35 kV or more. The recommendations on the certain parameters selection of the MTU stator winding are presented. The formulas for copper cost calculating on the MTU field winding and synchronous salient-pole generator are developed. In a specific example it is shown that such costs in synchronous generator exceed 2.5 times the similar ones in the MTU. References 3, figures 2.

Key words: **wind power, wind turbines, inductor electric machine, transformer-machine unit, pole, stator winding, generator.**

В работе предложена новая конструкция индукторной электрической машины, которая в технической литературе называется – машинно-трансформаторный агрегат (МТА). Для такого агрегата получено соотношение для определения расчетной мощности. На конкретном примере показано, что при одинаковых габаритах расчетная мощность МТА может превышать таковую для обычных синхронных машин. Конструкция МТА позволяет разместить катушки обмотки статора на некотором расстоянии от подвижных элементов машины, а именно, в закрытой емкости, заполненной электроизоляционной жидкостью. Это позволит увеличить мощность за счет более эффективного охлаждения обмотки, а также повысить выходное напряжение МТА как генератора до уровня 35 кВ и более. Библ. 3, рис. 2.

Ключевые слова: **ветроэнергетика, ветроэнергетические установки, индукторная электрическая машина, машинно-трансформаторный агрегат, полюс, обмотка статора, генератор.**

Introduction. Electric generators of wind turbines should meet the following requirements: they must be multi-polar, have a minimum size and weight, but be guided contactless, while working on the electrical system to provide maximal possible output voltage.

Problem definition. Multi-polarity and contactlessness are relatively simply realized in synchronous generators with excitation from permanent magnets and the inductor synchronous generator with electromagnetic excitation, and at first, as a drawback – no ability to control output voltage, the second – small (up to 0.4) utilization factor of magnetic flux of excitation.

State of the problem. In [1] the new design of electric machines – machine-transformer unit, which is non-contact, has electromagnetic excitation type inductor generator and a greater relative to the last utilization of magnetic flux is proposed. But the design of the unit, especially in three-phase version, is complex and, in addition, requires a significant copper consumption for stator windings. In [2] an improved design of machine-transformer unit with vertical shaft in three-phase design is presented.

Materials of investigations. A considered machine-transformer unit consists of two parts – the machine (Fig. 1,*a* above) and transformer (Fig. 1,*a* below), which have a common external magnetic core (stator) in a longitudinal package 1 of isolated plates electrical steel. On the machine shaft 2 of the rotor hub 3 is fixed on the outer surface of which is placed radial toothed packages 4 and 5, also made of insulated electrical steel plates and are relatively shifted in the axial direction. Teeth in these packages are oriented toward the gap between the rotor and the stator longitudinal packages and mutually displaced in the tangential direction geometric angle π/z_2, where z_2 is the number of teeth in one package of the rotor. Between toothed package contains 6 annular excitation coil attached on its outer surface to the longitudinal stator packs. Winding divided into two sections, located nearby. Each of the leading bands wound in mutually opposite directions, and the sections are interconnected at the end of the part winding rotor. Longitudinal package 1 along the length of the machine unit fixed by fill gaps between nonmagnetic alloy, which also forms part of the housing 7. In the radial direction packs 1 are based on the cylindrical sidewall 8 and 9, which made holes for their passage. In sidewalls constipation Leno-bearings 10 and 11 are seated on the shaft bearings 2. Outside bearings are closed by lids.

Width of each of the packages 1 is made less than width corresponding groove in its outer rotor (radial) side. The packages of the transformer, in extreme along the length of the working areas mounted coil windings interconnected respective schemes – «triangle» or «star». The lower end oppression packages to the ring yoke 13 wound with insulated ferromagnetic tape. Package 1 of the transformer coils 12 and 13, yoke placed in a closed container 14, which is filled electrical insulating fluid. The outside of the containers secured cooling device 15 combined with the internal volume of the pipes 16.

At supply of the excitation winding 6 by DC magnetic system unit, a magnetic flux, which is obtained, for example, tine rotor pack 4 and included in those packages stator longitudinal area «overlap» and whose maximum rotor teeth (in Fig. 1 direction magnetic excitation flow shows by arrows). Next, the magnetic flux of 1 packet enters the ring yoke 13 and then – in other packages stator 1, and it is in those areas «overlap» which package and rotor teeth 5 maximum. Then, with a package of one stator magnetic flux enters the rotor pack teeth 5 and the sleeve 3 again in package 4 of the rotor.

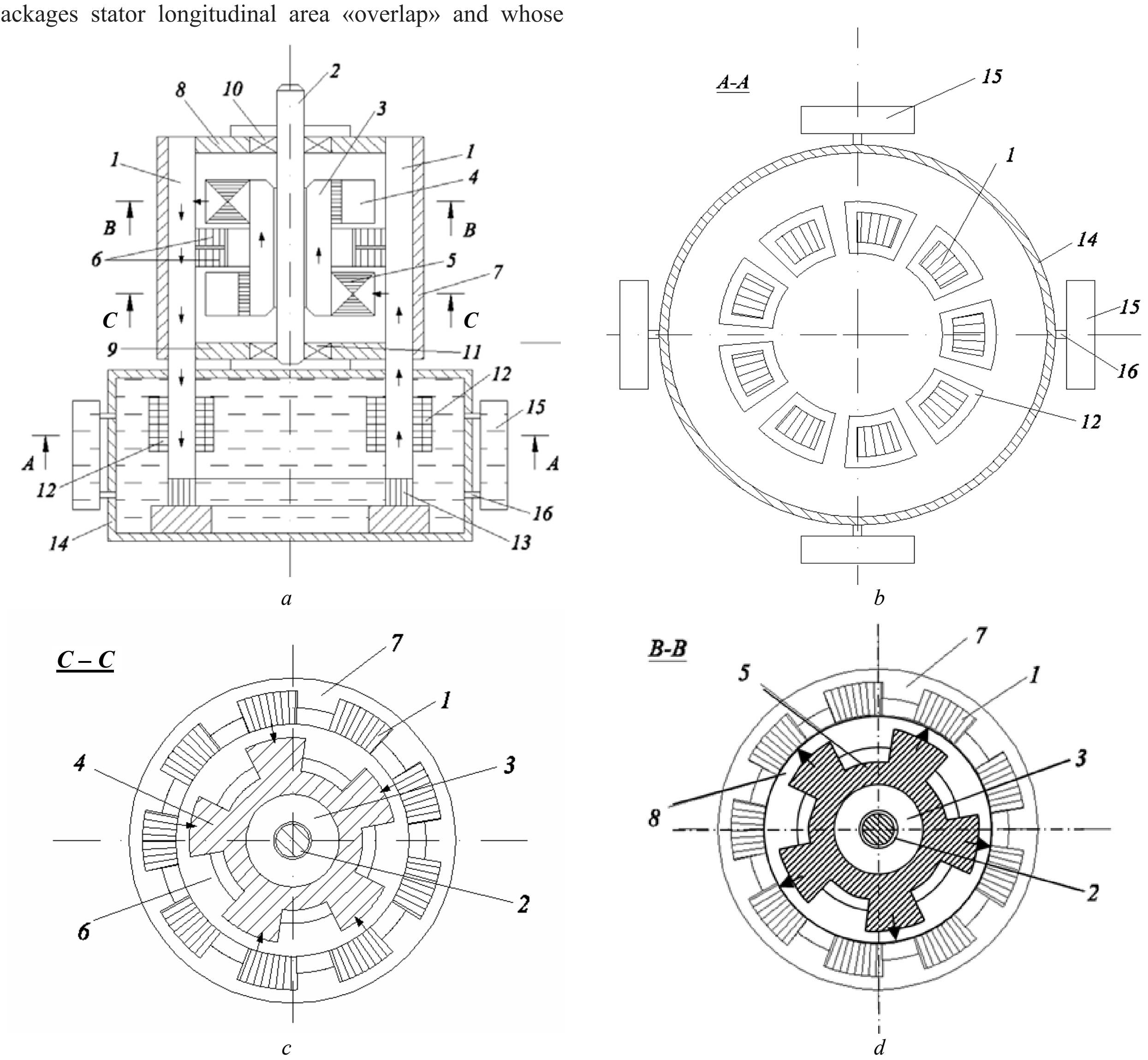


Fig. 1. Machine-transformer unit design
(*a* – longitudinal axial section; *b*, *c*, *d* – cross-sections in different places in height)

As the rotor rotates, for example by the wind turbine its teeth continuously change their position relative to the longitudinal stator packs, which leads to changes in the size and direction of the magnetic flux in the past. These flows permeate the working coil winding 12 that it causes the electromotive force (EMF) with frequency $f = z_2 n/60$, where n is the rotor rotation speed, rev/min.

Design power of the machine-transformer unit (MTU):

$$P' = mE_1 I_1 \,, \tag{1}$$

where m is the number of phases of the stator winding; E_1 is the electromotive force (EMF) of the phase; I_1 is the phase current.

On each package longitudinal magnetic stator coil one phase is placed. Number of coils per phase will be $z_{ph} = z_1/m$, respectively, EMF of the phase

$$E_1 = z_{ph} E_c K_r = z_{ph} E_c K_r \,/\, m,$$

where z_1 is the total number of packages загальна кількість пакетів; E_c is the EMF of one coil; K_r is the distribution ratio that takes into account the mutual phase shift vector EMF coils phase.

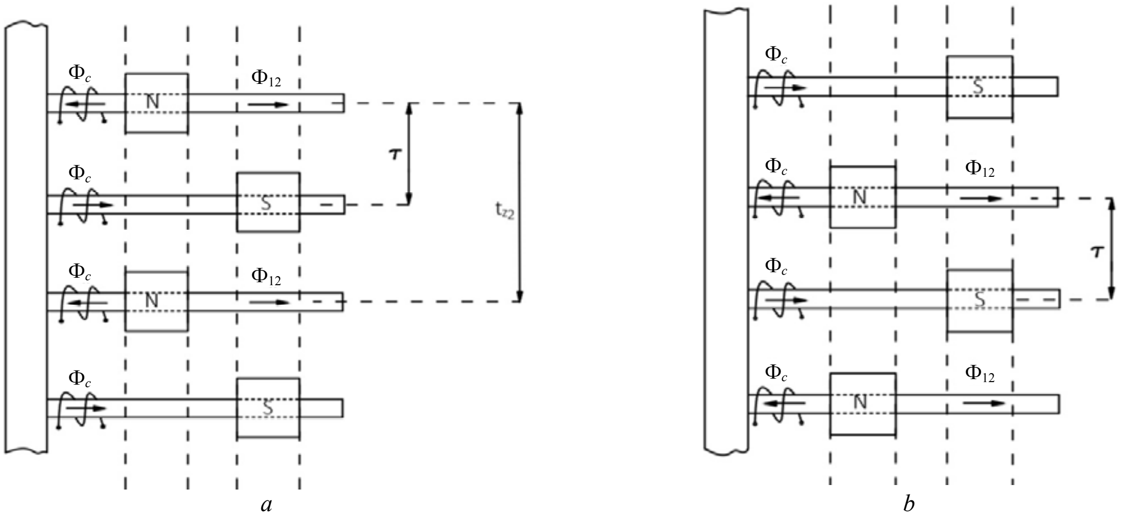
Figure 2 conventionally shows the relative position of the stator packs and rotor teeth at some initial time and after displacement of the rotor on the pole notch $\tau = 0.5t_2$, where t_2 is the tooth division of the rotor.

The magnetic flux which penetrates the coil turns, $\Phi_c = \Phi_{z1} - \Phi_{12}$ where Φ_{z1} is the flow, part of the package of the stator tooth rotor; Φ_{12} is the flow that of the stator package includes a groove adjacent rotor package.

Average EMF of the coil

$$\left\langle E_c \right\rangle = w_c \frac{\Delta\Phi}{\Delta t} = w_c \frac{2\Phi_c}{T/2} = 4 f w_c \left(\Phi_{z1} - \Phi_{12}\right), \qquad (2)$$

where w_c is the number of windings of the coil; $\Delta\Phi = 2\Phi_c$ is the magnetic flux change through the coil during time $\Delta t = 0.5T$, corresponding to a distance of displacement of the rotor relative to the initial position. $T = 1/f$ is the EMF period; f is its frequency.



a *b*

Fig. 2. Schemes of relative position of stator packets and rotor teeth at different times

Magnetic flux values:

$$\Phi_{z1} = \frac{\mu_0 F_\delta S_{z1}}{\delta_1}; \quad \Phi_{12} = \frac{\mu_0 F_\delta S_{12}}{\delta_2},$$

where μ_0 is the magnetic constant; F_δ is the magnetomotive force (MMF) winding one air gap; δ_1, δ_2 are the air gaps between the package and the stator tooth and rotor, respectively, between the package and the stator slot rotor; S_{z1}, S_{12} are the area magnetic flux between the tooth and the package and between package and groove, and, $S_{z1}=b_{z1}l_{z2}$; $S_{12}=b'_{g2}l_{z2}$, where b_{z1} is the width package; l_{z2} is the axial length (thickness) wave rotor; b'_{g2} is the estimated width of the groove of the rotor.

After the substitutions above formulas in expression (2) we have:

$$\left\langle E_c \right\rangle = 4 w_c f B_\delta l_{z2} b_{z_1} \left(1 - \frac{\delta_1 b'_{g2}}{\delta_2 b_{z_1}}\right), \qquad (3)$$

where B_δ is the magnetic flux density in the air gap between the stator package tooth and rotor (maximum value).

We write: $b_{z1}=\alpha_\delta\tau$, where α_δ is the pole arc ratio. As a result, the corresponding calculations obtained ratio $(b'_{g2}/b_{z1})=1.2$. The machine that analyzed by the rotor has two packages; area of the excitation magnetic flux action in the axial direction is the active length of the core, i.e. $l_\delta = 2l_{z2}$. We write the expression in parentheses of the formula (3) as follows:

$$\left(1 - \frac{\delta_1}{\delta_2}\frac{b'_{g2}}{b_{z_1}}\right) = \left(1 - \frac{1{,}2\delta_1}{\delta_2}\right) = K_\sigma,$$

where K_σ is the coefficient taking into the magnetic leakage flux.

In view of the above we write the expression for the current value of the EMF of the coil

$$E_c = K_f \left\langle E_c \right\rangle = 2K_f \alpha_\delta K_\sigma w_c f B_\delta l_\delta \tau, \qquad (4)$$

where K_f is the shape factor of the excitation magnetic flux.

Stator winding coils similar in design to the same bars of power transformers. As for transformers we write ratio for linear load: $A = I_1 w_c / l_c$ where l_c is the axial length of the coil. From here the phase current

$$I_1 = \frac{A l_c}{w_c}. \qquad (5)$$

Substituting relation (3), (4), (5) in the formula (1) taking into account the fact that: $f = pn/60$ and $\tau = \pi D/(2p)$, where p is the number of pairs of poles of the machine, which is the number of rotor teeth z_2 in one package; D is the diameter bore on which stator packets placed; n is the rotor rotation speed, rev / min we receive:

$$P' = \frac{\pi}{60D} \alpha_\delta K_f K_r K_\sigma B_\delta A D^2 l_\delta l_c z_1 n. \qquad (6)$$

Let's consider in detail the expression for the linear load:

$$A = \frac{I_1 w_c}{l_c} = \frac{j_a S_c w_c}{l_c} = \frac{j_a h_c l_c K_d}{l_c} = j_a h_c K_d,$$

where h_c is the length of the coil; K_d is the filling factor of the copper coil longitudinal section; j_a is the current density in the coil.

The interval between packets in a circle on the stator diameter D denote as b_{g1}, and $b_{g1} = t_1 - b_{z1}$, where t_1 is the tooth division of the stator. It is desirable to ensure $b_{g1} = 0.5t_1$. Then, the thickness of the coil $h_c \approx 0.45 b_{g1} \approx 0.23 t_1$. The value in the next product of formula (6) will be the following:

$$\frac{A l_c z_1}{D} = 0{,}72 j_a l_c K_d.$$

After substituting the last value in (6) we obtain:

$$P' = 3{,}8 \cdot 10^{-2} \alpha_\delta K_f K_\sigma K_r K_d B_\delta j_a D^2 l_\delta l_c n. \qquad (7)$$

Regarding the coefficient $\alpha_\delta = b_{z1}/\tau$:

- the width of the stator package $b_{z1} = t_1 - b_{g1} = 0.5t_1$;
- the pole dividing $\tau = \pi D/(2z_2)$.

So

$$\alpha_\delta = \frac{t_{z_1}}{t_{z_2}} = \frac{z_2}{z_1}.$$

To make the machine as 3-phase one it is necessary to provide:

$$z_1 = 2z_2 + K,$$

where $K = 1, 2, 3 \ldots$, then

$$\alpha_\delta = \frac{z_2}{2z_2 + K} = \frac{1}{2 + K/z_2} < 0.5.$$

The formula for the design power of classical synchronous machines with electromagnetic excitation is the following [3]:

$$P'_s = 0{,}164\alpha_i K_f K_w B_{\delta_c} A_s D^2 l_\delta n. \tag{8}$$

Design power ratio for the same overall dimensions

$$\frac{P'}{P'_s} = \frac{0{,}23\alpha_\delta K_r K_\sigma K_d B_\delta j_a l_c}{\alpha_i K_w B_{\delta_c} A}. \tag{9}$$

Perform by the last formula calculations (generators in the power range up to 1000 kVA).

Assume: α_δ=0.45; K_r=0.95; K_d=0.58; B_δ=1.5 T; j_a = $4\cdot10^6$ A/m^2; α_i=0.85; K_w=0.92; $B_{\delta s}$=0.9 T; A_s=$4\cdot10^4$ A/m.

As a result of calculations obtain:

$$\frac{P'}{P'_s} = \frac{0{,}23\cdot0{,}45\cdot0{,}95\cdot0{,}58\cdot1{,}5\cdot4\cdot10^6}{0{,}85\cdot0{,}92\cdot0{,}9\cdot4\cdot10^4} l_c = 11{,}2 l_c.$$

When l_c = 0.1 m we have $P' = 1.12P'_s$, i.e. the estimated capacity of the MTU exceed this for conventional synchronous generator. Selecting the l_c value, you can change the size of the power within the allowable heat load stator windings. It should be noted that the induction in the air gap B_δ of the MTU is limited only by magnetic saturation of the stator electrical steel package, i.e. $B_\delta \le 1.8$ T, which is significantly higher compared with classical generators.

Spatial distribution transformer and machine parts in the MTU will post stator coil windings at some distance from moving parts, such as in a closed container filled with electrical insulating fluid. This provides more efficient cooling of the stator winding in operation, which makes it possible to increase the current density in the winding and, therefore, power MTU compared with the case of air cooling. On the other hand, placing windings in electrical insulating fluid will increase the output voltage in generator mode MTU to the level of 35 kV and above and thus refuse the use of power transformer, which increases voltage before feeding electricity into the high-voltage network.

MTU stator winding consists of individual coils attached to the longitudinal packets. Reels are concentrated, which will provide the minimum length frontal parts. In conventional synchronous generator stator teeth number is selected according to the formula: $z_1=2pmq$, where $q\ge2$. For low-speed generators, for example, when n = 150 rev/min, f = 50 Hz, q = 2 must provide p = 20 and $z_1 = 2\cdot20\cdot3\cdot2=240$. This is complicated by the stator performance and forced to increase the size of the generator. Consider the opportunity to realize three-phase machine (MTU) where $z_1=2z_2+K$. The magnetic field provides excitement in the air gap of each packet number of rotor pole pairs $p = z_2$. Mutual angle γ (in electrical degrees) of two coils located on adjacent stator packets in this magnetic field will be:

$$\gamma = \frac{2\pi p}{z_1} = \frac{2\pi(z_1 - K)}{2z_1} = \pi - \frac{K\pi}{z_1}.$$

Neighboring packets belonging to one of the phases and coil these packages are interconnected in series opposite, the electrical angle between the vectors EMF coils will be the following

$$\gamma_c = \pi - \gamma = \frac{K\pi}{z_1}.$$

Number of packages in the three-phase stator electric machine $z_1 = am$, where a = 2, 3, 4 ... are the packets numbers per phase. In the formula $z_1 = 2z_2 + K$ the K number denotes the number of branches winding of one phase, connected in series or parallel. Number of coils in one winding branch is:

$$a_b = \frac{z}{Km} = \frac{a}{K}.$$

Electric angle that they occupy by the coil bore of one branch

$$\gamma_b = a_b\gamma_c = \frac{z_1}{K\cdot m}\cdot\frac{K\cdot\pi}{z_1} = \frac{\pi}{m} = 60^\circ \text{ el.}.$$

The last formula confirms the possibility of creating asymmetrical three-phase windings with 60 degree phase zone. From the preceding considerations it follows that the number a_b and K must be whole. Connection between them describes by the relationship:

$$a_b = \frac{z_1}{K\cdot m} = \frac{2z_2/(K+1)}{m}. \tag{10}$$

The value of K is desirable minimal. Consistently increasing the value of K, starting with one, we find from formula (10) ah appropriate value as the first whole number. For example, when n = 150 rev/min, f = 50 Hz, z_2 = 20, m = 3, then only at K = 2 we will obtain a_b =7. Then: $z_1 = 2\cdot20 + 2 = 42$, $a = z_1/m = 42/3 = 14$.

As noted earlier, the excitement of the MTU provides one fixed ring winding. Define the cost of copper for the creation of such winding. For magnetic circuit through which the excitation flow passes, the fair equation:

$$2\delta H_\delta K_F = I_f w_f = F_f,$$

where H_δ is the magnetic field strength in the air gap pack size δ_1 between stator and rotor teeth; $K_F > 1$ is the coefficient taking into account ferromagnetic of the chain; I_f and w_f are the current and number of turns of winding; F_f is the magnetomotive force (MMF) of the winding.

Consider the following: $H_\delta = B_\delta/\mu_0$; $I_f w_f = j_f S_f w_f$ = $= S_d w_f$ where j_f is the current density in the winding; S_f is the pre sectional area of the conductor; $S_d = S_f w_f$ is the sectional area of copper windings, and

$$S_d = \frac{F_f}{j_f} = \frac{2\delta B_\delta K_F}{\mu_0 j_f}.$$

Taking into account that the average length of the coil $\langle l\rangle = \pi(D-h_0)$, where h_0 is the radial thickness of winding, winding copper volume is as follows:

$$V_d = S_d\langle l\rangle = \frac{2\pi D\delta B_\delta K_F}{\mu_0 j_f}\left(1-\frac{h_0}{D}\right) = \frac{2V_\delta B_\delta K_F}{\mu_0 j_f}\left(1-\frac{h_0}{D}\right),$$

where $V_\delta = \pi D\delta$ is the volume of the air gap between stator packages and rotor teeth.

For comparison, we determine the cost of copper for the excitation winding of synchronous salient-pole generators. We write the equation of magnetic equilibrium magnetic circuit which passes through two adjacent poles,

$$2\delta H_{\delta_c} K_F K_\delta = 2I_c w_c = 2F_c ,$$

where K_δ is the coefficient taking into account the stator toothness; I_c and w_c are the current and number of turns of the pole winding; $F_c = I_c w_c$ is the EMF of the winding.

Cross-sectional area of copper of the coil

$$S_d = S_f w_c = \frac{F_c}{j_c} = \frac{\delta B_{\delta_c} K_F K_\delta}{\mu_0 j_c},$$

where j_c is the current density in the coil.

Volume of copper of the coil

$$V_d = S_d\langle l'\rangle ,$$

where $<l'>$ is the intermediate winding length.

It is about $<l'> = 2,5(l_\delta + b_p)$; l_δ is the length of the stator core; b_p is the width of the pole core.

Usually $b_p \approx 0.35\tau$. We write:

$$\langle l'\rangle = 2,5(l_\delta + 0,35\tau) = 2,5D\left({l_\delta}/{D} + {0,55}/{p}\right) = 2,5D\left(\lambda + {0,55}/{p}\right),$$

where $\lambda = l_\delta/D$. Then

$$V_d = \frac{0,8V_\delta B_{\delta_c} K_F K_\delta}{\mu_0 j_c}\left(\lambda + {0,55}/{p}\right).$$

The total volume of copper of the excitation winding consisting of $2p$ coils, taking into account the recommendation to the choice $\lambda = 0.8/p^{1/2}$, will be the following

$$V_{ds} = 2pV_d = \frac{0,9V_\delta B_{\delta_c} K_\delta K_F}{\mu_0 j_c}\left(1,45\sqrt{p}+1\right).$$

The ratio of the volume of copper windings excitation with the same volume of air gap, current density in the windings and magnetic cores saturation:

$$\frac{V_{ds}}{V_d} = \frac{0,45B_{\delta_c} K_\delta\left(1,45\sqrt{p}+1\right)}{B_\delta\left(1-h_0/D\right)}.$$

For example, for $p = z_2 = 20$; $B_\delta = 1.5$ T; $B_{\delta s} = 0.9$ T; $K_\delta = 1.2$; $h_0/D = 0.05$, we will obtain: $V_{ds}/V_d = 2.5$.

Conclusion.

1. A synchronous electrical machine in the form of a machine-transformer unit because of silent-pole design and large magnetic flux density in the air gap will permit to increase the design power and reduce the cost of copper on the excitation winding compared to a classical synchronous machine with electromagnetic excitation.
2. Placement of transformer part of the unit in a closed container filled by electrical insulation fluid will permit to increase the output voltage in the generator mode as well as the power of the unit.

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